"REVIEWED"

WINTER OROGRAPHIC CLOUD SEEDING OVER THE KERN RIVER BASIN IN CALIFORNIA

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Abstract. An operational cloud seeding program using solely airborne treatment to augment precipitation over the full watershed of the Kern River in the southern Sierra Nevada of California has been conducted for eight of the past ten water years. A target-control regression analysis of the non-randomized program indicates a 15% increase in average annual streamflow during the seeded period to date, significant at better than the .01 level. Support for the regression results is found in double mass analysis of target-control streamflow, as well as in comparisons of radar characteristics between seeded and not-seeded precipitation echoes. The program design, operations and evaluations are described.

1. INTRODUCTION

Atmospherics Incorporated (AI) of Fresno, CA has conducted a winter orographic cloud seeding program over the full watershed of the Kern River in the southern Sierra Nevada of California during eight of the past ten water years. The program is operational in its design and is sponsored by the North Kern Water Storage District. Operations were initiated in March of 1977 in response to rather severe drought conditions, continued through May of that year, and were conducted again during the winter of 1977/78. Following the extremely wet water year of 1977/78 with nearly twice normal precipitation, the seeding program was deactivated for two winters. Operations were reinstated for 1980/81 and have been conducted annually since then.

2. PROJECT DESCRIPTION

The Kern River basin is the southernmost major western slope watershed in the Sierra Nevada of California. The Kern River originates in rugged high elevation terrain with numerous peaks and ridges ranging from 3000 m to well over 4000 m in elevation, including Mt. Whitney (4419 m), the highest peak in the continental U.S. It flows southward through its watershed of approximately 4650 sq km into Lake Isabella and then to the rich San Joaquin Valley. Emerging from the foothills east of Bakersfield, the total annual unregulated and not-seeded flow (e.g., water years 1925/26 through 1949/50) ranges from 185,000 to 1,290,000 acre feet, averaging approximately 595,000 acre feet. A project area base map is shown in Figure 1.

The seeding project includes full time treatment of all suitable cloud systems with no randomization. Seeding operations focus on winter storms, generally from December through April, with occasional seeding in November and/or May as water conditions dictate.

Cloud treatment is accomplished solely through airborne releases of pyrotechnic-generated silver iodide. All seeding missions are supported by dedicated ground-based radar operations, with liberal exchange of information between the seeding aircraft pilot and radar meteorologist, enabling tailoring of operations to each storm situation as it develops and evolves. This combination of inputs to the seeding decision process is considered to be crucial in striving for optimized operations. Seeding is performed using twin engine Piper Aztec or Piper Navajo aircraft equipped with burn-in-place and ejectable pyrotechnics.

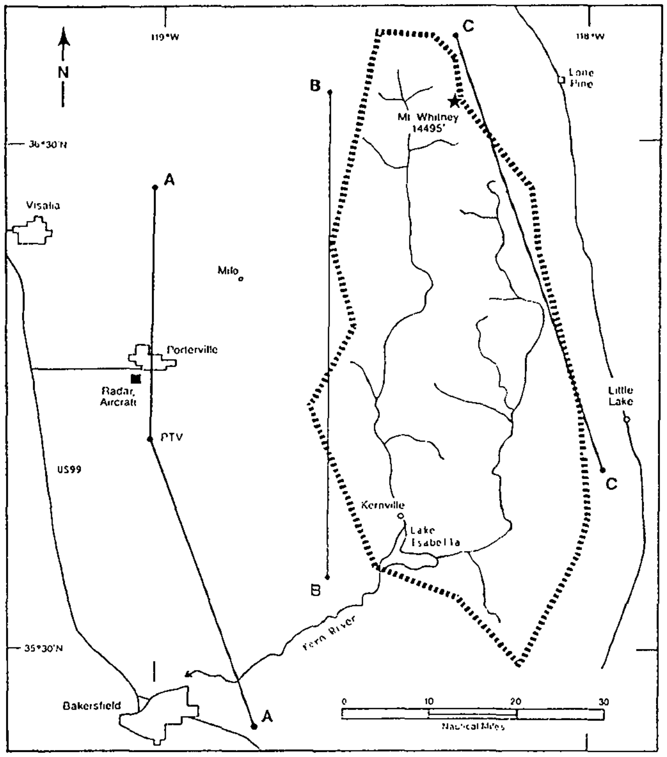

FIGURE 1 Project area base map showing the full-watershed target area boundary by the heavy dashed line. The project radar and aircraft are based at the Porterville Airport. A, B and C are examples of flight tracks for varying wind conditions.

