WINTER OROGRAPHIC CLOUD SEEDING OVER THE KAWEAH RIVER BASIN IN CALIFORNIA

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Abstract. An ongoing program of operational cloud seeding for precipitation increase over the Kaweah River basin in California's southern Sierra Nevada has been conducted for eleven seasons. A 13% increase in average annual streamflow is indicated by target-control regression analysis of overall seeding effectiveness, with an attendant statistical significance of better than .01. Support for the regression analysis results is found in comparisons of the seeded period regression line against the base period regression line and in comparisons of radar characteristics of seeded and not-seeded radar echoes. The program's basic design, operations and evaluations are described.

1. INTRODUCTION

Atmospherics Incorporated (AI) has conducted a winter orographic cloud seeding program over the full watershed of the Kaweah River in the southern Sierra Nevada of California during the past eleven water years. The operational program is sponsored by the Kaweah Delta Water Conservation District. Seeding operations were initiated in November of 1975 and continued for the full winter season. In response to developing drought conditions, operations were resumed in October of 1976 and continued for 17 months, through February of 1978. Beginning with water year 1978/79 a more normal winter schedule has been maintained.

2. PROJECT DESCRIPTION

The Kaweah River basin is a western slope watershed of modest proportions located very near the southern limit of the Sierra Nevada range. The river originates in rugged high elevation terrain with peaks to 3750 m elevation, although it differs from many west slope Sierra basins in that its eastern boundary is not at the Sierra crest. The river system drains the watershed of approximately 1500 sq km into Lake Kaweah and then to the San Joaquin Valley (Fig. 1).

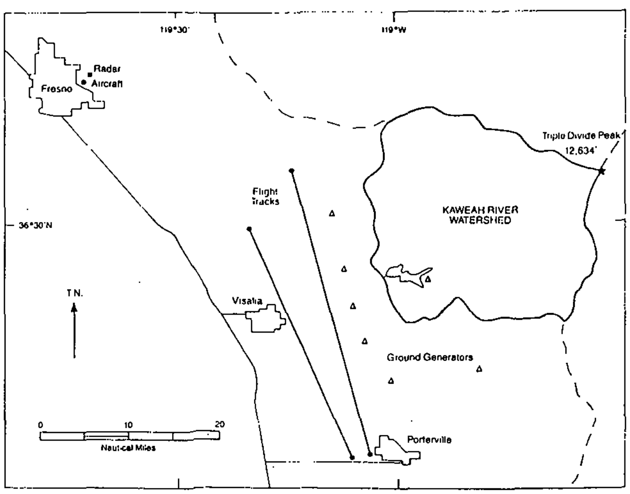

FIGURE 1 Project area base map. The target area boundary is indicated by the heavy solid line. Ground generator sites are shown as triangles. Flight tracks for light and moderate wind situations are shown as examples.

Emerging from the foothills east of the city of Visalia, the total annual unregulated and not-seeded flow (e.g., water years 1925/26 through 1949/50) ranges from 115,000 to 870,000 acre feet, averaging approximately 385,000 acre feet.

The operational seeding project includes full-time treatment of all suitable cloud systems, with no randomization. Seeding operations focus on winter storms, generally from November through April, with occasional seeding during other months as water conditions dictate.

Clouds are treated by releases of silver iodide from airborne pyrotechnic and/or ground-based solution burners, enabling tailoring of operations to each cloud situation. All seeding operations are coordinated using dedicated ground-based radar observations, with liberal information exchange between pilot and radar meteorologist during airborne seeding missions. The combined inputs of the pilot and radar meteorologist into the airborne seeding decision process are crucial to optimizing operations. Twin engine Piper Aztec or Piper Navajo aircraft are equipped for burn-in-place and ejectable pyrotechnics. The ground-based generators, or burners (Fig. 1), dispense silver iodide nuclei at a rate of approximately 15 grams per hour from a silver iodide-ammonium iodide solution burner. The generators are operated by local residents under the direction of the project meteorologist.

