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An evaluation of eleven operational cloud seeding programs in the watersheds of the Sierra Nevada Mountains

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ABSTRACT

A target–control statistical evaluation of 11 operational cloud seeding programs carried out in watersheds of the Sierra Nevada Mountains was conducted using Monte Carlo permutation (re-randomization) analysis. The water year (October–September) streamflow served as the response variable in the evaluations. The evaluation estimated the effect of seeding on unimpaired streamflow at each of the Sierra targets using the controls that give the most precise evaluation results possible with the available data. It was found that operational cloud seeding succeeded in increasing the streamflow in 6 of the 11 major watersheds in the Sierra Nevada Mountains. All 6 major watersheds indicating a positive seeding effect are on the western (upwind) side of the Sierra Nevada Mountain range. There was insufficient statistical evidence to reject the null hypothesis of no seeding effect in the other 5 major watersheds that were evaluated. It is noteworthy that the 5 watersheds whose evaluation was inconclusive include the 3 watersheds on the eastern (downwind) side of the Sierra Nevada Mountain range. The results of these evaluations and, in particular, those for the San Joaquin, Upper American and Carson–Walker operational cloud seeding programs illustrate the complexities involved in the transport and dispersion of silver iodide plumes from ground-based generators in mountainous terrain. The results suggest that aircraft seeding, either by itself or as a supplement to ground seeding, was able to affect targets that could not be affected by ground seeding alone. There was a statistically significant, positive seeding effect at the West Walker River Near Coleville target that was most likely due to contamination from an upwind seeding program, most likely the Mokelumne operational seeding program. Although contamination may have been present at the other seeding targets, it was not strong enough to affect the statistical results. Follow-on physical-statistical studies are needed to identify and understand the physical reasons for the statistical results of this study. In the opinion of this author, a comprehensive set of silver iodide tracer studies would contribute most to our understanding of the results, especially the dichotomy of seeding results for the operational seeding programs on the western and eastern watersheds of the Sierra Nevada Mountains.

1. Introduction

The Sierra Nevada stretches 645 km from Fredonyer Pass in the north to Tehachapi Pass in the south. It is bounded on the west by California's Central Valley, and on the east by the Great Basin. The height of the mountains in the Sierra Nevada gradually increases from north to south. Between Fredonyer Pass (just North of Lake Almanor) and Lake Tahoe, the peaks range from 1,525 m to more than 2,745 m. The crest near Lake Tahoe is roughly 2,745 m high, with several peaks approaching the height of 3,355 m including Mount Rose (3,285 m), which overlooks Reno from the north end of the Carson Range. The crest near Yosemite National Park is roughly 3,960 m and the entire range attains its peak at Mount Whitney (4,420 m). South of Mount Whitney, the

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range diminishes in elevation, but there are still several high points like Florence Peak (3,780 m). The range still climbs almost to 3,050 m near Lake Isabella (Kern River watershed), but south of the lake, the peaks reach only to a modest 2,440 m.

Operational (non-randomized) cloud seeding programs have been conducted in 12 of the major watersheds of the Sierra Nevada Mountains. These watersheds include the Lake Almanor, Upper American, Stanislaus, Mokelumne, Tuolumne, San Joaquin, Kings, Kaweah, Kern, Eastern Sierra, Carson–Walker, and Tahoe-Truckee river basins. Except for the Stanislaus operational cloud seeding program, which began only 3 years ago, all of the other programs have operated long enough to make the conduct of a meaningful statistical evaluation feasible. Fig. 1 shows the location of these 11 operational cloud seeding programs. Of the 11 operational cloud seeding programs, 3 are located in watersheds on the eastern or leeward side of the Sierra Nevada Mountains, i.e., the Eastern Sierra, Carson–Walker and Tahoe-Truckee operational cloud seeding programs, hereafter referred to as the Sierra East operational cloud seeding programs. The other 8 operational cloud seeding programs are located in watersheds on the western or windward side of the Sierra Nevada Mountains. Four of these operational cloud seeding programs are located in watersheds on the southwest side of the Sierra Nevada Mountains, i.e., the Kern, Kaweah, Kings, and San Joaquin operational cloud seeding programs, hereafter referred to as the Sierra Southwest operational cloud seeding programs. The other 4 operational cloud seeding programs are located in watersheds on the west-northwest side of the Sierra Nevada Mountains, i.e., the Tuolumne, Mokelumne, Upper American and Lake Almanor operational cloud seeding programs, hereafter referred to as the Sierra Northwest operational cloud seeding programs. Table 1 lists the operational cloud seeding programs by watershed, sponsor, seeding operator and the water year seeding started.

All of the operational cloud seeding programs have, for the most part, been conducted continuously since their inception, the earliest one starting in the San Joaquin River Basin in water year 1951. All the operational programs expect to increase precipitation according to the same seeding conceptual model, i.e., by seeding for microphysical effects to improve the precipitation efficiency of the clouds. Some operational programs try to accomplish this by conducting seeding operations on both summer and winter storms to increase rainfall and to augment snowpack, respectively, whereas some conduct seeding operations on only winter storms to augment snowpack. Both ground-based and aircraft seeding is being applied on some of the operational programs

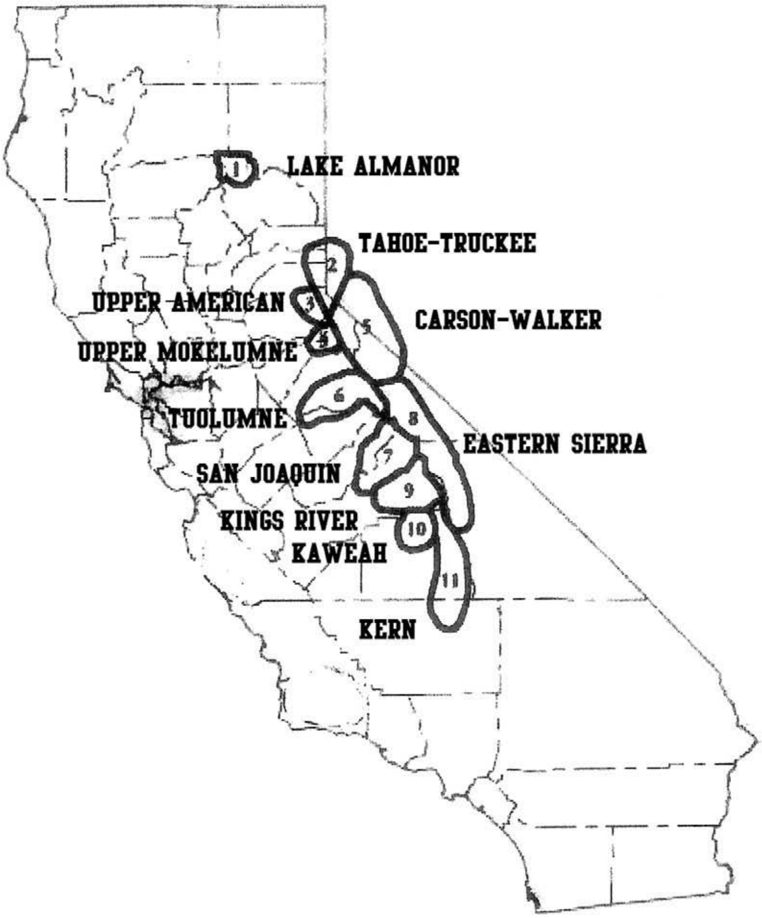

Fig. 1. Map of California showing the watersheds of the Sierra Nevada Mountains that are subject to operational cloud seeding programs. Map Scale: 1 cm = 80 km.

Table 1
Sierra operational cloud seeding programs.