Two basic strategies are employed for cloud treatment. The first involves continuous release of silver iodide into confirmed regions of supercooled liquid water along crosswind flight tracks (e.g., A, B and C on Figure 1) within widespread stratiform cloud systems. The second entails focused treatment of relatively isolated convection or strongly emergent embedded convective elements. Those situations involve either cloud top releases into growing cumulus turrets using ejectable pyrotechnics or sub-cloud seeding in well-defined inflow areas.

Seeding rates are adjusted as conditions vary, with the intent of achieving ice nuclei concentrations greater than 10 per liter to enhance the clouds' efficiency in producing precipitation from cloud condensate. Seeding is curtailed or suspended in the presence of very high natural ice crystal concentrations, and as is prudent according to suspension criteria relating to excess snowpack, flood potential, severe weather threat or other special circumstances which may arise. A detailed description of the overall program appears in Henderson et al. (1986a).

3. EVALUATIONS AND RESULTS

A number of evaluation methods can be applied to a variety of data to assess precipitation augmentation efforts. The usual methods can be categorized as (1) statistical, dealing directly with measured precipitation, streamflow or other parameters and (2) physical studies, which can provide evidence of apparent seeding effects but are not necessarily formal tests of seeding results. The past 15 years have seen increasing interest, especially within research-oriented programs, in establishing evidence of seeding effects at various stages of the overall precipitation process. Evidence of effects within "links of the precipitation chain" prior to any ground-truth measurements can serve to enhance the strength of those end-product results (e.g., water in the reservoir). In this evaluation, historical and statistical comparisons of streamflow data are presented, complemented by radar information summarized in the physical study context.

3.1 Streamflow Analyses

Streamflow records were chosen for the primary analyses of the project for several reasons, including (1) the availability of long-standing high quality records, coupled with the demonstrated high correlation among many Sierra watersheds (Henderson, 1966), (2) the sparsity of raingage data in the more remote portions of the watershed, (3) the prospect, based on earlier work in the Kings River basin (Henderson, 1966; Henderson et al., 1986c), that analysis of snow survey data would likely not reach an acceptably high level of statistical significance for the current eight-year evaluation period, and (4) that dealing directly with runoff values seems entirely appropriate inasmuch as the project is designed specifically to increase water for irrigation use.

Historical Comparisons

As a first step in investigating seeding effects, a traditional historical (i.e., percentage of normal) comparison was made between a not-seeded base period and the eight seeded seasons combined. Such comparisons can identify changes from historical normal values, but carry a relatively large uncertainty as to whether the observed difference can be attributed to the cloud seeding program, largely because of the high natural variability in streamflow from year to year and the possibility of climatic shifts. Using water year "full natural flow" totals as available from the U.S. Geological Survey for the Kern River near Kernville plus No. 3 Canal (USGS gaging station #11186000), a 25-year base period was evaluated to characterize the not-seeded flow. The flow measured at this site constitutes approximately 84% of the total watershed output.

The period of 1925/26 through 1949/50 predates any seeding over the Kern basin; some sporadic airborne seeding was done there from 1951 to 1970. For the base period the average annual flow at that point was 497,019 acre feet, with a standard deviation of 231,179. For the eight seeded years the same measurement site indicated an average value of 797,690, some 300,671 acre feet (60%) greater than the not-seeded baseline. Although the base period standard deviation was relatively high, the indicated increase during the seeded years still represents 1.30 times that value; there is only a 10% likelihood that such an increase would have happened by chance. This, however, does not suggest that the total increase was actually due to the cloud seeding program. A large part of the indicated increase was likely due to natural variations in precipitation and a smaller part due to the cloud seeding since, for example, the same comparison using records from the Merced River, an unseeded traditional control well correlated with the Kern, indicated a 36% increase. Thus the increase in the Kern flow due to seeding was obviously something less than the 300,671 acre foot average value yielded by this initial method.