Three basic strategies are employed for cloud treatment. One involves continuous airborne release of silver iodide into confirmed regions of supercooled liquid water along crosswind flight tracks within widespread stratiform cloud systems (Figure 1). A second airborne strategy entails focused treatment of relatively isolated convection or strongly emergent embedded convective elements. These conditions involve either cloud top releases into cloud turrets using ejectable pyrotechnics or sub-cloud seeding in well-defined inflow areas. The third approach, ground-based, is used in a variety of storm phases and cloud types, depending on airflow at various levels and atmospheric stability considerations. Airborne seeding rates are adjusted as conditions warrant, 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 (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 compari-sons of streamflow data are presented, complemen- ted 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., 1986b), that analysis of snow survey data would likely not reach an acceptably high level of statistical significance for the current 11-year evaluation period, and (4) that dealing directly with runoff values seems entirely appropriate for a project 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 11 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 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 California Deptartment of Water Resources for "The Kaweah River, Inflow to Terminus", a 25-year base period was evaluated to characterize the not-seeded flow.

The period of 1925/26 through 1949/50 predates any seeding over the Kaweah and nearby basins. For this 25-year base period the average annual flow at that point was 384,756 acre feet, with a standard deviation of 195,305. For the 11 seeded years the same measurement site indicated an average value of 579,608, some 194,852 acre feet (51%) greater than the not-seeded baseline. The base period standard deviation is relatively high, with the indicated increase during the seeded years essentially equal to that value. However, given the magnitude of the indicated increase, the likelihood that such an increase would have happened by chance is only 16%. This 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 Kaweah, indicated a 27% increase. Thus the increase in the Kaweah flow due to seeding was obviously something less than the 194,852 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 of the Kaweah River measured at the inflow to Terminus. 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; Henderson et al., 1986b and 1986c; and Solak et al., 1987). Several candidate control streams were evaluated for possible use in this analysis; the Merced at Pohono provided the highest statistical significance of the group. Further, 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 .900 with a standard error, S_E, of the base period for the Kaweah River of 86,941 acre feet. Using the regression equation to predict not-seeded target flows for the 11 seeded years, a comparison was made with the observed values (Table 2). The usefulness of regression analysis comes not from the comparison of individual seasons but in the evaluation of the overall project. If an individual season's streamflow accumulation falls outside of the range of the base period streamflow accumulations, as was the case during the 1977 and 1983 water years, it cannot be adequately predicted by the base period regression equation. At best, using regression analysis to evaluate a project on a season by season basis can realistically only give an indication of the seeding effect. Table 2 does point out, however, that eight of the eleven seeded years did register a positive effect, the overall change in flow over the lifetime of the project is positive, and an overall average increase of 13% was indicated, with an attendant 99.5% probability of a positive effect. By contrast, using the same base period regression equation to predict the not-seeded streamflows from 1950/51 through 1974/75 yields an average

TABLE 1

STREAMFLOW (ACRE FEET) FOR KAWEAH RIVER, INFLOW TO TERMINUS AND MERCED RIVER AT POHONO BRIDGE

WATER YEAR	KAWEAH	MERCED
1925/26	218,750	343,670
27	483,180	537,850
28	203,030	370,650
29	222,790	255,580
30	217,530	277,840
1930/31	114,270	144,740
32	519,560	506,690
33	283,750	289,900
34	130,760	187,260
35	357,630	527,170
1935/36	486,940	504,380
37	677,230	493,230
38	870,900	849,330
39	247,180	252,610
40	512,750	499,470
1940/41	641,730	616,830
42	490,810	599,290
43	671,290	537,850
44	315,370	327,660
45	550,620	478,280
1945/46	356,480	497,860
47	265,200	309,700
48	261,320	387,710
49	218,870	332,650
50	300,960	399,670
TOTAL	9,618,900	10,527,870
AVG. (25 yrs)	384,756	421,115
STD. DEV.	195,305	156,841