Sierra watershed	Sponsor	Seeding operator(s)	WY start seeding
Sierra Southwest			
Kern	North Kern Water Storage District (NKWSD)	AI, RHS	1977
Kaweah	Kaweah Delta Water Conservation District (KDWCD)	AI	1976
Kings	Kings River Conservation District (KRCD)	AI, NAWC	1955
San Joaquin	Southern California Edison (SCE)	NAWC, AI, RHS	1951
Sierra Northwest			
Tuolumne	Turlock and Modesto Irrigation Districts (TID & MID)	AI, WMI	1991
Upper Mokelumne	Pacific Gas & Electric (PG&E)	PG&E	1954
Upper American	Sacramento Municipal Utility District (SMUD)	SMUD	1969
Lake Almanor	Pacific Gas & Electric (PG&E)	PG&E	1954
Sierra East			
Eastern Sierra	Los Angeles Department of Water & Power (LADWP)	AI	1987
Carson–Walker	Desert Research Institute (DRI)	DRI	1980
Tahoe-Truckee	Desert Research Institute (DRI)	DRI	1978

AI = Atmospherics Inc.; NAWC = North American Weather Consultants; RHS = RHS Consulting; WMI = Weather Modification Inc.

using seeding systems such as ground-based silver iodide generators, airborne silver iodide generators, airborne silver iodide flares, and/or airborne hygroscopic flares whereas some of the operational programs only use ground-based silver iodide generators.

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 concerned with assessing the evidence resulting from the statistical evaluation of the Sierra operational cloud seeding programs. The main purposes of this study are (1) to conduct an independent statistical evaluation of the 11 operational cloud seeding programs conducted in the watersheds of the Sierra Nevada Mountains over their period of operations for which adequate streamflow data is available, (2) to compare and contrast the resulting estimates of seeding effectiveness of the 11 operational cloud seeding programs, and (3) to identify statistical/physical studies that will lead to improvements in the cost-effectiveness of current cloud seeding operations. It is beyond the scope of this study to assess the physical evidence in support of the statistical results.

Some of the programs conducted on the western or windward side of the Sierra Nevada Mountains have already been independently evaluated to determine their effectiveness. Silverman (2007, 2008, 2009a) evaluated the Kings River, Kern and San Joaquin operational cloud seeding programs and found that each produced a positive, statistically significant seeding effect. Silverman (2008) showed that the pooling of the estimates of the seeding effects for the Kings River, Kern 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 evaluations of these programs will be updated by extending their evaluation period and/or by applying a more robust statistical methodology.

2. Statistical evaluation procedures

The ratio statistics method developed by Gabriel (1999, 2002) and, in particular, the bias-adjusted regression ratio, as applied by Silverman (2007, 2008), was used in a target–control evaluation of the effectiveness of seeding on streamflow for targets in the Kings River, Kern and San Joaquin watersheds. Silverman (2009a) used the Monte Carlo permutation test to conduct a more comprehensive evaluation of the San Joaquin operational cloud seeding program.

Monte Carlo permutation analysis of the regression ratio test statistic (RR) will be the 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 based on a random Monte Carlo sample of 10,000 permutations. For an observed *P*-value of 0.05, the accuracy from 10,000 random permutations is, with 95% confidence, ±0.0044.

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. Monte Carlo re-randomization (permutation) analysis involves the calculation of the permutations in the reference set of possible experimental outcomes chosen by random Monte Carlo sampling 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. It is the most robust statistical methodology for evaluating weather modification programs, especially non-randomized weather modification programs. This was emphasized by Gabriel and Petrondas (1983) who discussed the problems in evaluating non-randomized weather modification programs by parametric statistical methodologies.

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 regression equations were derived by the least squares method for each of the targets that predict the streamflow at the target station as a function of the streamflow at the control station. The regression results should be accurate and robust since there were no outliers in the data and the regression residuals exhibited homoscedacity (constant variance).

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). The World Meteorological Organization (WMO, 2007) recommends “Confidence intervals should be included in the statistical analyses to provide an estimate of the strength of the seeding effect so informed judgments can be made about its cost effectiveness and societal significance”. The method of Fletcher and Steffens (1996) is used to calculate the confidence limits estimated by the Monte Carlo permutation test. In this study, an evaluation result is considered to be statistically significant if its 90% confidence interval does not include the null hypothesis value of $RR = 1$ or 0% change in streamflow, i.e., it satisfies a 2-sided level of significance of 0.10.

3. Selection of the targets and controls

The evaluation of all 11 operational cloud seeding programs was based on using water year (October–September) unimpaired or full natural flow (FNF) streamflow data. This included FNF data that was measured directly or could be derived from measured data by adjusting it for upstream diversions and/or storage and evaporation in upstream reservoirs. It is emphasized at the outset that the selection of target and control stations for each of the operational cloud seeding programs was limited to those streamflow gauging sites for which full natural flow (FNF) data could be obtained/derived from sources in the public domain, i.e., the California Data Exchange Center (CDEC) and the United States Geological Survey (USGS) web sites. With very few exceptions, there are no papers in the open literature that describe the seeding history, seeding procedures and intended target area of the 11 operational cloud seeding programs. As a result, all streamflow stations in each watershed for which suitable FNF data is available were selected as potential targets. Since the streamflow stations that are available in the public domain may not be in locations that are most affected by the seeding, the author requested FNF data for such streamflow stations from the agency that is sponsoring the operational cloud seeding program. In some cases, FNF data for additional streamflow stations were made available to the author and their cooperation is gratefully acknowledged. However, representatives of SCE's San Joaquin operational cloud seeding program and PG&E's Upper Mokelumne and Lake Almanor operational cloud seeding programs denied the author's request for the data claiming it was proprietary information.

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. 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. 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. There are six streamflow stations that qualify as potential controls for the targets in the Sierra operational cloud seeding programs, They are the Sacramento Inflow-Shasta (CDEC ID SIS), the Yuba River Nr Smartville (CDEC ID YRS), the Cosumnes River at Michigan Bar (CDEC ID CSN), the Merced River at Pohono Bridge (USGS site #11266500, hereafter referred to as MDP), the Merced River at Happy Isles Bridge near Yosemite (USGS site # 11264500, hereafter referred to as MHI), the Success Dam (CDEC ID: SCC), and the Cottonwood Creek (hereafter referred to as CCR). Each of the Sierra targets was correlated with the potential control stations in its proximity, by themselves (linear correlation) and in physically reasonable combinations (multiple correlation), and the control or combination of controls that yielded the highest correlation was used in the statistical evaluation of that target.

4. Evaluation of Sierra Southwest operational cloud seeding programs

4.1. Kern operational cloud seeding program

The Kern River Basin is the southern-most major western slope watershed in the Sierra Nevada Mountains. According to Solak, et al. (1987), operational cloud seeding began during water year 1951 and was carried out sporadically until 1970. 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 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.

Silverman (2008) evaluated the Kern River operational cloud seeding program from water year 1977 through water year 2006 using the bias-adjusted regression ratio statistical method. Evidence for positive, statistically significant 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. This is an update of that evaluation through water year 2007 using Monte Carlo permutation statistics. Analysis of the potential controls indicated that the combination of SCC and CCR was the best control for all of the Kern targets. Table 2 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 2 shows the relative locations of all the selected targets and controls used in the Kern evaluations. The evaluation results are presented in Table 3.

The results shown in Table 3 indicate that the seeding effect for all the Kern targets was positive and statistically significant. Seeding increased the streamflow of North Fork of the Kern River, represented by KRK from about 2.4% to 12.9%. The North Fork of the Kern River merges with the South Fork of the Kern River below KRK at Lake Isabella. The main stem of the Kern River then flows out of Lake Isabella west-southwest towards Bakersfield passing through KRI and then on to KRB. Since the seeding effect at KRI is greater than that at KRK, with an increase in streamflow that is greater than can be accounted for by the increase on the North Fork of the Kern River (KRK), it is likely that seeding also increased the streamflow of the South Fork of the Kern River above Lake Isabella. If the intended target area of the Kern River operational cloud seeding program was the area above Lake Isabella that drains into the North and South Forks of the Kern River, the results of this evaluation indicate that the seeding operations was successful.

