A Ten Year Non-Randomized Cloud Seeding Program on the Kings River in California

Thomas J. Henderson
Atmospherics Incorporated, Fresno, Calif.

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ABSTRACT

In 1954 a cloud seeding program designed to increase rainfall and snowpack was initiated over the watershed of the Kings River in the Sierra Range of California. The project has been funded by the Kings River Conservation District, Fresno, California, and operated continuously each season during the 7-month October–April periods. At the end of the first three-year period, a multiple regression analysis was developed utilizing the unregulated historic flow of the Kings River and the flow of adjacent rivers presumed to be unaltered by cloud seeding activities. This statistical analysis has been applied to the flow of the rivers. During the ten-year seeded period 1954–1964, the analysis shows an apparent increase in flow amounting to 6 per cent of the total predicted by the regression analysis. This apparent increase is significant at the 0.005 level.

1. Introduction

The Kings River is one of several streams which originates in the high snow fields along the western slope of the Sierra Range in California and flows from its 1600-mi² watershed to the rich San Joaquin Valley. Emerging from the foothills east of Fresno, the total annual flow has ranged from a minimum of less than 400,000 to a maximum of more than 4,000,000 acre feet. The average for the past 35 years has been slightly less than 1.5 million acre feet.

There are presently about 1,000,000 acres of irrigated land in the area served by the Kings River. In years of normal runoff, no water from the river reaches the ocean. Present estimates indicate it takes nearly 135 per cent of normal runoff before surplus water would reach the coast. This depends, of course, on the condition of the watershed, the amount of carryover storage, the manner in which the water runs out of the basin and the other hydrologic and meteorologic factors governing the flow of the river.

There are presently three main dams in the watershed. Two of these, Wishon and Courtright, are storage reservoirs for power generation, built and operated by the Pacific Gas and Electric Company. The other is Pine Flat, a 5,000,000 cubic yard concrete dam built by the Army Corps of Engineers.

In 1955 the Kings River Conservation District began sponsorship of an operational research weather modification program designed to increase the annual flow of the Kings River above Pine Flat Dam. Since that time the program has been operated each year during the 7-month period from 1 October through 30 April.

This report summarizes in some detail the operation of the weather modification program and presents the results of the evaluation for the total 10-year period. The location of the Kings River target area is shown in *Fig. 1*.

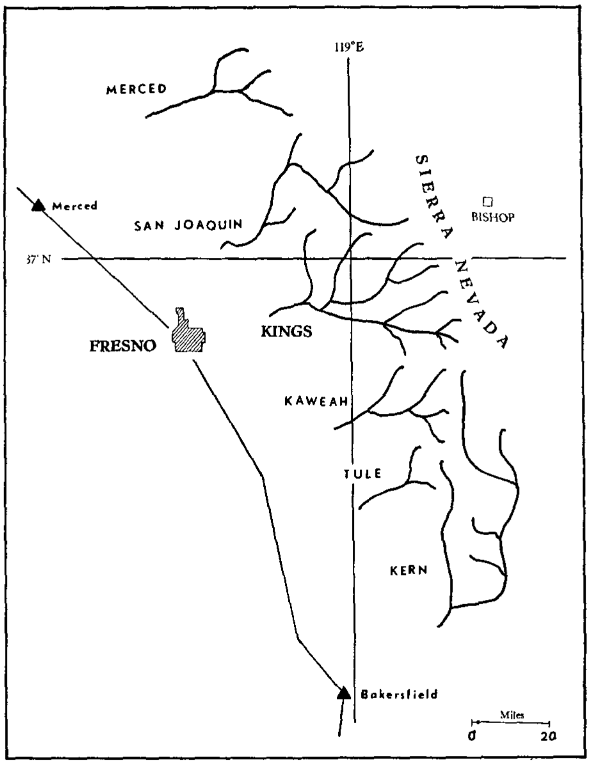

Fig. 1. Watersheds of the southern Sierra.

2. General operations

a. Meteorology. The normal storm meteorology, if there really is any such thing, involves a low pressure center positioned off the Washington coast with an associated frontal system trailing southwestward into the Pacific. As the system moves southeastward over Oregon and California the activity in the frontal zone diminishes. The Kings River watershed usually marks the southern boundary of any intense weather activity. Precipitation amounts usually diminish rapidly south of this area.

