AN INDEPENDENT STATISTICAL EVALUATION OF THE VAIL OPERATIONAL CLOUD SEEDING PROGRAM

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

Abstract. An independent target-control statistical evaluation of the Vail operational cloud seeding program over its period of operations from 1977 to 2005 was conducted using ratio statistics and, in particular, the bias-adjusted regression ratio. The water year (October-September) streamflow expressed in Acre-Feet (AF) served as the response variable in the evaluations. The effect of seeding on eight (8), closely-spaced sub-basins in the Vail watershed was evaluated using the controls that give the most precise evaluation results possible with the available data. Evidence for statistically significant seeding effects ranging from +6.3% to +28.8% was found for 5 of the 8 seeding targets. The maximum seeding effect is centered on Bighorn Creek (GBH) and decreases for targets both northwest and southeast of GBH. An analysis of the time evolution of the seeding effect suggests that the percent change in streamflow at each of the target sub-basins was about the same from water year to water year.

1. INTRODUCTION

The Vail operational cloud seeding program began during the last half of the 1976-77 winter season. The ski areas and water conservancy districts contracted Western Weather Consultants to mount a wintertime cloud seeding program in the Vail basin in an attempt to counter the effects of drought conditions and poor winter snowpack. The Vail Program has operated continuously since then with a regularly scheduled three-month program that starts on November first and continues to the end of January each winter season. A few of the operational seeding seasons have been extended into February and occasionally into March during winters of below normal precipitation. Only once has the seeding season been terminated early (in late December) during a winter with exceptionally above normal snowfall amounts. Brief periods of suspensions of seeding operations have occurred during periods of avalanche concerns or warnings.

The initial program at Vail had 8 ground-based silver iodide nuclei generators that could provide continuous seeding plume coverage over and around the Vail ski slopes with targeting wind directions varying from 240 degrees to about 350 degrees. In 1981, the target area was expanded to include the Beaver Creek ski area and the network of seeding generators was expanded to 14 seeding sites within the same approximate targeting wind direction envelope. Over the next few years an additional three seeding sites were added to the total generator network (for a total of 17) to further improve the total seeding plume coverage of cloud nuclei that would feed into the cloud systems forecast to move over the two ski areas. In the seeding methodology of Western Weather Consultants, the ground generators are located at sites that utilize upwind ridges and channeling valleys to push the seeding material into the lower cloud region with the most favorable seeded regions being downwind of the initial barriers.

In 2001, Western Weather Consultants completed a ten-year evaluation (Hjermstad, 2001) of the more recent operational years with the most complete sets of available precipitation data. A non-statistical analysis of the Snotel data suggested a seeded precipitation increase of 15% on all of the seeded days and an increase of 7% for the average seasonal precipitation. A non-statistical analysis of the Ski area data suggested an average 31% increase of the precipitation on seeded days in the ski areas and a 15% increase of the average seasonal precipitation. Western Weather Consultants (Hjermstad, Personal Communication) obtained its estimates of the non-seeded precipitation for each of the Vail targets by extrapolating the average precipitation value of 2 nearby non-seeded sites (one on each side of the target) to the Vail target by adjusting them for the differences in natural precipitation due to elevation and distance. The Vail operational cloud seeding program has never been subjected to a statistical evaluation. Until now, statistical

Corresponding author address: Bernard A. Silverman, 7038 E. Peakview Place Englewood, CO 80111; e-mail: silvermanb@aol.com

evaluations of snowpack enhancement cloud seeding programs in the Colorado Rockies were all based on precipitation measurements taken over a period of several hours to several days as the response variable.

Both statistical and physical evidence are required to establish the success of any cloud seeding activity (AMS, 1998). Because the expected effects of cloud seeding are within natural meteorological variability, statistical methods are needed to detect a seeding effect with reasonable certainty. Physical evidence is needed to establish plausibility that the effects suggested by the results of the statistical evaluation could have been caused by the seeding intervention. This study is primarily concerned with assessing the statistical evidence in support of the Vail operational cloud seeding program. The purpose of this study is to conduct an independent statistical evaluation of the Vail operational cloud seeding program from water year 1977 through water year 2005. The objectives of the evaluation are (1) to determine if cloud seeding enhanced streamflow in the Vail 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 follow-up physical studies that will help explain and support the plausibility of the statistical results.