4.2. Kaweah operational cloud seeding program

Seeding under the Kaweah operational cloud seeding program started in water year 1976 and continued thereafter until 2007 when it was discontinued. The seeding was carried out by dispensing silver iodide from aircraft. A search of the public domain for streamflow stations in the Kaweah River watershed with adequate FNF data records revealed only one station, Kaweah River-Terminus Dam (CDEC ID KWT). FNF data for streamflow stations higher up in the Kaweah River watershed could not be found in the public domain nor could the KDWCD provide any. Analysis of the potential controls indicated that the combination of SCC and MHI was the best control for the Kaweah target. Table 2 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 2 shows the relative locations of all the selected target and controls used in the Kaweah evaluation. The evaluation results are presented in Table 3.

It can be seen from Table 3 that there is no evidence of a seeding effect at KWT. However, one cannot rule out with certainty that seeding had no effect at all. The seeding effect may have occurred at higher elevations in the Kaweah River watershed. Nevertheless, considering that the KDWCD does its

Table 2

Location, average historical period FNF, and data record length of the selected target and control stations used to evaluate the Sierra Southwest operational cloud seeding programs. Following the name of each operational cloud seeding program is the water year that operational cloud seeding started.

Station name	Station ID	Latitude (° N)	Longitude (° W)	Elevation (m)	Average FNF (m^3) (1)	Period of data
Targets						
Kern (1977)						
Kern R Nr Kernville (2)	KRK	35.945	118.477	1,103	6.6687E + 08	1913–1995
Kern R Bel Isabella (2)	KRI	35.639	118.484	742	8.0988E + 08	1930–2007
Kern R-Bakersfield (2)	KRB	35.432	118.945	43	8.7292E + 08	1901–2007
Kaweah (1976)						
Kaweah R Term. Dam (2)	KWT	36.412	119.003	151	5.2642E + 08	1901–2007
Kings R (1955)						
Kings NF Nr Cliff Camp (2)	KGC	36.994	118.897	1,872	3.2948E + 08	1922–1995
Kings Pre-Project Piedra (2)	KGP	36.833	119.325	136	2.1293E + 00	1901–1991
Kings R-Pine Flat Dam (2)	KGF	36.831	119.335	296	1.2466E + 08	1901–2007
San Joaquin (1951)						
Bear Creek (3)	BCK	37.339	118.973	2,245	8.7525E + 07	1922–2007
Mono Creek (4)	MNO	37.361	118.991	2,249	1.4499E + 08	1922–2007
Pitman Creek (3)	PIT	37.199	119.213	2,140	3.8322E + 07	1929–2007
San Joaquin R Bl Friant (2)	SJF	36.984	119.723	90	2.3886E + 09	1901–2007
Controls						
Success Dam (2)	SCC	36.061	119.922	211	1.9855E + 08	1931–2007
Cottonwood Creek (5)	CCR	36.439	118.080	478	2.1552E + 07	1935–2007
Merced R-Happy Isles Br (3)	MHI	37.732	119.558	1,224	3.3343E + 08	1916–2007
Merced R-Pohono Br (3)	MDP	37.717	119.665	1,177	5.8694E + 08	1922–2007

(1) Average water year full natural flow (FNF) during the historical period for the targets and during the period 1935-1950 for the controls.

(2) Data obtained from the California Data Exchange Center (CDEC) web site online at http://cdec.water.ca.gov.

(3) Data obtained from the United States Geological Survey (USGS) web site online at http://waterdata.usgs.gov/nwis/nwis.

(4) 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).

(5) Data obtained from the Los Angeles Department of Water and Power (personal communication).

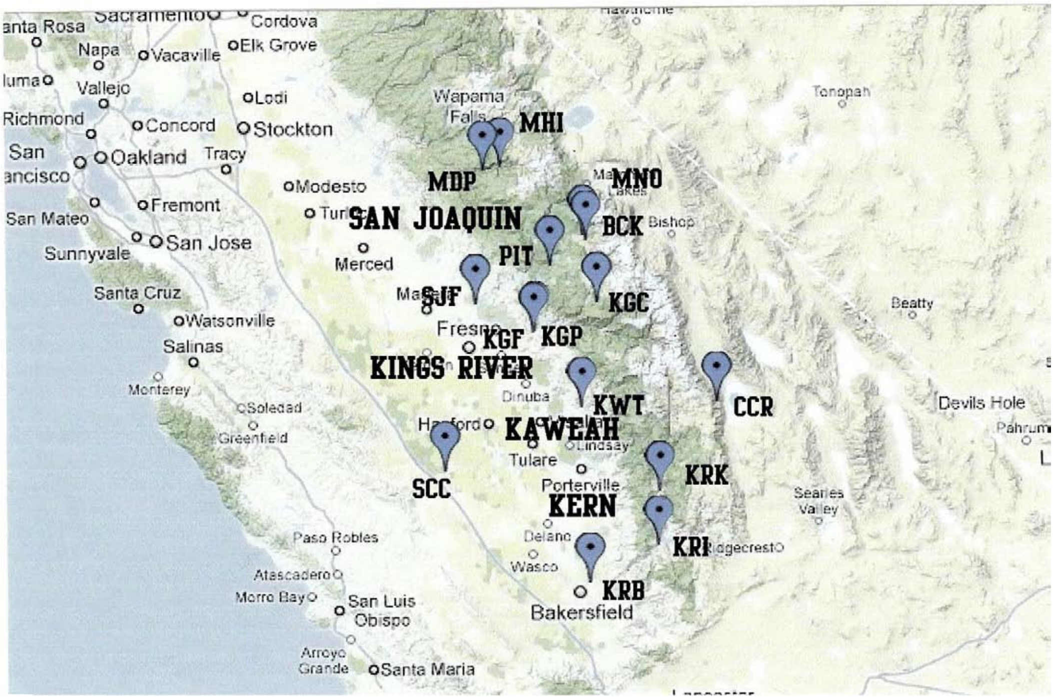

Fig. 2. Map showing the locations of the selected targets and controls used in the evaluation of the Kern, Kaweah, Kings River, and San Joaquin operational cloud seeding programs. Map Scale: 1 cm = 40 km.

accounting of the Kaweah streamflow at KWT and expected to see a seeding effect there (KDWCD, Personal Communication), one would have to conclude that the operational cloud seeding program did not succeed in accomplishing its objective.

Table 3
Water year seeding effects are shown for each of the selected Sierra Southwest targets. Shown are the multiple correlation coefficient (ρ) with the controls, and LB and UB are the lower and upper bound of the 90% confidence interval for the proportional effect of seeding ($100 \times (RR-1)$, where RR is the regression ratio), respectively. Statistically significant results are italicized.

Target	End WY	Controls	ρ	90% confidence interval	
				LB	UB
KERN					
KRK	1995	SCC, CCR	0.979	*+2.4*	*+12.9*
KRI	2007	SCC, CCR	0.981	*+5.3*	*+15.2*
KRB	2007	SCC, CCR	0.987	*+3.0*	*+10.9*
KAWEAH					
KWT	2007	SCC, MHI	0.988	−4.0	+0.6
KINGS					
KGC	1995	MDP, CCR	0.972	*0.0*	*+7.5*
KGP	1991	MDP, CCR	0.981	*+2.2*	*+9.2*
KGF	2007	MDP, CCR	0.975	*+1.3*	*+6.6*
SAN JOAQUIN					
BCK	2007	MHI, CCR	0.984	−1.2	+2.9
MNO	2007	MDP, CCR	0.975	*+2.1*	*+8.9*
PIT	2007	MDP, CCR	0.981	*+1.5*	*+9.4*
SJF	2007	MDP, CCR	0.993	−0.6	+3.3

4.3. Kings River operational cloud seeding program

The Kings River operational cloud seeding program started in water year 1955. With the exception water years 1981–1987 when seeding was totally suspended while the Pine Flat Power Plant was being constructed and several partial year, weather-related suspensions thereafter, the seeding program has been operated each year since its inception. Seeding has been conducted by dispensing silver iodide from both ground generators and aircraft 6–7 months each year in an effort to increase rainfall and snowpack.