A second weather pattern, one which is less common but produces very large amounts of precipitation in the southern Sierra, is associated with a high pressure center in British Columbia which shunts the low center further south off the coast of northern or central California. In this situation the freezing levels move upward from the usual 4000 ft level to around 8000 ft.

A third and rather unusual weather pattern in the southern Sierra is associated with the low pressure center located off the southern California coast. This produces easterly to southeasterly flow along the Sierra Crest with the eastern slopes being favored for the larger precipitation amounts. This pattern usually produces large amounts of precipitation in the Los Angeles basin and far less amounts in the downslope regions along the western portions of the Sierra.

500-mb troughs are usually associated with all these weather patterns and exert a variety of influences on the total precipitation amounts resulting from each system. However, in each precipitation period there is a tendency toward "bands" of precipitation to move across the area and seldom does the radar show long periods of unbroken continuous precipitation.

At the moment a feeling persists on the operational level that the most pronounced seeding effects can be found during the most intense portions of all storms. Radar photographs and aircraft penetrations within the general storm systems seem to point in this direction. By these same observations there is further indication that seeding is ineffective or may even produce negative results, when 500-mb temperatures are below −24C.

b. Ground generators. The evolution of the individual silver iodide ground generator has progressed from the use of a chemical-propane mixture disbursed through a regular paint spray nozzle to the present modified Wells-Fuquay aspirator type in which the chemical is drawn from a ten-gallon storage reservoir by the passage of a propane jet across the tip of a hypodermic needle. This finely divided mixture is burned in a three-inch flame chamber of about 1800F and produces about 10^{15} nuclei (−20C) per gram of silver iodide.

The chemical solution strength is presently fixed at 2 per cent silver iodide (by weight) in acetone but in previous seasons has ranged between $1\frac{1}{2}$ and 4 per cent. Each generator consumes about 14 grams of silver iodide per hour through the #21 hypodermic needle. Propane use rate is 0.7 gallon per hour when the pressure is regulated at 10 psi through a #60 standard gas orifice.

The total number of silver iodide ground generators installed each season during the past 10-year period has ranged from as few as 15 to the present level of 30 units. From year to year the actual locations of the individual generators have been shifted in a number of cases. These modifications have resulted from studies of wind flow characteristics throughout the watershed and from silver iodide plume tracking during operational periods. In general, the present silver iodide ground generator network is reasonably well fixed. The main line of units is along the southwest border of the target boundary with additional units scattered in certain sections of the western and northwestern areas.

The total number of ground generators used during any individual storm period has ranged between two and twenty-four. The number is dependent upon the intensity and duration of the particular storm. Insofar as possible, the general method of operation involves ignition of units located along a path perpendicular to the surface wind flow. All storm periods have been seeded regardless of intensity or duration.

In the 10-year operational period a total of 2007 ground generators were ignited during the 212 storm periods. Total time logged was 21,648 hours. Total silver iodide consumed during this period was 251,243 gm (553.9 lb), an average of about 11.6 gm hr^{-1}.

Silver iodide ground generator operations during the individual seasons are shown in Table 1.

c. Aircraft. In the past ten years of operation there have been six types of seeding aircraft used on the Kings River Project, P-40 (Warhawk), F-51 (Mustang), F8F (Bearcat), T-28 (Trainer), Cessna 180 and the Piper Apache. The twin-engine Piper Apache has been used since 1960. This aircraft is equipped with Rajay turbochargers and complete de-icing equipment, plus all normal navigational aids. While its altitude capability is only about 23,000 ft MSL, the ship has performed well and has served as a reasonably good platform for both nuclei dispensing equipment and meteorological instruments.

The aircraft has had two main functions. It has first served as supplemental equipment to the overall ground generator network. Secondly, it has provided a platform for certain research equipment provided within the structure of the total program. Certain terrain

TABLE 1. Silver iodide ground generator operations.