Target-Control Regression

The next step in streamflow analysis took the form of a straightforward target-control comparison. The regression approach is, by design, able to minimize (mathematically account for) the otherwise confounding effects of climatic shifts. The target area measurement was the same as in the historical comparison, total water year natural flow measured near Kernville plus the No. 3 Canal (USGS #11186000). Control values were drawn from the Merced River measured at Pohono Bridge (USGS #11266500), a traditional control used in evaluations of seeding programs in the central and southern Sierra (see Henderson, 1966, and Henderson et al., 1986b and 1986c). Several candidate control streams were evaluated for possible use in this analysis; the Merced at Pohono exhibited the highest single-station correlation with the target site. Further, a study by Hannaford and Williams (1968) addressed the possibility of seeding carry-over (contamination) effects in the central and southern Sierra and indicated no significant effects in Merced River streamflow records related to seeding projects on nearby watersheds.

The base period for the regression representing long-term not-seeded conditions included water years 1925/26 through 1949/50. Table 1 presents the streamflow data used in establishing the relationship, and Figure 2 shows the plotted values and linear regression. The correlation coefficient between the two was found to be .876 with a standard error, S_E, of the base period for the Kern River of 114,036 acre feet. Using the regression equation to predict not-seeded target flows for the eight seeded years, a comparison was made with the observed values. The results are shown in Table 2. An overall average increase of slightly more than 15% was indicated, with an attendant 99.6% probability of a positive effect.

Double Mass Analysis

A final method used to identify seeding effects on streamflow involved double mass analysis. This technique is frequently used to detect changes in the hydrologic response of a watershed caused by factors such as relocations of measurement sites or water diversions.

TABLE 1

STREAMFLOW (ACRE FEET) FOR KERN RIVER NEAR KERNVILLE PLUS #3 CANAL AND MERCED RIVER AT POHONO BRIDGE

WATER YEAR	KERN+3	MERCED
1925-26	299,050	343,670
27	616,040	537,850
28	303,000	370,650
29	287,190	255,580
30	299,140	277,840
1930-31	176,640	144,740
32	585,270	506,690
33	390,000	289,900
34	219,760	187,260
35	421,160	527,170
1935-36	634,110	504,380
37	858,520	493,230
38	1,014,690	849,330
39	388,020	252,610
40	608,450	499,470
1940-41	946,000	616,830
42	618,560	599,290
43	802,530	537,850
44	443,500	327,660
45	665,710	478,280
1945-46	528,240	497,860
47	355,500	309,700
48	301,420	387,710
49	271,840	332,650
50	391,140	399,670
TOTAL	12,425,480	10,527,870
AVG.(25 yrs)	497,019	421,115
STD. DEV.	231,179	156,841

FIGURE 2

LINEAR REGRESSION OF THE KERN RIVER VS. THE MERCED RIVER, WATER YEARS 1926 THROUGH 1950.