The Kings River operational cloud seeding program was designed to increase the annual flow of the Kings River into Pine Flat Reservoir. Consequently, Kings River-Pine Flat Dam (CDEC Station ID KGF), representing a drainage area of 1545 square miles, was selected as the primary target for evaluation. Silverman (2007) evaluated the Kings River operational cloud seeding program at the KGF target for the water year period from 1977 through water year 2006 using the bias-adjusted regression ratio statistical method. Evidence for a positive, statistically significant seeding effect was found, with an estimated increase in streamflow due to seeding of about 5.1%. This is an update of that evaluation through water year 2007 using Monte Carlo permutation statistics. The streamflow stations Kings NF Nr Cliff Camp (CDEC ID KGC) and Kings Pre-Project Piedra (CDEC ID KGP) were included as targets because they are above KGF, higher up in the Kings River watershed Analysis of the potential controls indicated that the combination of MDP and CCR was the best control for all of the Kings River targets. Table 2 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 2 shows the relative locations of all the selected targets and controls used in the Kings River evaluations. The evaluation results are presented in Table 3.

The results shown in Table 3 indicate that the seeding effect for all the Kings River targets was positive and statistically significant. Seeding increased the streamflow at the primary target (KGF) by about 6.1% with 90% confidence that the true effect of seeding lies somewhere between +1.3% and +6.6%. Thus, the results of this evaluation indicate that the operational seeding program succeeded in meeting its objective.

4.4. San Joaquin operational cloud seeding program

The San Joaquin River Basin Weather Modification Program 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. 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.

Silverman (2009a) evaluated the San Joaquin operational cloud seeding program from water year 1951 through water year 2006 using Monte Carlo permutation statistics. Evidence for positive, statistically significant and cost-effective increases in streamflow after 56 years of seeding was found for Mono Creek (MNO) and Pitman Creek (PIT), but the results for Bear Creek (BCK) were not statistically significant. This is an update of that evaluation through water year 2007. In addition to using MNO, PIT and BCK as targets as before, the San Joaquin River Blw Friant (CDEC ID SJF) was included as a target. Analysis of the potential controls indicated that the combination of MDP and CCR was the best control for all of the San Joaquin targets except for BCK where MHI and CCR was the best control combination. Table 2 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 2 shows the relative locations of all the selected targets and controls used in the San Joaquin evaluations. The evaluation results are presented in Table 3.

It can be seen from Table 3 that the results of this study confirm those of the previous evaluation (Silverman, 2009a). A positive, statistically significant increase in streamflow was found for Mono Creek (MNO) and Pitman Creek (PIT), about +8.3% and +8.7%, respectively, but the result for Bear Creek (BCK) was not statistically significant. In addition, there was no evidence of a seeding effect at SJF. It is speculated that the increases in streamflow at MNO and PIT were diluted by under-seeded and/or non-seeded streams as it flowed to SJF.

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. Pitman Creek (PIT) showed a significant increase in seeding effectiveness in 1975 (Silverman, 2009b) that was consistent with the introduction of aircraft seeding as a supplement to the ongoing ground-based seeding. With the addition of the supplemental aircraft seeding, a statistically significant seeding effect became evident. 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.

5. Evaluation of Sierra Northwest operational cloud seeding programs

5.1. Tuolumne operational cloud seeding program

The Tuolumne operational seeding program began in water year 1991 and has been conducted every year thereafter. The seeding is carried out by dispensing silver iodide from aircraft. A search of the public domain for streamflow stations in the Tuolumne River watershed with adequate FNF data records revealed only one station, Tuolumne R-La Grange Dam (CDEC ID TLG). Since the Hetch Hetchy reservoir was the primary target of the seeding, a request was made to the Hetch Hetchy Water and Power Department to provide FNF data for this evaluation. They complied and provided data for the Tuolumne Nr Hetch Hetchy (hereafter referred to as THH). Although THH was the primary target for the seeding, the Turlock Irrigation District (TID) expected to see the seeding effect at TLG where it does its accounting for the streamflow of the Tuolumne River watershed. Analysis of the potential controls indicated that the combination of CSN and MDP was the best combination of controls for TLG, whereas CSN and YRS was the best control combination for THH. Table 4 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 3 shows the relative locations of all the selected targets and controls used in the Tuolumne evaluations. The evaluation results are presented in Table 5.

It can be seen from Table 5 that seeding succeeded in increasing the average water year streamflow at THH, the intended target of the seeding. However, there is no evidence of a seeding effect at TLG where the TID does its accounting of the streamflow for the Tuolumne River watershed. It is speculated that the increase in streamflow at THH was diluted by under-seeded and/or non-seeded streams as it flowed to TLG.

5.2. Upper Mokelumne operational cloud seeding program

The Upper Mokelumne operational seeding program began in water year 1954 and was conducted every year thereafter. Seeding was carried out by a network of silver iodide ground generators. A search of the public domain for streamflow stations in the Upper Mokelumne River watershed with adequate FNF data records revealed two stations, i.e., Cole Creek Nr Salt Springs Dam (USGS 11315000, hereafter referred to as MCC) in the upper reaches of the watershed, and Mokelumne-Mokelumne Hill (CDEC ID MKM) in the lower part of the watershed. Analysis of the potential controls indicated that the combination of CSN and MDP was the best

Table 4
Location, average historical period FNF, and data record length of the selected target and control stations used to evaluate the Sierra Northwest operational cloud seeding programs. Following the name of each operational cloud seeding program is the water year that operational cloud seeding started.

Station name	Station ID	Latitude (° N)	Longitude (° W)	Elevation (m)	Average FNF (m^3) (1)	Period of data
Targets						
Tuolumne (1991)						
Tuolumne-Hetch Hetchy (5)	THH	37.938	119.797	1,157	9.2801E+08	1971–2007
Tuolumne R-La Grange Dam (2)	TLG	37.666	120.441	52	2.2260E+09	1901–2007
Mokelumne (1954)						
Cole Creek Nr Salt Springs Dam (3)	MCC	38.519	120.212	1,804	5.6271E+07	1928–2007
Mokelumne-Mokelumne Hill (2)	MKM	38.313	120.719	175	8.4653E+08	1906–2007
American (1969)						
Loon Lake (4)	ALO	38.983	120.323	592	1.2878E+08	1925–2008
Robbs/Gerle (4)	ARO	38.966	120.394	485	9.7035E+07	1925–2008
Union Valley (4)	AUO	38.864	120.438	448	1.9034E+08	1925–2008
Area A (4)	AAO	38.853	120.453	430	5.4423E+07	1925–2008
Area B (4)	ABO	38.828	120.537	268	4.5154E+07	1925–2008
Ice House (4)	AIO	38.824	120.359	507	6.6065E+07	1925–2008
SF American River(4)	ASO	38.772	120.699	198	5.1784E+08	1925–2008
Lake Almanor (1954)						
Feather NF Nr Prattville (2)	FPR	40.169	121.091	1,338	8.5403E+08	1906–1992
Feather NF-Pulga (2)	FPL	39.794	121,451	398	2.6580E+09	1912–1995
Feather SF at Ponderosa (2)	FTP	39.548	121.303	549	3.0377E+08	1901–1992
Feather River at Oroville (2)	FTO	39.522	121.547	45	4.8448E+09	1906–2007
Controls						
Merced R-Pohono Br (3)	MDP	37.717	119.665	1,177	5.8694E+08	1922–2007
Cosumnes R-Michigan Bar (2)	CSN	38.500	121.044	51	4.6703E+08	1908–2007
Yuba R Nr Smartville (2)	YRS	39.235	121.273	85	2.8643E+09	1901–2007
Sacramento Inflow-Shasta (2)	SIS	40.718	122.420	853	6.7790E+09	1922–2007

(1) Average water year full natural flow (FNF) during the historical period for the targets and during the period 1935–1950 for the controls.
(2) Data obtained from the California Data Exchange Center (CDEC) web site online at http://cdec.water.ca.gov.
(3) Data obtained from the United States Geological Survey (USGS) web site online at http://waterdata.usgs.gov/nwis/nwis.
(4) Data obtained from the Sacramento Municipal Utility District (personal communication).
(5) FNF data obtained from the Hetch Hetchy Water and Power Department (personal communication).

control for both of the Upper Mokelumne targets. Table 4 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 3 shows the relative locations of all the selected targets and controls used in the Upper Mokelumne evaluations. The evaluation results are presented in Table 5.