Year	Storm periods	Number operated	Total hours	Silver iodide dispersed (gm)
1954–55	16	87	783	9788
1955–56	23	277	2694	30,981
1956–57	18	241	1715	25,725
1957–58	23	258	2064	26,832
1958–59	15	145	1276	17,226
1959–60	26	275	3221	35,431
1960–61	26	225	2677	26,770
1961–62	23	195	3212	32,120
1962–63	24	184	2401	24,010
1963–64	18	120	1597	22,360
Total	212	2007	21,640	251,243
Average	21	201	2164	25,124

TABLE 2. Aircraft operations.

Year	Storm periods	Total flights	Aircraft seeding: Total hours	Aircraft seeding: AgI dispersed (gm)	Aircraft seeding: CO_2 dispersed (lb)	Aircraft research: Total flights	Aircraft research: Total hours
1954–55	16	9	16	450	—	—	—
1955–56	23	41	58	1300	—	—	—
1956–57	18	66	153	3750	—	—	—
1957–58	23	49	118	2950	—	—	—
1958–59	15	31	68	1750	—	—	—
1959–60	26	29	56	1430	—	—	—
1960–61	26	46	69	—	2065	—	—
1961–62	23	34	70	—	2234	—	—
1962–63	24	44	52	37	2685	32	39
1963–64	18	32	27	387	1109	24	29
Total	212	381	687	12054	8093	56	68
Average *	21	38	69	1507	2023	28	34

* Averages are for total years in which figures are listed.

features, locations of National Park boundaries, and specific wind flow patterns make it impossible to place silver iodide ground generators in locations suitable for complete nuclei coverage in all areas of the Kings River watershed. Silver iodide plume tracking, under a program funded by the National Science Foundation, indicates the seeding capability of the aircraft has helped fill this gap.

In most storm situations, both aircraft and ground generators are operated. In these cases it is difficult, and no attempt has been made, to separate the effects from the individual sources. However, there have been a number of cases throughout the period when the aircraft was used on small cumulus formations (post-frontal) which were not producing precipitation. In some of these cases the only clouds which produced precipitation were those which were seeded. There continues to be substantial evidence that the aircraft is essential for any full-scale efficient cloud seeding program in this particular mountain area.

Silver-iodide seeding is accomplished from the aircraft by ignition of flare devices each containing 10 gm of AgI. Burning time of each unit is about 10 min and twelve are carried in racks mounted on the sides of the aircraft. The flares can be ignited individually or in groups. The output of these units has been checked at Colorado State University and found to be about 2.5×10^{13} nuclei per gram of silver iodide at −20C. Auger type dry ice equipment is also carried on board with dispensing rates available in the range of 1–10 pounds per mile. Silver iodide seeding is accomplished at the −5C level and dry ice is dispensed at cloud tops.

A total of 381 aircraft seeding flights have been made during the 212 storm periods. Total silver iodide dispersed from the aircraft has been 12,054 gm (26.6 lb) and since 1960 a total of 8093 lb of dry ice has been dispensed mainly in post-frontal cumulus clouds over the upper portions of the Kings River watershed. In the past two seasons there have been 56 additional flights made for pure research purposes.

A summary of aircraft operations during each season may be found in Table 2. Total nucleating agents dispersed from all sources is shown in Table 3.

d. Radar. The radar system used on the Kings River project was designed and built by Atmospherics Incorporated. The system operates on a frequency of 9375–9400 Mcs (3.2 cm) and produces a peak power of 50 kW. It has a maximum range of 200 miles in four steps of 10, 20, 80 and 200 miles. The antenna is a 30-inch parabola with 3° pencil beam radiation. Two scope presentations of the 7-inch Plan Position Indicator type are on-the-air during most seeding operations. One of the indicators is used for general viewing and data procurement which is applied to the direction of both ground generator and aircraft operations.

TABLE 3. Summary of total nucleating agents.

Year	Storm periods	Silver iodide (gm)	Carbon dioxide (lb)
1954–55	16	10,223	—
1955–56	23	32,281	—
1956–57	18	29,475	—
1957–58	23	29,782	—
1958–59	15	18,976	—
1959–60	26	36,861	—
1960–61	26	26,770	2065
1961–62	23	32,120	2234
1962–63	24	24,047	2635
1963–64	18	23,847*	1109
Total	212	264,397	8093
Average	21	26,440	2023

* Includes ignition of 110 pyrotechnic units each containing 10 gm of silver iodide.