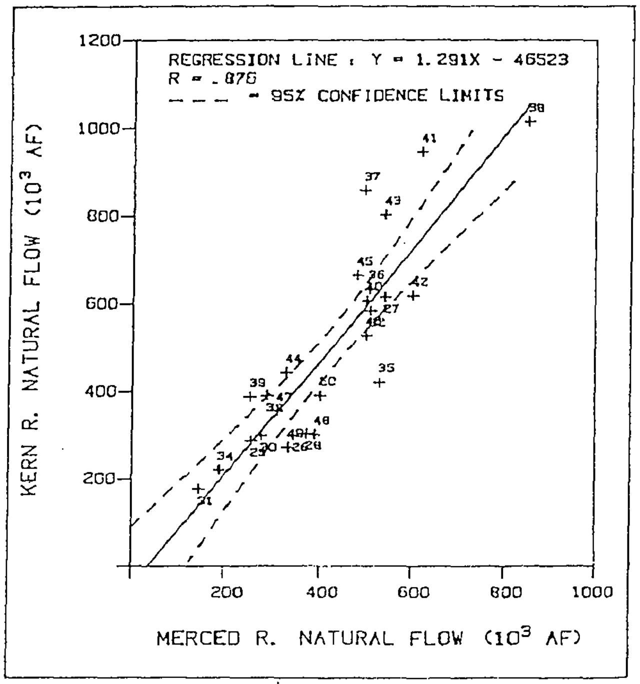

TABLE 2

KERN RIVER EVALUATION - LINEAR REGRESSION

WATER YEAR	MERCED OBSERVED (AF)	KERN OBSERVED (AF)	KERN PREDICTED (AF)	KERN DIFFERENCE (AF)	PERCENT CHANGE	DEPARTURE IN S_E	PROBABILITY OF POSITIVE EFFECT
1976/77	91,660	171,500	71,785	+ 99,715	+138.9%	+0.87	80.8%
1977/78	724,600	1,138,000	888,734	+249,266	+ 28.0%	+2.19	98.6%
1980/81	263,590	367,140	293,698	+ 73,442	+ 25.0%	+0.64	73.9%
1981/82	836,170	888,440	1,032,740	-144,300	- 14.0%	-1.27	10.2%
1982/83	1,061,600	1,638,860	1,323,707	+315,153	+ 23.8%	+2.76	99.7%
1983/84	581,690	676,540	704,277	- 27,737	- 3.9%	-0.24	40.5%
1984/85	307,100	526,880	349,858	+177,022	+ 50.6%	+1.55	93.9%
1985/86	707,473	974,157	866,628	+107,529	+ 12.4%	+0.94	82.6%
TOTAL (8 yr)	4,573,883	6,381,517	5,531,427	+850,090			
AVERAGE (8 yr)	571,735	797,690	691,428	+106,262	+15.4%	+2.64*	99.6%

*Obtained by dividing the average difference between the observed and predicted seeded period Kern streamflows by the average standard error of estimate for the 8-yr seeded period (i.e., 114,036 AF/ $\sqrt{8}$ = 40,318 AF).

Plotting cumulative annual values from well-correlated watersheds against one another over a number of years usually results in a very nearly straight line. A sustained change in the slope of the line connecting the consecutive points signals a systematic change in the basins' relationship.

Examination of the Kern-Merced relationship in that manner over several decades, beginning with the regression base period and continuing to the present, provides an opportunity to identify possible seeding effects since seeding operations were started, stopped and restarted during the period. A summary of the Kern-Merced relationship during those seeded and not-seeded periods is presented in Table 3.

TABLE 3

DOUBLE MASS STREAMFLOW ANALYSIS SUMMARY

Water Years	Description of Period	Slope (Kern/Merced)
1926 - 1950	Regression base period	1.18
1951 - 1970	Kern sporadic seeding by others	1.24
1971 - 1976, 1979, 1980	Kern "modern" not-seeded period	1.19
1978, plus 1981 - 1986	Kern seeded, AI program	1.40

The 25-year regression base period target/control double mass slope was found to be 1.18, with the plotted annual values conforming reasonably well to a straight line. The relationship changed during the 1951-1970 interval, during which sporadic airborne seeding was performed over the Kern basin. The double mass slope of 1.24 during that 20-year seeded period indicates an overall positive change of about 5%. However, the sporadic nature of the treatment is seemingly reflected in annual values which exhibit more scatter and "trendiness" during the period.

The eight-year "modern" not-seeded interval of 1971-1976 plus 1979 and 1980 provides a good opportunity to confirm the stability of the natural target/control relationship. Those not-seeded years yield a slope of 1.19, in very good agreement with the 25-year not-seeded regression base period. This strongly suggests that no significant change had occurred in the relationship, thereby increasing the confidence that the positive changes found during the seeded periods using the regression base period or "modern" not-seeded data could be attributed to the effects of cloud seeding. Finally, the eight seeded seasons of the current program conducted by AI show a distinct, sustained positive departure to a slope of 1.40, a change of approximately 17-18%, providing support for the seeding effects shown in the regression analysis. A plot beginning with water year 1971 is shown in Figure 3 to document the effects of the current program.