It can be seen from Table 5 that there is no evidence of a seeding effect at either MCC or MKM. However, one cannot rule out with certainty that seeding had no effect at all. The seeding effect may have occurred at other locations in the Upper Mokelumne watershed. A request was made to PG&E for FNF data for additional sreamflow stations in the intended target area of the seeding program but they would not provide it. In the absence of such streamflow stations, one would have to conclude that the operational cloud seeding program did not succeed in accomplishing its objective.

5.3. Upper American operational cloud seeding program

The Upper American River operational seeding program began in water year 1969 and was conducted every year thereafter. Seeding was carried out by a network of silver iodide ground generators. The Sacramento Municipal Utility District (SMUD) facilitated the evaluation of the Upper American operational cloud seeding program by (1) identifying seven streamflow stations in the intended target area and (2) providing the water year FNF data for these stations. The 7 seeding targets include Loon Lake (ALO), Robbs/Gerle (ARO), Union Valley (AUO), Area A (AAO), Area B (ABO), Ice House (AIO), and SF American River (ASO). It was found that the combination of CSN and YRS was the best control for all of the Upper American targets. Table 4 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 3a shows the relative locations of all the selected targets and controls used in the Upper American River evaluations. The evaluation results are presented in Table 5.

There are 3 noteworthy findings in the evaluation results for the Upper American operational cloud seeding program shown in Table 5. First, statistically significant increases in the average water year streamflow were found but only in 4 out of the 7 target sub-basins. The 90% confidence interval for the average water year increase (%) in streamflow for all the individual target sub-basins combined is (+2.3, +7.6). Second, the correlation coefficient (ρ) between the target and controls for AAO and ABO is noticeably smaller than that for the other target sub-basins. The physical reasons why this is the case is a matter worthy of further investigation. Third, the result for AUO is statistically significant and that for AAO is not despite the fact that they are quite close to each other. The second and third findings once again illustrate the complexities involved in the transport and dispersion of silver iodide plumes from ground-based generators in mountainous terrain. Silverman (2009a, 2009c) found that the silver iodide plumes from ground-based generators behaved in a similar manner in the San Joaquin and Vail operational cloud seeding programs, respectively. Also, the analysis of the Colorado River Basin Pilot Project by Elliott et al. (1978) found that, under low-level stable conditions, the silver iodide from ground-based generators was transported northwestward parallel to the mountain barrier instead of northeastward and up into the clouds over mountain as intended.

5.4. Lake Almanor operational cloud seeding program

The Pacific Gas and Electric Company (PG&E) has been engaged in operational cloud seeding in the Lake Almanor area since 1954. Seeding has been carried out by a network of silver iodide ground generators. A search of the public domain for streamflow stations in the Lake Almanor watershed with adequate FNF data records revealed four stations, i.e., the Feather NF Near Prattville (CDEC ID FPR), the Feather NF-Pulga (CDEC ID FPL), the Feather SF at Ponderosa (CDRC ID FTP), and the Feather River at Oroville (CDEC ID FTO). The streamflow record for FTO was current but the streamflow records for FPR, FPL, and FTP ended in the early 1990s. PG&E would not provide FNF data for other streamflow stations in the Lake Almanor target area nor would they update the records for FPR, FPL, and FTP. Analysis of the potential controls indicated that the combination of CSN and Sacramento Inflow-Shasta (CDEC ID SIS) was the best control for FPR, and the combination of CSN and YRS was best for FPL, FTP, and FTO. Table 4 shows the location, the average historical period FNF, and the data record length of the target and control stations used in the evaluation. Fig. 3 shows the relative locations of all the selected targets and controls used in the Lake Almanor evaluations. The evaluation results are presented in Table 5.

It appears that seeding succeeded in increasing the average water year streamflow at FTP and FTO, the target sub-basins in the lower part of the Lake Almanor watershed. However, there is no evidence of a seeding effect at TPR and FPL, the target sub-basins in the upper part of the Lake Almanor watershed.

6. Evaluation of Sierra East operational cloud seeding programs

It was recognized from the outset that seeding operations had been conducted in the Sierra East watersheds prior to the start of the operational cloud seeding programs. For example, the Pyramid Lake Pilot Project in the Tahoe watershed was conducted from 1970 to 1975 (Squires, 1977) and the Bishop area in the Eastern Sierra watershed was seeded during the period 1948–1950 (Hall et al., 1953). In such cases, part of the usually used historical period of the target would be contaminated and would serve to mask any seeding effect that may have been produced by the operational seeding. It was also recognized from the outset that the Sierra East watersheds were very vulnerable to contamination by the seeding programs conducted in the upwind watersheds on the western side of the Sierra Nevada Mountains prior to and during the Sierra East operational seeding periods. For example, DRI (Huggins, 2006) conducted a snow chemistry study in the Tahoe-Truckee watershed and found silver

Fig. 3. Map showing the locations of the selected targets and controls used in the evaluation of the Tuolumne, Upper Mokelumne, Upper American, and Lake Almanor operational cloud seeding programs. Map Scale: 1 cm = 40 km. An expanded map of the Upper American operational cloud seeding program is shown in panel a. (a) Expanded map showing the locations of the selected targets and controls used in the evaluation of the Upper American operational cloud seeding programs. Map scale: 1 cm = 10 km.

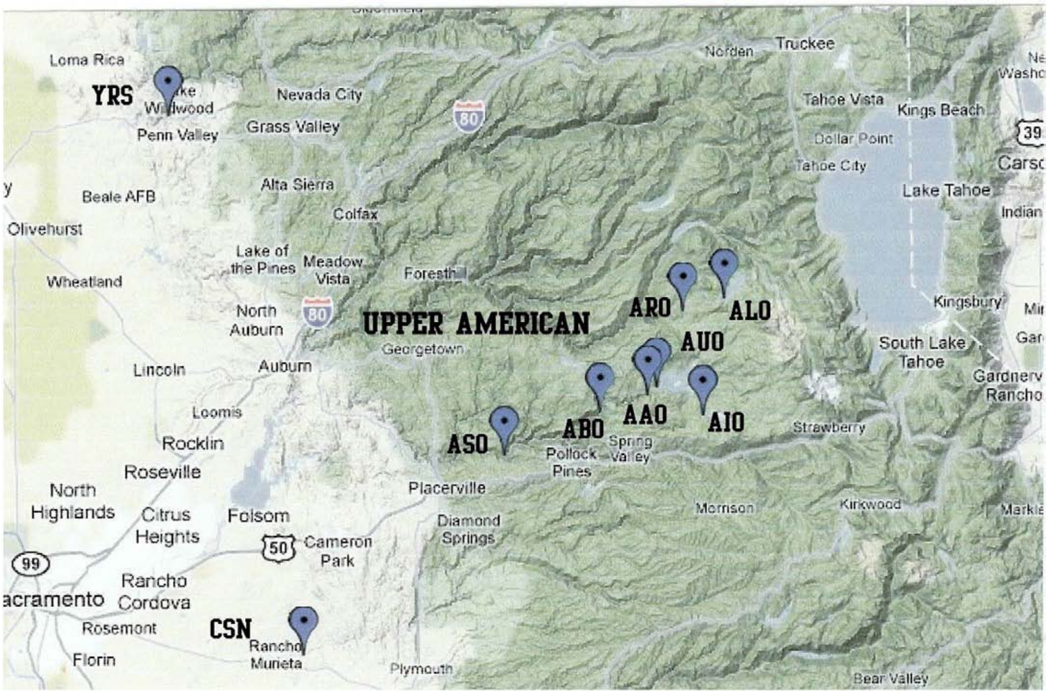

Fig. 3 (*continued*).