2. EVALUATION PROCEDURES

The bias-adjusted regression ratio was used in a target-control evaluation of the effect of seeding on streamflow in the Vail River Basin. The water year (October-September) streamflow expressed in Acre-Feet (AF) served as the response variable in the evaluations. Silverman (2007) 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 (2007) and the Kern River operational cloud seeding program (Silverman, 2008) 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, 2002) for a description of the ratio statistics methodology, and Silverman (2007) 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 then 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 (Gabriel and Petrondas, 1983). For this study, the adjustment factor was found to be slightly less than 2. However, an adjustment factor of 2 was used so the calculated values of the bias-adjusted regression ratio are conservative estimates of the seeding effects. The results using the regression ratio that were adjusted for bias in this way are called RR_A.

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 only assess the probability that an effect is due to chance (Gabriel, 2002; Nicholls, 2001). Confidence intervals were calculated as prescribed by Gabriel (2002). 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. In this study, an evaluation result is considered to be statistically significant if its 90 percent confidence interval does not include the null hypothesis value of $RR_A = 1$ or zero percent change in streamflow, i.e., it satisfies a 2-sided level of significance of 0.10.

3. SELECTION OF THE TARGETS AND CONTROLS

3.1 Targets

The primary targets of the seeding operations were eight small basins in and directly adjacent to the Vail Ski Area that were all very likely seeded under most of the meteorological conditions for each operational season. They include Piney River (PNY), Booth Creek (GBO), Middle Creek (MID), Pitkin Creek (GPT), Bighorn Creek (GBH), Upper Gore Creek (GUP), Black Gore Creek (GBL) and Turkey Creek minus Wearyman Creek (TMW). These basins should give the best potential to represent the target area snowpack under all operationally seeded weather conditions.

3.2 Potential Controls

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. All upwind, non-seeded basins within about 75 miles of the target area that met these criteria were selected as potential control sites. They include White River North Fork at Buford (WNF), White River South Fork at Buford (WSF), West Divide Creek (WDC) and the Fryingpan River Near Ruedi (FRR). WNF and WSF are about 75 miles west northwest of the target area. WDC and FRR are about 70 miles and 30 miles west southwest of the target area, respectively.

Table 1 gives the geographical characteristics, average water year streamflow and data record lengths of the selected targets and the potential control stations used in this study. Fig. 1 is a map of the Vail region showing the location of all the targets and controls, and the location of the ground generators used for the original Vail program and for the Vail-Beaver Creek program.

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

Station Name	Sta. ID	USGS No	Latitude (° N)	Longitude (° W)	Elevation (feet)	Avg FNF[4]	Record WaterYrs
Primary Targets							
Piney River	PNY[1]	09059500	39.800	106.583	7,272	54,234	1948-2005
Booth Creek	GBO[1]	09066200	39.648	106.323	8,325	8,091	1965-2005
Middle Creek	MID[1]	09066300	39.646	106.382	8,200	3,944	1965-2005
Pitkin Creek	GPT[1]	09066150	39.644	106.302	8,525	7,395	1967-2005
Bighorn Creek	GBH[1]	09066100	39.640	106.293	8,625	5,842	1964-2005
Upper Gore Creek	GUP[1]	09065500	39.623	106.278	8,600	20,523	1948-2005
Black Gore Creek	GBL[1]	09066000	39.596	106.264	9,150	12,052	1948-2005
Turkey Creek [3]	TMW[1]	09034000	39.523	106.336	8,918	10,312	1965-2005
Potential Controls							
West Divide Creek	WDC[2]	09089500	39.331	107.579	7,060	22,582	1909-2005
NF White Rvr at Buford	WNF[2]	09303000	39.988	107.614	7,010	225,164	1909-2005
SF White Rvr at Buford	WSF[2]	09304000	39.974	107.625	6,970	189,524	1909-2005
Fryingpan Rvr -Ruedi	FRR[2]	09080400	39.366	106.825	7,473	177,090	1909-2005