The second indicator is used exclusively for 16-mm time-lapse scope photography of precipitation echoes.

The location of the system is about 14 miles NNE of Fresno at an elevation of 350 ft MSL. This site provides an unobstructed view of the total Kings River watershed. The power and sensitivity of the radar system make it possible to view considerable detail in precipitation echoes as the storms move across the San Joaquin Valley and into the higher mountain areas.

The radar system has two important functions within the application of the total cloud seeding program. As an operational tool, it provides the meteorological information necessary for proper direction of aircraft and operation of ground generators. Routine forecasting by individuals and agencies is not sufficient for direction of a full-scale cloud seeding operation. Secondly, the equipment provides significant information to the research effort presently an important part of the total seeding program.

e. Research. Since 1960 the National Science Foundation[1] has provided modest funding for supplemental meteorological tools considered basic to the total effort. The actual equipment procured in this research effort, such as time-lapse cameras, temperature measuring devices, calibrated cold boxes, microscopes, potential gradient recorders, small particle detectors and miscellaneous laboratory equipment, has permitted a more definitive examination of storms and seeding effects within and beyond the boundaries of the Kings River watershed.

The total research effort in the southern Sierra area has not been limited to the boundaries of the Kings River watershed. Extensions have been made into the watersheds of the Merced, San Joaquin, Kern, Kaweah, and Tule rivers along the western slope of the Sierra and to many of the smaller streams along the eastern slope of the range.

Under the present aims of the program it is unlikely there will be more than a casual pursuit of the present statistical evaluation for two reasons. First, the effect of an adjacent seeding program rules out the use of one of the control streams. Second, it does not seem logical that a more rigorous approach or a variation in program design will produce anything more statistically significant than the present 0.005 level.

3. Statistical evaluation

The 1963–64 season completed the tenth consecutive year of weather modification operations on the Kings River watershed. During this period, many hours were spent attempting to find the most significant evaluation procedure. One of these early attempts at evaluation dealt with the comparison of rain gage figures. As in almost all cases using rain gage data, the figures did not produce relationships with high significance levels. In addition, the network of established rain gages is too small to give adequate sampling of the areas inside and beyond the target boundaries.

In the early stages of the program an investigation of all snow survey courses and compiled data was initiated. This investigation indicated a more significant relationship between seeded and unseeded areas. However, even though the analysis produced rather high positive indications of the success of cloud seeding on the Kings River, the confidence levels were considered inadequate. It is important to note that many of these snow survey data can serve as clues pertaining to the effects of seeding operations within certain areas of the program and should not be ignored in the investigation of specific local effects.

An examination of the stream flow records along the western slopes of the Sierra range yields much basic data which are considerably more meaningful than either the snow survey data or the precipitation figures. It also seems appropriate to deal directly with the amount of runoff inasmuch as the program is designed to increase this figure and the numbers dealing with acre feet of water are more meaningful to the water users.

Applications of statistical methods have been made to many of the stream flow figures from streams along both the western and eastern slopes of the Sierra. The results of these analyses indicate a very high confidence level may be placed on results from comparisons between the flow of the Kings River and combinations of flows from the Merced and Kern Rivers. The use of control streams from areas both north and south of the target area seems appropriate in any search for methods of eliminating bias from years which contain a predominance of either northerly or southerly type storms.

The possible bias from persistent storm directions was not the only item investigated in this analysis. For example, the total number of acres covered by forest fires in both control and target areas was tabulated, methods of stream flow measurements were checked, types of measuring devices and locations of measuring points were investigated, and the historic record of stream flow itself was repeatedly checked. All the possible items which may have had some abnormal effect on the flows of either the control or target streams are now considered insignificant.

It was thought desirable to keep any statistical analysis as simple as possible without resorting to complex transformations of the basic data or to controversial methodology. Consequently, a straightforward multiple regression analysis has been used to indicate any possible change in the flow of the Kings river. No peculiar manipulation of these data has been made during the evaluation nor has there been any change in methodology since the initial choice was made in 1957.