FIGURE 2

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

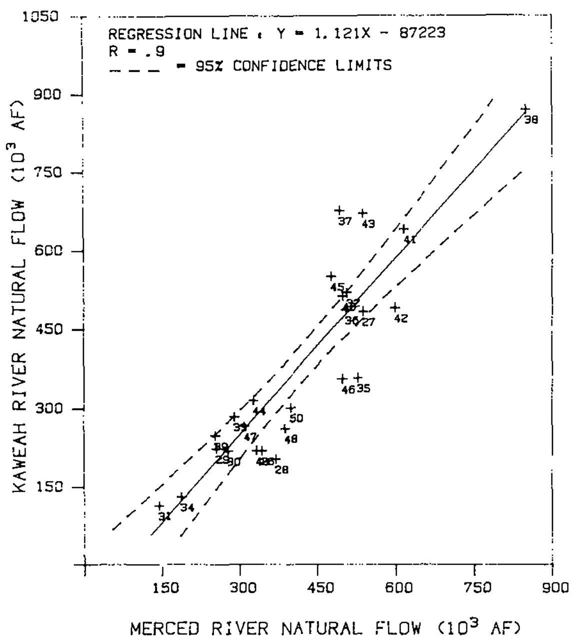

TABLE 2

KAWEAH RIVER EVALUATION - LINEAR REGRESSION

WATER YEAR	MERCED OBSERVED (AF)	KAWEAH OBSERVED (AF)	KAWEAH PREDICTED (AF)	KAWEAH DIFFERENCE (AF)	PERCENT CHANGE	DEPARTURE IN S_E	PROBABILITY OF POSITIVE EFFECT
1975/76	157,000	145,600	88,740	+ 56,860	+ 64.1%		
1976/77	91,660	92,220	15,508	+ 76,712	+494.7%		
1977/78	724,600	832,840	724,897	+107,943	+ 14.9%		
1978/79	468,500	414,600	437,864	- 23,264	- 5.3%		
1979/80	692,000	885,800	688,360	+197,440	+ 28.7%		
1980/81	263,590	246,790	208,204	+ 38,586	+ 18.5%		
1981/82	836,170	771,570	849,943	- 78,373	- 9.2%		
1982/83	1,061,600	1,402,190	1,102,601	+299,589	+ 27.2%		
1983/84	581,690	516,860	564,726	- 47,866	- 8.5%		
1984/85	307,080	332,330	256,947	+ 75,383	+ 29.3%		
1985/86	707,473	734,884	702,339	+ 32,545	+ 4.6%		
TOTAL (11 yr)	5,891,363	6,375,684	5,640,131	+735,553			
AVERAGE (11 yr)	535,578	579,608	512,739	+ 66,869	+13.0%	+2.55*	99.5%

*Obtained by dividing the average difference between the observed and predicted seeded period Kaweah streamflows by the average standard error of estimate for the 11-year seeded period (i.e., 86,941 AF/ 11 = 26,214 AF).

change of about +8,894 AF (+2%) with only 46% of the water years recording a positive change in the streamflow. It is possible that this small increase could be due, in part, to contamination from a cloud seeding project operating during this period on the nearby Kings River watershed.

Base Period/Seeded Period Regression Comparison

As a final step in the streamflow analysis a comparison was made between the base period regression line and the seeded period regression line. The regression line for the base period is described by the formula:

Kaweah(base) = 1.121 (Merced) - 87,223

with a correlation of 0.900 and a standard error of 86,941 AF. The regression line for the seeded period is described by the formula:

Kaweah(seeded) = 1.235 (Merced) - 81,929

with a correlation of 0.965 and a standard error of 108,318 AF. Comparison with the base period formula shows that although the two regression lines share a nearly common y-intercept (-87,223 AF vs. -81,929 AF), the slopes of the regression lines differ significantly with the seeded period slope of 1.235 being over 11% greater than the base period slope of 1.121. This result, although not statistically significant by itself, indicates a consistant increase over the entire range of measured streamflows and adds further support to the regression analysis.

3.2 Radar Data Comparisons

The 5 cm radar system used to support the project is located at AI's home office in Fresno, some 90 km northwest of the center of the target area (Fig. 1). Using PPI overlays and tabulated RHI-derived echo characteristics routinely obtained at 15 to 30 minute intervals during all operational periods from 1975/76 through 1985/86, characteristics of seeded and not-seeded radar echoes were compared. Some 108 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. Of primary interest were (1) maximum echo intensity, (2) maximum echo height, (3) duration of precipitation period and (4) precipitation area coverage. These particular characteristics are closely related to changes in precipitation at ground level and represent strong indicators in the physical study.

In all categories the seeded individual or area-wide precipitation echoes exhibited strong average positive effects in the 11-year sample (Table 3). 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 3

COMPARISON OF RADAR ECHO CHARACTERISTICS

CATEGORY	AVG.PCT. RATIO SEEDED/NOT-SEEDED
Maximum Echo Intensity	+6%
Maximum Echo Height	+17%
Duration of Precipitation	+29%
Area Coverage	+19%

4. SUMMARY

Target-control statistical evaluation of streamflow records for a multi-year operational precipitation enhancement project over the Kaweah River basin of the southern Sierra Nevada indicates a 13% increase in average annual streamflow, with an attendant significance of better than .01. Comparison of the seeded period regression line against the base period regression line supports the indicated seeding effect by exhibiting a positive effect over the entire range of measured streamflows. Physical studies comparing seeded and not-seeded radar echoes show positive effects in a number of 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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