[1] Full natural flow data reported by the USGS
[2] Full natural flow data provided by the Colorado Water Conservation Board (CWCB)
[3] Full natural flow data for Turkey Creek minus that portion for Wearyman Creek

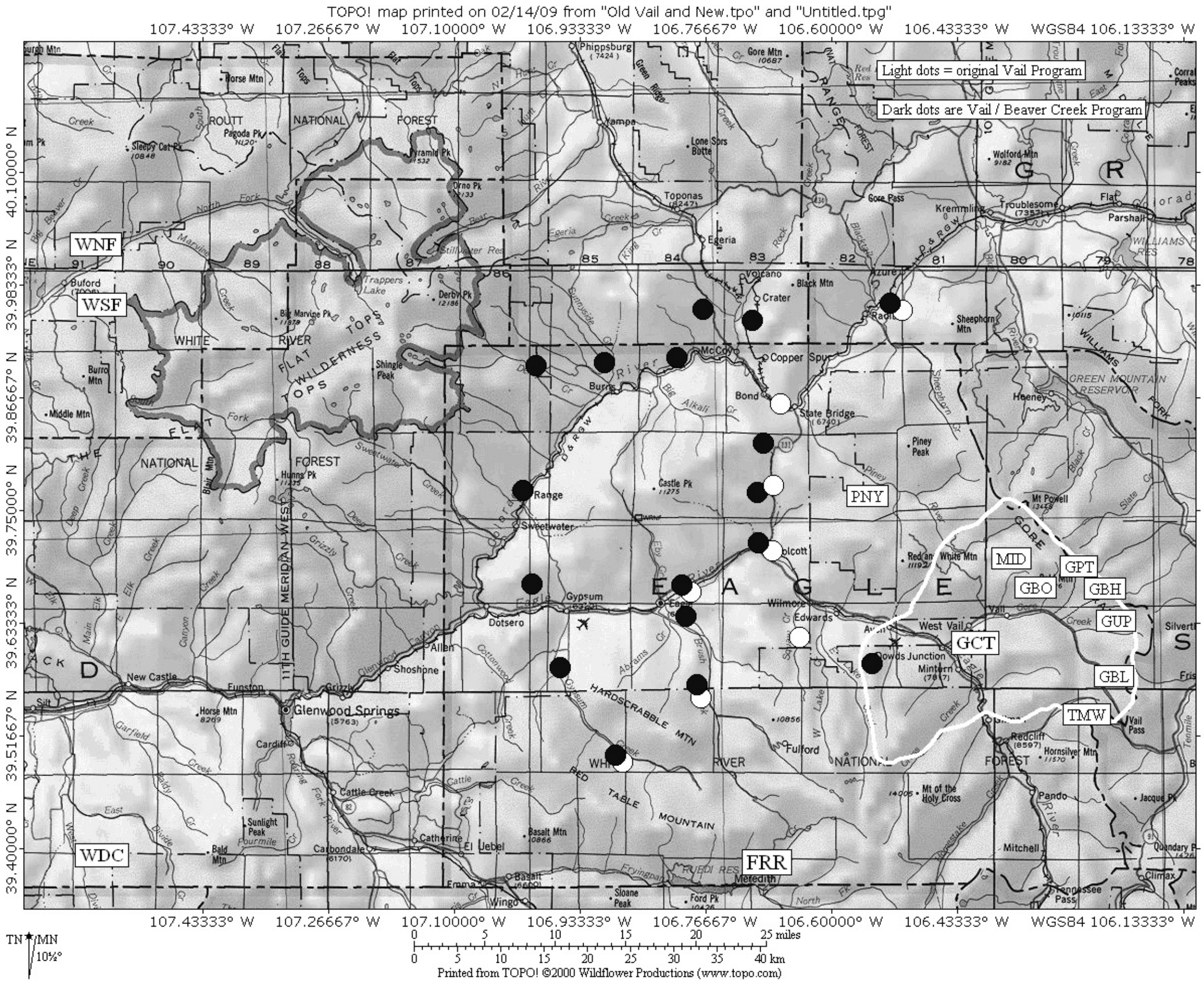

Fig. 1. Map of the Vail region showing the location of all the targets and controls, and the location of the ground generators used for the original Vail program (blank circles) and for the Vail-Beaver Creek program (shaded circles). The white "circle" encompassing the target stations is the intended target area.