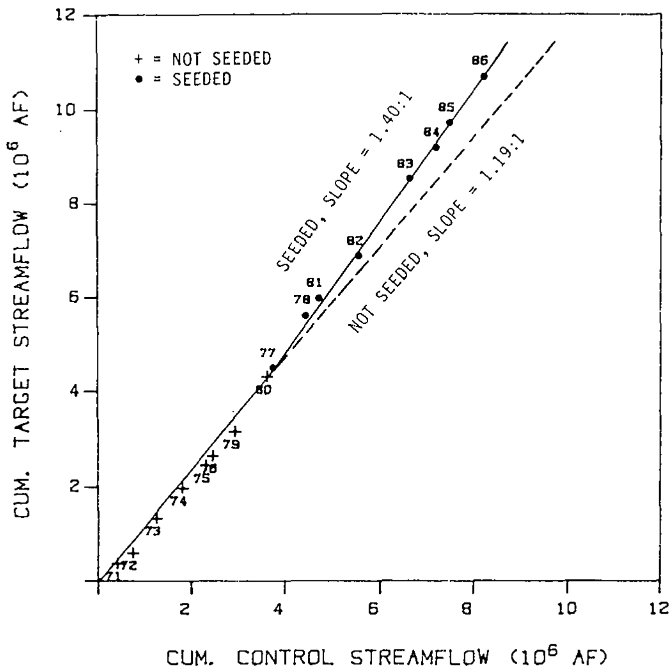

FIGURE 3 Double mass plot of water year streamflow totals for target (Kern) and control (Merced) measurements. The "modern" not-seeded sample includes 1971-1976 plus 1979 and 1980. The seeded years include 1977, 1978 and 1981-1986.

3.2 Radar Data Comparisons

The 5 cm radar system used to support the project was initially located at AI's home office in Fresno, some 140 km northwest of the center of the target area. However, beginning with the 1980/81 season a separate dedicated 5 cm system was operated at the Porterville, CA airport (Figure 1). Using PPI overlays and tabulated RHI-derived echo characteristics routinely obtained at 15-30 minute intervals during all operational periods from 1980/81 through 1985/86, characteristics of seeded and not-seeded radar echoes were compared. Some 46 time periods were chosen when both seeded and not-seeded portions of storm systems were present within the overall operational area and were clearly visible to the radar. These periods were examined in considerable detail. Of primary interest in this study were (1) maximum echo intensity, (2) maximum echo height, (3) duration of precipitation period and (4) precipitation area coverage. These particular characteristics are ones closely related to changes in precipitation at ground level and represent strong indicators in the physical study context.

In all categories the seeded individual or area-wide precipitation echoes exhibited strong average positive effects in the six-year sample (Table 4). This study was not intended as a carefully controlled statistical exercise, but rather as a source of supporting evidence. The methodical (albeit manual) data collection procedures routinely employed in AI's operational programs provide sufficient information for characterizations and summaries of this kind.

TABLE 4

COMPARISON OF RADAR ECHO CHARACTERISTICS

CATEGORY	AVG.PCT. DIFFERENCE SEEDED/NOT-SEEDED
Maximum Echo Intensity	+9%
Maximum Echo Height	+12%
Duration of Precipitation	+23%
Area Coverage	+16%

4. SUMMARY

Target-control statistical evaluation of streamflow records for a multi-year operational precipitation enhancement project over the Kern River basin of the southern Sierra Nevada indicates a 15% increase in average annual streamflow, with an attendant significance of better than .01. Double mass analysis of water year streamflow totals for the target and control watersheds supports the indicated seeding effect by exhibiting a distinct upward inflection corresponding with the start of seeding, and with that departure from the not-seeded slope sustained through the seeding period. Physical studies comparing seeded and not-seeded radar echoes show positive effects in cloud characteristics which relate to precipitation production. The statistical and physical indications are (1) in agreement with our conceptual model of winter storm seedability/response and (2) within the range of credible effects as suggested in theoretical work and reported by other similar operational programs.

5. REFERENCES

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