deposits from sources other than the Nevada seeding program, the likely source of which was attributed to the upwind, Upper American River operational cloud seeding program. In such cases, the operational period as well as part of the usually used historical period of the target would be contaminated and would serve to mask any seeding effect that may have been produced by the operational seeding. In an attempt to identify a seeding effect that may have been produced by the operational seeding programs, the evaluation was conducted in the following manner

Table 5
Water year seeding effects are shown for each of the selected Sierra Northwest targets. Shown are the multiple correlation coefficient (ρ) with the controls, and LB and UB are the lower and upper bound of the 90% confidence interval for the proportional effect of seeding ($100 \times (RR-1)$, where RR is the regression ratio), respectively. Statistically significant results are shown in bold italics font.

Target	End WY	Controls	ρ	90% confidence interval	
				LB	UB
TUOLUMNE					
THH	2007	CSN, YRS	0.922	***+2.4***	***+7.5***
TLG	2007	CSN, MDP	0.994	−3.0	+0.2
MOKELUMNE					
MCC	2007	CSN, MDP	0.972	−3.3	+1.8
MKM	2007	CSN, MDP	0.991	−1.7	+1.0
AMERICAN					
ALO	2008	CSN, YRS	0.962	***+5.6***	***+11.9***
ARO	2008	CSN, YRS	0.966	−5.3	+0.1
AUO	2008	CSN, YRS	0.976	***+2.7***	***+8.6***
AAO	2008	CSN, YRS	0.931	−6.4	+5.0
ABO	2008	CSN, YRS	0.918	***+8.8***	***+24.4***
AIO	2008	CSN, YRS	0.974	−0.5	+4.2
ASO	2008	CSN, YRS	0.975	***+1.8***	***+7.9***
LAKE ALMANOR					
FPR	1992	CSN, SIS	0.942	−4.9	+0.6
FPL	1995	CSN, YRS	0.965	−0.7	+4.4
FTP	1992	CSN, YRS	0.940	***+2.5***	***+12.6***
FTO	2007	CSN, YRS	0.981	***+2.3***	***+7.0***

1) The data record for the target and control was divided into 3 parts, i.e., (a) a historical period that starts with the earliest water year of record and ends in water year 1947, thereby pre-dating any known seeding activities in or upwind of the Sierra East watersheds, (b) a pre-operational period that starts in 1948 and ends the water year before operational seeding started, and (c) an operational period that starts the water year operational seeding started and ends at the last year of the evaluation.
2) An evaluation was done for each seeding target, i.e., for the operational period against the historical period.
3) If the evaluation for the operational period shows evidence of a seeding effect, an evaluation is done for the pre-operational period, i.e., for the pre-operational period against the historical period, to make sure the seeding effect during the operational period was due to the operational seeding program and not due to contamination from a source external to the operational seeding program. If the evaluation of the pre-operational period results in a statistically significant change in streamflow (a seeding effect), it is considered to be due to contamination and, in such cases, the seeding effect found for the operational period is likely to be due, partially if not entirely, to the continuing influence of the contamination. If the evaluation of the pre-operational period results in a statistically non-significant change in streamflow (no

seeding effect), the seeding effect during the operational period is considered to be caused by the operational seeding program. Contamination may still be present but is not strong enough to cause the null hypothesis to be rejected.

6.1. Eastern Sierra operational cloud seeding program

The Eastern Sierra operational cloud seeding program was launched in 1987. Seeding operations have been carried out primarily by aircraft dispensing silver iodide particles into the clouds. Four seeding targets were chosen for the evaluation. They include the Owens River-Long Valley Dam (OWV), the Bishop Area Runoff (BAR), the Big Pine Runoff (BPR), and the Long Valley Runoff (LVR). The Los Angeles Department of Water and Power (Paul Scantlin, Private Communication) provided this author with the full natural flow data for all of targets and controls in the Eastern Sierra region. The location, the average water year full natural flow (FNF), and the data record lengths for the target and control sites are given in Table 6. MDP in combination with CCR was selected as the control for all of the Eastern Sierra targets. Fig. 4 shows the relative locations of all the selected targets and controls used in the Eastern Sierra evaluations.

Table 7 shows the results of the evaluation for the operational periods. Since the confidence interval for all the targets includes 0%, none of the results are statistically significant. Thus, there is not any evidence to reject the null hypothesis that seeding had no effect on the average water year streamflow at any of the selected Eastern Sierra targets.

6.2. Carson–Walker operational cloud seeding program

Operational seeding in the Carson–Walker operational cloud seeding program started in 1980. Except for 1984 and 1985, seeding operations have continued every year since then. The winters of 1982 and 1983 were very wet and no funding was allocated to the project in 1984 and 1985 Seeding operations have been carried out with both silver iodide ground generators and aircraft dispensing silver iodide particles into the clouds. Three seeding targets were chosen for the evaluation. They include the East Walker River Near Bridgeport (CDEC ID: EWR), the West Walker River Near Coleville (CDEC ID: WWR), and the East Fork Carson River Near Gardnerville (CDEC ID: EFC). The location, the average water year full natural flow (FNF), and the data record lengths for the target and control sites are given in Table 6. CSN was chosen for the evaluation of EFC and MDP was chosen for the evaluation of WWR and EWR Fig. 4 shows the relative locations of all the targets and controls used in the Carson–Walker evaluations.

Table 7 shows the results of the evaluation for the operational periods. Water years 1984 and 1985 were omitted from the seeded sample since there was no seeding during those years. Since the confidence interval for the operational periods for the EFC and EWR targets includes 0%, none of those results are statistically significant. Thus, there is not any evidence to reject the null hypothesis that seeding had no effect on the average water year streamflow at the EFC and EWR targets.

On the other hand, the result for WWR for the operational period is statistically significant. Therefore, an evaluation was done for the pre-operational period to see if this result is due to the operational seeding or due to contamination. The result for WWR for the pre-operational period is shown in parentheses in Table 7. It can be seen that the 90% confidence interval for the pre-operational period is almost identical to that for the operational period. Thus, the seeding effect during the pre-operational period is most likely the result of contamination from an upwind operational cloud seeding program since WWR was not being directly seeded during that period. The seeding effect during the operational period is most likely due, in part or in whole, to the continuing influence of this contamination. As a further check, an evaluation was done for the operational period against the combination of the historical and pre-operational

Table 6
Location, average historical period FNF, and data record length of the selected target and control stations used to evaluate the Sierra East operational cloud seeding programs. Following the name of each operational cloud seeding program is the water year that operational cloud seeding started.