Combinations of possible control streams were examined and these included the Merced, San Joaquin, Kern, Kaweah, Tule and Owens. The combination of

[1] Cost sharing contracts NSF C-206, C-402.

streams which resulted in the highest correlation with the Kings River was found to be the Merced River measured at Pohono bridge and the Kern River measured at Kernville. Mathematical analysis tells us the combination of these control streams which best minimizes the departure during the base period prior to any cloud seeding activity. The analysis also gives us the correlation coefficient between the target stream and this best combination of the two control streams.

A study of this analysis follows:

Let X = flow of the Kings River for any water year,
C_1 = flow of the Merced River for any water year,
C_2 = flow of the Kern River for any water year.

Let averages over the base period be denoted by bars and standard deviations by S. Thus

$\bar{X}$ = mean annual flow (unregulated) of the Kings River at Piedra during the base period, and
S_1 = standard deviation of the annual flow of the Merced River during the base period, etc.

The correlation coefficients will be denoted by R. Thus

R_{X1} = correlation coefficient between the annual runoff of the Kings and Merced rivers for the base period,
R_{12} = correlation coefficient between the annual runoff of the Merced and Kern rivers for the base period, etc.

The correlation coefficients are defined by the standard formula,

$$R_{X1}=\frac{\overline{XC_1}-\bar{X}\bar{C}_1}{S_x S_1},$$

where $\overline{XC_1}$ is computed by averaging the products of the stream flow of the Kings and Merced rivers over the base period.

The result of the computations are as follows where all values except the correlation coefficients are expressed in thousands of acre feet:

$\bar{X}=1509.4$ $S_X=662.0$ $R_{X1}=0.947$
$\bar{C}_1=421.1$ $S_1=153.7$ $R_{X2}=0.967$
$\bar{C}_2=497.0$ $S_2=226.6$ $R_{12}=0.876$

These results show that the chosen control streams have a very high relationship to the flow of the Kings River and will produce a formula that will predict the Kings River flow with a very high degree of confidence.

According to statistical theory, the correlation coefficient between the best possible combination of the two control streams and the Kings river runoff is given by

$$R^2=\frac{R_{X1}^2+R_{X2}^2-2R_{X1}R_{X2}R_{12}}{1-R_{12}^2}.$$

Substitution of numerical values leads to

$$R^2=0.978.$$

To see what improvement this represents over the better of the individual controls, let us compute the standard error for each case. For the Kern river alone, the standard error (thousands of acre feet) is given by

$$S_E=S_X\sqrt{1-R_{X2}^2}=661.9\times0.255=168.8.$$

For the combination control figure,

$$S_E=S_X\sqrt{1-R^2}=661.9\times0.15=99.3.$$

The use of the combination control figure reduces the standard error by approximately 70,000 acre feet.

Table 4. Stream flows in acre feet.*

Water year	Kings River	Merced River	Kern River+#3
1925–26	1,036,200	343,700	299,000
27	1,984,200	537,800	616,000
28	970,900	370,600	303,000
29	849,400	255,600	287,000
30	862,800	277,800	299,000
1930–31	465,800	144,700	177,000
32	2,083,500	506,700	585,000
33	1,180,900	289,900	390,000
34	658,800	187,300	220,000
35	1,621,300	527,200	421,200
1935–36	1,876,500	504,400	634,100
37	2,340,800	493,200	858,500
38	3,275,100	849,300	1,015,000
39	974,400	252,600	388,900
40	1,790,400	499,500	608,400
1940–41	2,542,800	616,800	946,000
42	2,005,300	599,300	618,600
43	2,026,600	537,800	802,500
44	1,168,200	327,700	443,500
45	2,062,400	478,300	665,700
1945–46	1,612,000	497,900	528,200
47	1,107,300	309,700	355,500
48	996,200	387,700	301,400
49	960,700	332,600	271,800
50	1,281,000	399,700	399,100
Total	37,734,500	10,527,800	12,425,500
Average	1,509,400	421,100	497,000
1954–55	1,143,000	296,200	331,400
1955–56	2,695,000	783,700	766,000
1956–57	1,259,000	361,700	387,200
1957–58	2,615,000	613,100	810,700
1958–59	823,700	241,700	246,000
1959–60	718,900	252,000	246,400
1960–61	571,500	186,900	165,300
1961–62	1,871,850	461,700	550,400
1962–63	1,902,000	501,200	628,500
1963–64	877,900	254,900	273,800
Total	14,477,850	3,953,100	4,405,700
Average	1,447,800	395,300	440,600