3.3 Choosing the Best Control

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. He showed the control or combination of controls that has the highest correlation with the target and, especially, the lowest standard deviation of the residuals (differences between the observed and predicted values) will yield the most precise evaluation results.

The four potential control basins, by themselves and in various physically meaningful combinations, were regressed against each of the targets to determine which had the highest correlation and, especially, which had the smallest standard deviation of the residuals. Since GBH is near the center of the overall Vail target, it is used to represent and illustrate the kind of results that were obtained. The resulting linear and multiple correlation coefficients, ρ, and standard deviations of the residuals, s_o, for GBH are given in Table 2.

It was found that the control that had the highest correlation with GBH and had the lowest standard deviation of the residuals was FRR. It was also found that FRR was the best control for each of the other targets. In accordance with the regression ratio method (see Section 2), regression equations were derived by the least squares method for each of the targets that predicts the streamflow at the target station as a function of the streamflow at the control station FRR. The regression results should be accurate and robust since there were no outliers in the data and the regression residuals exhibited homoscedacity (constant variance).

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

Control	Corr. Coeff. ρ	Std Dev Res s_o (AF)
WSF	0.679	1,602
WNF	0.718	1,520
WDC	0.703	1,551
FRR	**0.775**	**1,406**
WSF, FRR	0.766	1,420
WNF, FRR	0.771	1,407
WSF, WDC	0.732	1,505
WNF,WDC	0.716	1,543

4. EVALUATION RESULTS

The evaluation results for the primary targets are given in Table 3. It can be seen from Fig. 2 that the maximum seeding effect is centered on GBH and decreases for targets both northwest and southeast of GBH. The seeding effect for GBH and all the targets north of it are impressively large and statistically significant except for MID which is almost, but not quite, statistically significant. The seeding effect for targets south of GBH decreases rapidly with increasing distance from GBH. The seeding effect is large and statistically significant for GUP and modest but not quite statistically significant for GBL, but TMW indicates no seeding effect at all. Keeping in mind that the choice of the bias adjustment factor gave rise to conservative estimates of seeding effects, it is possible that the seeding effects for MID and GBL are statistically significant after all. The fact that the seeding effect changes rapidly over the very short distances between seeding targets suggests, as one possible explanation, that the silver iodide nuclei from the ground generators are channeled by the terrain into a focused plume, and not widely dispersed as intended. This possible explanation was motivated by the analysis of the Colorado River Basin Pilot Project by Elliott *et al.* (1978) who found that under low-level stable conditions the silver iodide was transported northwestward parallel to the mountain barrier instead of northeastward and up into the clouds over mountain as intended. This and other possible explanations warrant further investigation and verification through appropriate meteorological and hydrological studies.

Table 3. Results of the Vail evaluation for each of the primary targets. Results are given for the proportional effect of seeding, δ (%) = 100* (RR_A-1), where RR_A is the bias-adjusted regression ratio, ρ is the correlation between the indicated target and the control (FRR), and CI90L and CI90U are the lower and upper bound of the 90% confidence interval, respectively. Statistically significant results in accordance with a 2-sided level of significance of 0.10 are shown in bold.