Station name	Station ID	Latitude (° N)	Longitude (° W)	Elevation (m)	Average FNF (m^3) (1)	Period of data
Targets						
Eastern Sierra (1987)						
Long Valley Runoff (4)	LVR	37.708	118.792	637	1.4325E+08	1935–2004
Owens River-Long Valley Dam (4)	OWV	37.588	118.708	629	1.8970E+08	1922–2007
Bishop Area Runoff (4)	BAR	37.367	118.383	383	1.0542E+08	1935–2004
Big Pine Runoff (4)	BPR	37.167	118.292	372	7.0092E+07	1935–2004
Carson–Walker (1980)						
East Walker River Near Bridgeport (2)	EWR	38.328	119.214	1,951	1.1974E+08	1923–2007
West Walker River Near Coleville (2)	WWR	38.378	119.449	2,009	2.0584E+08	1922–2007
East Fork Carson River Near Gardnerville (2)	EFC	38.847	119.703	1,519	2.7884E+08	1923–2007
Tahoe-Truckee (1978)						
Truckee River at Farad (2)	TRF	39.428	120.033	1,571	4.2031E+08	1908–2007
Controls						
Merced R-Pohono Br (3)	MDP	37.717	119.665	1,177	5.8694E+08	1922–2007
Cottonwood Creek (4)	CCR	36.439	118.080	478	2.1552E+07	1935–2007
Cosumnes R-Michigan Bar (2)	CSN	38.500	121.044	51	4.6703E+08	1908–2007

(1) Average water year full natural flow (FNF) during the historical period for the targets and during the period 1935–1950 for the controls.
(2) Data obtained from the California Data Exchange Center (CDEC) web site online at http://cdec.water.ca.gov.
(3) Data obtained from the United States Geological Survey (USGS) web site online at http://waterdata.usgs.gov/nwis/nwis.
(4) Data obtained from the Los Angeles Department of Water and Power (personal communication).

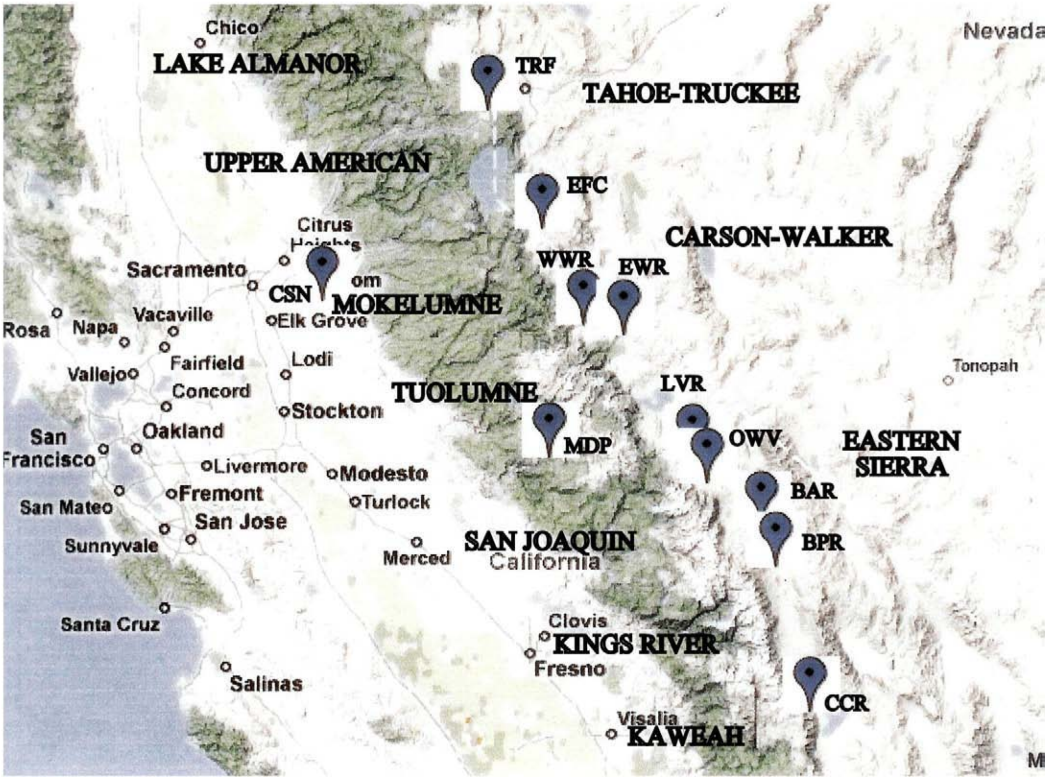

Fig. 4. Map showing the locations of the selected targets and controls used in the evaluation of the Sierra East operational cloud seeding programs. Also shown are the locations of the operational cloud seeding programs on the western side of the Sierra Nevada Mountains that are upwind of the Sierra East seeding programs. Map Scale: 1 cm = 40 km.

periods. There was no statistically significant effect, indicating that the seeding effect during the operational period was offset by the seeding effect due to contamination during the pre-operational period. It is likely that the contamination is from the Mokelumne operational cloud seeding program. This speculation is based on the following 2 factors: (1) the Mokelumne operational cloud seeding program began in 1954 so its duration covers almost all of the pre-operational period, and (2) it is plausible that the effect of seeding under the Mokelumne operational cloud seeding program, which was not evident in the streamflow stations of the Mokelumne watershed (see Section 5.2), manifested itself further downwind in the West Walker streamflow.

6.3. Tahoe-Truckee operational cloud seeding program

Operational seeding in the Tahoe-Truckee operational cloud seeding program started in 1978. Except for 1984 which followed a very wet winter, seeding operations have continued every year since then. Seeding operations have been carried out with both silver iodide ground generators and aircraft dispensing silver iodide particles into the clouds. The Truckee River at Farad (CDEC ID: TRF) was chosen as the seeding target for the evaluation. The location, average water year full natural flow (FNF) and data record lengths for the target and control sites are given in Table 6. CSN was chosen as the control for TRF. Fig. 4 shows the relative locations of the target and control used in the Tahoe-Truckee evaluation.

Table 7 shows the results of the evaluation for the operational period. Water Year 1984 was omitted from the seeded sample since there was no seeding during that year. Since the confidence interval for TRF includes 0%, the result is not statistically significant. Thus, there is not any evidence to reject the null hypothesis that seeding had no effect on the average water year streamflow at TRF.

Table 7
Water year seeding effects are shown for each of the selected Sierra East targets. Shown are the multiple correlation coefficient (ρ) with the controls, and LB and UB are the lower and upper bound of the 90% confidence interval for the proportional effect of seeding ($100 \times (RR-1)$, where RR is the regression ratio), respectively. Statistically significant results are shown in bold italics font.

Target	End WY	Controls	ρ	90% confidence interval	
				LB	UB
Eastern Sierra					
LVR	2004	MDP,CCR	0.920	−9.2	+1.1
OWV	2007	MDP,CCR	0.903	−2.3	+10.7
BAR	2004	MDP,CCR	0.952	−5.9	+0.8
BPR	2004	MDP,CCR	0.935	−5.2	+3.4
Carson–Walker					
EWR	2007	MDP	0.940	−11.9	+1.5
WWR	2007	MDP	0.978	***+1.5*** ***(+1.5)***	***+8.3*** ***(+8.0)***
EFC	2007	CSN	0.955	−7.8	+1.1
Tahoe-Truckee					
TRF	2007	CSN	0.961	−6.9	+1.5

Table 8
Summary of the statistically significant results of the evaluation of the Sierra operational cloud seeding programs.

Sierra watershed	Seed mode	N_T	N_{SS}	90% confidence interval
	(1)	(2)	(3)	(4)
Sierra Southwest				
Kern	A	3	3	KRK(2.4, 12.9); KRI(5.3, 15.2); KRB(3.0, 10.9)
Kaweah	A	1	0	None
Kings	G + A	3	3	KGC(0.0, 7.5); KGP(2.2, 9.2); KGF(1.3, 6.6)
San Joaquin	G + A	4	2	MNO(2.1, 8.9); PIT(1.5, 9.4)
Tuolumne	A	2	1	THH(2.4, 7.5)
Sierra Northwest				
Upper Mokelumne	G	2	0	None
Upper American	G	7	4	ALO(5.6, 11.9); AUO(2.7, 8.6); ABO(8.8, 24.4); ASO(1.8, 7.9)
Lake Almanor	G	4	2	FTP(2.5, 12.6); FTO(2.3, 7.0)
Sierra East				
Eastern Sierra	A	4	0	None
Carson–Walker	G + A	3	0	None (5)
Tahoe-Truckee	G + A	1	0	None

(1) Seed mode: G = ground-based seeding; A = aircraft seeding.
(2) N_T = number of target sub-basins evaluated.
(3) N_{SS} = number of target sub-basins having a statistically significant seeding effect.
(4) 90% confidence interval = 90% confidence interval for target sub-basins having a statistically significant seeding effect; XXX(LB,UB) where XXX is the target station code, LB is the lower bound (%) and UB is the upper bound (%).
(5) There was evidence of a seeding effect at WWR(1.5, 8.3) but it was apparently due to contamination from an upwind seeding program.