* From Surface Weather Records—Annual Reports, U.S. Dept. of Interior, Geological Survey, Menlo Park, Calif.

TABLE 5. Apparent changes in Kings River flow.

Water year	Unregulated flow (acre feet) (USGS)*	Predicted flow from formula	Apparent change	Percentage change	Probability
1954–55	1,143,000	993,600	+149,400	+15.0	0.07
1955–56	2,695,000	2,643,000	+ 52,000	+ 2.0	0.30
1956–57	1,259,000	1,210,700	+ 48,300	+ 4.0	0.31
1957–58	2,615,000	2,404,200	+210,800	+ 8.8	0.02
1958–59	823,700	745,800	+ 77,900	+10.4	0.22
1959–60	718,900	765,600	− 46,700	− 6.1	0.68
1960–61	571,500	505,700	+ 65,800	+13.0	0.26
1961–62	1,871,850	1,676,450	+195,400	+11.7	0.02
1962–63	1,902,000	1,883,800	+ 18,200	+ 1.0	0.43
1963–64	877,900	818,100	+ 59,800	+ 7.3	0.27
Total	14,477,850	13,646,950	+830,900		
Average	1,447,785	1,364,695	+ 83,090	6.1	0.005

* From Surface Weather Records—Annual Reports, U. S. Dept. of Interior, Geological Survey, Menlo Park, Calif.

Let the control figure calculated from the Merced and Kern rivers be denoted by X_E. Then

$$X_E = b_0 + b_1C_1 + b_2C_2,$$

where $b_0 = \bar{X} - b_1C_1 - b_2C_2$,

$$b_1 = \frac{S_X}{S_1}\left[\frac{R_{X1} - R_{X2}R_{12}}{1 - R_{12}^2}\right],$$

$$b_2 = \frac{S_X}{S_2}\left[\frac{R_{X2} - R_{X1}R_{12}}{1 - R_{12}^2}\right].$$

Substituting numerical values we find

$$X_E = 1.85C_1(\text{Merced}) + 1.72C_2\ (\text{Kern}) - 124.4.$$

Using the proportions of the Merced and Kern control streams as indicated we now have a formula which will give us a relatively high confidence prediction of the flow of the Kings river in any single year. A tabulation of all stream flow figures is shown in Table 4. The years 1925–1950 was used as the base period for computation of runoff correlations.

4. Conclusions: 10-year period

The details of many investigations, oriented toward the measurement of the flows of rivers both along the eastern and western slopes of the Sierra, will not be covered in this report. These investigations have established that the figures, as submitted by the U. S. Geological Society, are reasonably accurate and do reflect a true picture of the unregulated flow of all streams used in this analysis.

The flow of the Kings River, as published by the U. S. Geological Survey, is the result of measurements at their gaging station below Pine Flat dam, plus the gain and loss in the upstream reservoirs, plus an evaporation factor applied to the surface of these reservoirs. Two streams, Mill and Hughes creeks, enter the Kings River between the dam and Piedra. These streams are measured by the Kings River Water Association and their flows added to the U.S.G.S. figures. A sound reconstruction of the historic unregulated flow is obtained.

If these unregulated flow figures of the Kings River are used in the statistical formula, then the apparent change in Kings River flow during the 10-year cloud seeding period is as shown in Table 5.

The figures appearing in the last column are the probability that the observed departure is a chance fluctuation as given by application of the standard statistical t test to the observed departures. The one-tailed test was employed.

The indicated total increase in Kings River flow is 830,900 acre ft over the 10-year period, representing an overall increase of 6.1 per cent. The probability that this total increase was due to chance is 0.005.

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