Target	δ	CI90L	CI90U	ρ
PNY	**+6.3**	**+0.4**	**+12.5**	0.910
GBO	**+9.3**	**+1.1**	**+18.1**	0.836
MID	+7.9	-0.2	+16.7	0.909
GPT	**+18.5**	**+7.3**	**+30.9**	0.812
GBH	**+28.8**	**+16.6**	**+42.2**	0.775
GUP	**+11.1**	**+4.7**	**+18.0**	0.837
GBL	+4.6	-0.6	+10.1	0.918
TMW	-2.0	-11.5	+8.3	0.871

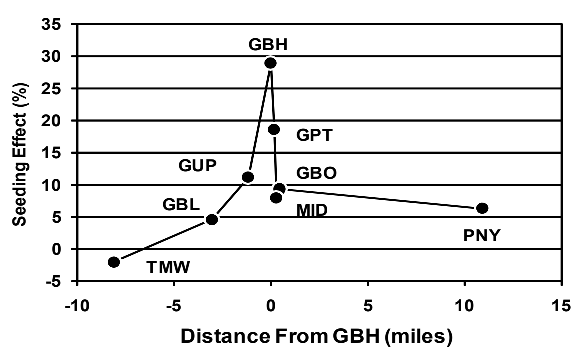

Fig. 2. Values of the seeding effect (%) as a function of the distance in miles northwest (positive) and southeast (negative) from the maximum effect at GBH.

The combined flows from GUP, GBL, GBH, GPT, GBO, and MID, hereafter called Gore Creek (GCT), flows into the Eagle River about 12 miles south of the target area at a point 3 miles downstream of Minturn, Colorado. An evaluation of the seeding effect for GCT indicates a statistically significant increase in GCT streamflow of +9.5% with 90% confidence that the true effect of seeding lies between +2.9% and +16.4%.

It can also be seen from Table 3 that the target-control correlation coefficients range from 0.775 to 0.918, accounting for about 58% to 85% of the variance of the target streamflows, respectively. There are two noteworthy aspects to this finding: (1) despite the fact that the targets are very close to one another, there is a big difference in their correlation coefficients with the control, and (2) the target-control correlation coefficients for the Vail targets are substantially smaller than those found for the evaluation of the operational seeding programs in the watersheds of the Sierra Nevada Mountains which ranged from 0.93 to 0.98. It appears that the spatial variability of annual runoff among watersheds in the Rocky Mountains is greater than that for watersheds in the Sierra Nevada Mountains. In view of the increased standard error of the estimate for the Vail targets, it is impressive that there is such strong statistical support for the estimated increases in streamflow due to seeding.

The +28.8% increase in water year streamflow at GBH is rather large compared to the results from similar seeding programs, especially when one takes into account that the water year streamflow is being affected by seeding during only 3 months of the year. Silverman (2007, 2008) evaluated the Kings River, Kern and San Joaquin operational cloud seeding programs and found that they produced a positive, statistically significant increase in water year streamflow ranging from +4.6% to +12.2%. Climax I and Climax II resulted in increases in precipitation of +9% and +13%, respectively, that could reasonably have occurred by chance (Grant and Kahan, 1974); however, for data stratifications of temperature and wind that are most favorable to seeding, statistically significant increases in precipitation as high as +55.2% were indicated (Mielke *et al.,* 1981). The evaluation of the Colorado River Basin Pilot Project resulted in no statistically significant increase in precipitation (Elliott *et al.,* 1978); however, a statistical reanalysis of the data suggested that, for data stratifications of wind direction that are most favorable to seeding, statistically significant increases in precipitation from +28% to +45% were apparent (Hjermstad and Mielke, 1976).

Lest the rather large seeding effect estimate for GBH be an anomalous function of the control that was used (FRR), the evaluation of GBH was repeated using several different controls. The results of the evaluations of GBH with all of the controls are shown in Table 4. It can be seen that the results of the evaluation using the other 7 controls are statistically comparable to the results obtained using FRR as the control. However, using FRR as the control yields the most precise result; i.e., the lowest standard error of the estimate of RR_A. Therefore, it is reasonable to conclude that the estimates of the seeding effect using FRR as the control for all of the targets, as given in Table 3, are statistically credible.

Table 4. Same as Table 2 except for the evaluation of GBH using different controls as indicated.