7. Summary

A target–control statistical evaluation of 11 operational cloud seeding programs carried out in watersheds of the Sierra Nevada Mountains was conducted using Monte Carlo permutation (re-randomization) analysis. The water year (October–September) streamflow served as the response variable in the evaluations. The evaluation estimated the effect of seeding on unimpaired streamflow at each of the Sierra targets using the controls that give the most precise evaluation results possible with the available data. The statistically significant results of the evaluations are summarized in Table 8.

The evaluation of the 11 operational cloud seeding programs has led to the following important findings:

1) Operational cloud seeding succeeded in increasing the streamflow in 6 of the 11 major watersheds in the Sierra Nevada Mountains. There was a statistically significant seeding effect in at least one sub-basin in each of the 6 watersheds. All 6 major watersheds indicating a positive seeding effect are on the western (upwind) side of the Sierra Nevada Mountain range.
2) There was insufficient statistical evidence to reject the null hypothesis of no seeding effect in the other 5 major watersheds that were evaluated. It is noteworthy that the 5 watersheds whose evaluation was inconclusive include the 3 watersheds on the eastern (downwind) side of the Sierra Nevada Mountain range.
3) The results of these evaluations and, in particular, those for the San Joaquin, Upper American and Carson–Walker operational cloud seeding programs illustrate the complexities involved in the transport and dispersion of silver iodide plumes from ground-based generators in mountainous terrain. It reinforces the conclusion of Warburton et al (1995) who made trace chemical measurements of the silver content of snow in the central Sierra Nevada Mountains and found evidence that the silver iodide from ground-based generators was transported in directions and into areas other than those intended. It adds to the body of evidence that recognizes that achieving adequate transport and dispersion of ground-released silver iodide is a key problem in seeding winter orographic clouds (Boe et al., 2004).
4) The results suggest that aircraft seeding, either by itself or as a supplement to ground seeding, was able to affect targets that could not be affected by ground seeding alone. Whether ground seeding, aircraft seeding, or a mixture of both are used in an operational cloud seeding programs will largely depend on logistical and cost considerations.
5) There was a statistically significant, positive seeding effect at the West Walker River Near Coleville (WWR) target that was most likely due to contamination from an upwind seeding program, most likely the Upper Mokelumne operational seeding program. Although contamination may have been present at the other seeding targets, it was not strong enough to affect the statistical results.

The findings of the statistical evaluation of the 11 Sierra operational cloud seeding programs suggest a number of physical-statistical studies that would undoubtedly lead to the optimization of all of them. Follow-on physical-statistical studies are needed to identify and understand the physical reasons for the statistical results of this study. In the opinion of this author, a comprehensive set of silver iodide tracer studies would contribute most to our understanding of the results, especially the dichotomy of seeding results for the operational seeding programs on the western and eastern watersheds of the Sierra Nevada Mountains.

8. Remarks

It is emphasized that this study is an a posteriori evaluation of non-randomized seeding programs. From a rigorous statistical standpoint, the suggested effects that are indicated must be confirmed through new, *a priori*, randomized experiments specifically designed to establish their validity. It is also emphasized that the lack of a statistically significant increase in average water year streamflow at any of the selected targets in the Sierra operational cloud seeding programs does not mean that the seeding of these watersheds was not effective. It merely means that there was insufficient statistical evidence to reject the null hypothesis.

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References

AMS, 1998. Scientific background for the AMS policy statement on planned and inadvertent weather modification. Bull. Amer. Meteor. Soc. 79, 2773–2778.

Boe, B., Bomar, G., Cotton, W.R., Marler, B.L., Orville, H.D., Warburton, J.A., 2004. The Weather Modification Association's response to the National Research Council's Report entitled "Critical Issues in Weather Modification Research" Report of a review panel. J. Wea. Mod. 36, 53–82.

Elliott, R.D., Shaffer, R.W., Court, A., Hannaford, J.F., 1978. Randomized cloud seeding in the San Juan Mountains. Colorado. J. Appl. Meteor. 17, 1298–1318.

Fletcher, L., Steffens, F.E., 1996. The use of permutation techniques in evaluating the outcome of a randomized storm seeding experiment. J. Appl. Meteor. 35, 1546–1550.

Gabriel, K.R., 1999. Ratio statistics for randomized experiments in precipitation stimulation. J. Appl. Meteor. 38, 290–301.

Gabriel, K.R., 2002. Confidence regions and pooling—some statistics for weather experimentation. J. Appl. Meteor. 41, 505–518.

Gabriel, K.R., Petrondas, D., 1983. On using historical comparisons in evaluating cloud Seeding operations. J. Climate Appl. Meteor. 22, 626–631.

Hall, F., Henderson, T.J., Cundiff, S.A., 1953. Cloud seeding in the Sierra near Bishop Creek. California. Bull. Amer. Meteor. Soc. 34, 111–116.

Huggins, A., 2006. Evaluating the impacts of wintertime cloud seeding on the snowpack and streamflow in a watershed. Final Report, Bureau of Reclamation under Cooperative Agreements 03-FC-81-0858 and 03-FC-81-0924. Desert Research Institute, Reno, NV (May 188pp).

McGurty, B.M., 1999. Turning silver to gold: measuring the benefits of cloud seeding. Hydro- Review 18, 2–6.

Nicholls, N., 2001. The insignificance of significance testing. Bull. Amer. Meteor. Soc. 82, 981–986.

Silverman, B.A., 2007. On the use of ratio statistics for the evaluation of operational cloud seeding programs. J. Wea. Mod. 39, 50–60.

Silverman, B.A., 2008. A statistical evaluation of Kern River operational cloud seeding program. J. Wea. Mod. 40, 7–16.

Silverman, B.A., 2009a. An evaluation of the San Joaquin operational cloud seeding program using Monte Carlo permutation statistics. J. Wea. Mod. 41, 15–22.

Silverman, B.A., 2009b. Reply to Paul Smith's Comment (Comments on Silverman's Evaluation of the Kern River Program) *J.* Wea. Mod. 41, 163–164.

Silverman, B.A., 2009c. An independent statistical evaluation of the Vail operational cloud seeding program. J. Wea. Mod. 41, 7–14.

Solak, M.E., Henderson, T.J., Allan, R.B., Duckering, D.W., 1987. Winter orographic seeding over the Kern River Basin in California. J. Wea. Mod. 19, 36–40.

Squires, P., 1977. The Pyramid Lake Pilot Project, 1970–1975. Final Report, Vols. 1 and 2, Bureau of Reclamation Contract 14-06-D-7000. : Lab. Atmos. Phys. Desert Research Institute, University of Nevada System, Reno (476pp).

Tukey, J.W., Brillinger, D.R., Jones, L.V., 1978. The Management of Weather Resources. Vol. II—The Role of Statistics in Weather Resources Management Weather Modification Advisory Board, Statistical Task Force, Washington, DC, June 30, 1978. US Government Printing Office.

Warburton, J.A., Stone III, R.H., Marler, B.L., 1995. How the transport and dispersion of AgI aerosols may affect detectability of seeding effects by statistical methods. J. Appl. Meteor. 34, 1929–1941.

WMO, 2007: WMO Weather Modification Statement and Guidelines. CAS-MG2/Doc4.4.1, Appendix C. (Available online at www.wmo.int/pages/prog/arep/wwrp/new/weathermod_new.html).