Control	δ	CI90L	CI90U	ρ
FRR	+28.8	+16.6	+42.2	0.775
WDC	+23.6	+10.9	+37.9	0.703
WNF	+26.8	+13.9	+41.2	0.718
WSF	+33.4	+19.2	+49.3	0.679
FRR,WSF	+28.7	+16.6	+42.0	0.766
FRR,WNF	+28.4	+16.4	+41.6	0.771
WDC,WSF	+27.9	+14.9	+42.4	0.716
WDC,WNF	+25.2	+12.8	+39.1	0.732

5. TIME EVOLUTION OF THE SEEDING EFFECT

The time evolution of the seeding effect for the Vail primary targets is shown in Fig. 3. In Fig. 3 the seeding effect calculated for each seeded water year is the value that would have been obtained if the evaluation were done for all seeded years up to and including that water year. It can be seen that the seeding effect appears to be consistent over time. For clarity of presentation, the 90 percent confidence limits are not shown. 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

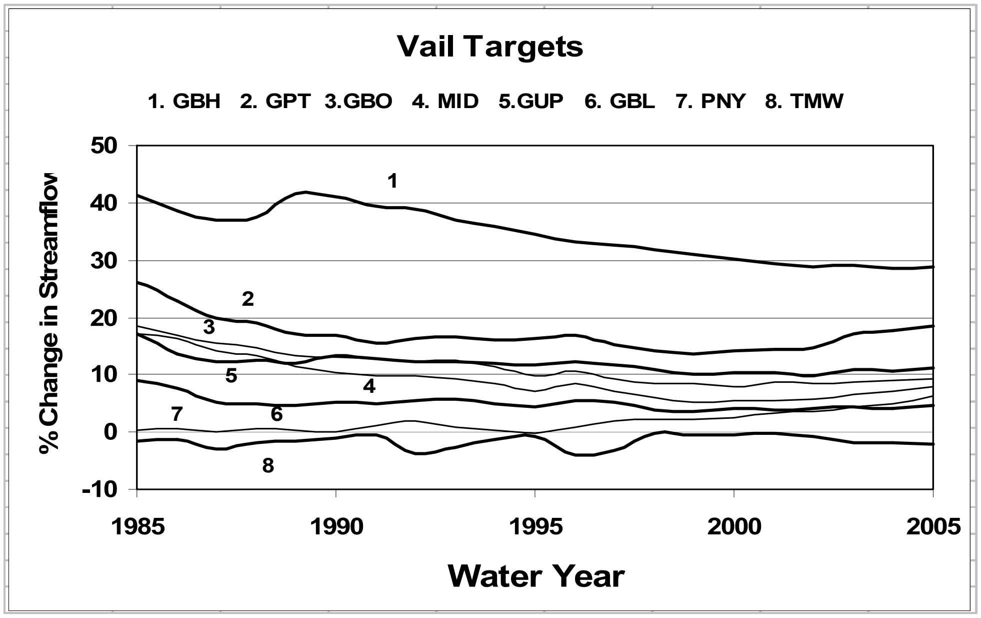

Fig. 3. Time evolution of the seeding effect (% change in streamflow)

estimate decreases with increasing sample size. See Table 2 for an indication of the 90 percent confidence limits for the final year (2005) of each target's evaluation.

It can be seen from Fig. 3 that there are no significant and/or abrupt changes in trend that might be indicative of a significant change seeding effectiveness and, in turn, a significant change in some aspect of the meteorology and/or seeding procedure that affected the seeding effectiveness.

6. SUMMARY

An independent statistical evaluation of the Vail operational cloud seeding program over its period of operations from 1977 to 2005 was conducted using ratio statistics and, in particular, the bias-adjusted regression ratio. The effect of seeding on eight (8) primary seeding targets in the Vail Basin was evaluated using the control that gives the most precise evaluation results possible with the available data. The following is a summary of the main findings of this evaluation study:

(1) The evaluation results suggests, as one possible explanation, that the dispersion of the silver iodide seeding agent tends to be narrowly focused rather than uniformly distributed across all the primary seeding targets. This and other possible explanations need to be investigated further through physical and hydrological studies such as silver iodide tracer experiments.

(2) Of the 8 primary seeding targets in the Vail Basin, statistically significant increases in streamflow due to seeding ranging from +6.3% to +28.8% was found in 5 of them (PNY, GBO, GPT, GBH and GUP); not quite statistically significant seeding-induced increases in streamflow was found in 2 of them (MID and GBL); and no seeding effect was found in one of them (TMW). The maximum seeding effect of +28.8% occurred at Bighorn Creek (GBH) and decreased rapidly with increasing distance for seeding targets both northwest and southeast of GBH.

(3) The time evolution of the seeding effect on the Vail primary seeding targets suggests that the seeding-induced changes in streamflow were steady and consistent over time.

7. REMARKS

It is emphasized that this study is an *a posteriori* evaluation of a non-randomized seeding operation. In addition, this evaluation is an exploratory study that involves consideration of a multiplicity of analyses, some of which are suggested by the results of previous analyses. With such a large number of tests, a few are likely to yield significant results purely by chance. In view of these considerations, the results of the evaluations in this study must be viewed with caution. It is emphasized that the results should be interpreted as measures of the strength of the suggested seeding effect. 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.

Mindful that the results from *a posteriori* analyses might evince a physically interesting result that in fact might only reflect chance, strong statistical support for a result, as obtained in this study, provide incentive to do a more in-depth study of past seeding operations. The ultimate aim of these studies should be to obtain the statistical and physical evidence needed to declare the unequivocal success of the Vail operational cloud seeding program that, in turn, establishes the basis for optimizing the cost effectiveness of future seeding operations. New studies are needed to clarify and extend the results, and to resolve the uncertainties in the statistical and physical evidence obtained thus far. Physical understanding is clarified and advanced through follow-up statistical and physical studies and experiments prompted by promising findings such as those obtained in this study. Progress in physical understanding comes from noting the unexpected and following it up as well as from confirming the expected.

Acknowledgments: The author gratefully acknowledges the support that the following organizations provided towards the publication of the results of this study - Western Weather Consultants, Southwestern Water Conservation District, Colorado Springs Utilities, Colorado Water Conservation Board, Pine River Irrigation District, San Juan RC&D, and San Juan Water Conservancy District. The author also thanks Larry Hjermstad of Western Weather Consultants for his cooperation in providing relevant information, including the regional map, about the Vail operational cloud seeding program that helped in the conduct of the evaluation and the interpretation of the evaluation results. The author offers a special thanks to Michelle Garrison of the Colorado Water Conservation Board for providing the unimpaired streamflow data for the control stations.

REFERENCES

AMS, 1998: Scientific Background for the AMS Policy Statement on Planned and Inadvertent Weather Modification. *Bull. Amer. Meteor. Soc.*, **79**, 2773-2778.

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

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

Gabriel, K.R., 2000: Planning and evaluation of weather modification projects. *Seventh WMO Sci. Conf. on Wea. Mod.*, Chiang Mai, Thailand, Supplement, Vol. III, World Meteor. Org., 39-59.

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

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

Grant, L. O. and A. M. Kahan, 1974: Weather and Climate Modification, Chapter 7. Weather Modification for Augmenting Orographic Precipitation, Edited by W. N. Hess, John Wiley and Sons, Inc, 1974, 282-317.

Hjermstad, L. and P.W. Mielke, 1976: A diagnostic procedure and evaluation of apparent seeding effects from observed cloud types over the Colorado River Basin Pilot Project. Western Weather Consultants Technical Report No. 001, Bureau of Reclamation Contract No. 6-01-ER-02552, 52pp.

Hjermstad, L., 2001: An Analysis of Regional Snotel and Ski Area Precipitation Data to Evaluate Precipitation Changes Resulting from Ten Seasons of Wintertime Cloud Seeding Operations over the Vail Ski area, March 2001. A Technical Report to Vail Associates, Inc.

Mielke, P.W. Jr., G.W. Brier, L.O. Grant, G.J. Mulvey and P.N. Rosenzweig, 1981: A statistical reanalysis of the replicated Climax I and II wintertime orographic cloud seeding experiments. *J. Appl. Meteor.,* **20**, 643-659.

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.