BENEFITS FROM HISTORIC CLOUD SEEDING PROGRAMS IN CALIFORNIA

by
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ABSTRACT

California has the longest history of operational cloud seeding programs of any area in the world. The technology was first applied by the California Electric Power Company (now Southern California Edison Co.) beginning on February 2, 1948 over the Bishop Creek watershed in the eastern Sierra. Within the next few years additional programs evolved over watersheds of the San Joaquin, Kings, Mokelumne, and Feather Rivers. As the years evolved, additional programs were initiated over other areas of California as funded by county water agencies, municipalities and hydroelectric interests. During the 1994/95 winter season a total of 15 operational programs were active. Evaluations of several cloud seeding programs in California have been extensive. In addition to serious statistical methods applied to precipitation and streamflow data, these evaluations have more recently focused on extensive radar data collected by operational 3cm and 5cm weather radar systems. The combined benefits are explored from ten programs in California which have been active for various periods since 1950.

INTRODUCTION

It began from a classic serendipitous event. On 13 July 1946 Dr. Vincent Schaefer, working at the General Electric Research Laboratory in Schenectady, New York, placed a piece of dry ice in one of his experimental cold boxes to reduce the temperature. Almost instantly, many of the supercooled fog droplets produced by his breath in the refrigerated chamber were converted to ice crystals which grew and fell to the bottom of the box. This discovery of an important fundamental principle came not only from the act itself but most importantly from Schaefer's intuitive understanding of what he had just observed. In November of that same year, Schaefer and a pilot took to the air about 50 miles east of Schenectady, New York, and sprinkled three pounds of dry ice pellets along the top of a supercooled stratus cloud deck. The result was the famous "race track" ice crystal and fallout pattern produced by this simple application of the dry ice.

Modern cloud seeding technology, as a unique method for modification of precipitation mechanisms, continued its evolution in the late 1940's and early 1950's after Drs. Vincent Schaefer, Bernard Vonnegut and Irving Langmuir seriously began seeking answers to complex questions about the basic nature of precipitation processes. Project Cirrus was certainly one of those early investigations which produced stimulating information of major importance. More recent investigations conducted over the past 20 years have illuminated a number of fundamental concepts as well as produced many specific insights to this complex array of static and dynamic properties. The various physical and chemical properties, plus the interrelated mechanisms which come together to produce clouds and precipitation, are complex and still not fully understood. However, the concept that cloud seeding can be practically used for beneficial purposes at favorable benefit/cost ratios, has gained considerably scientific acceptance and is rapidly expanding at international levels.

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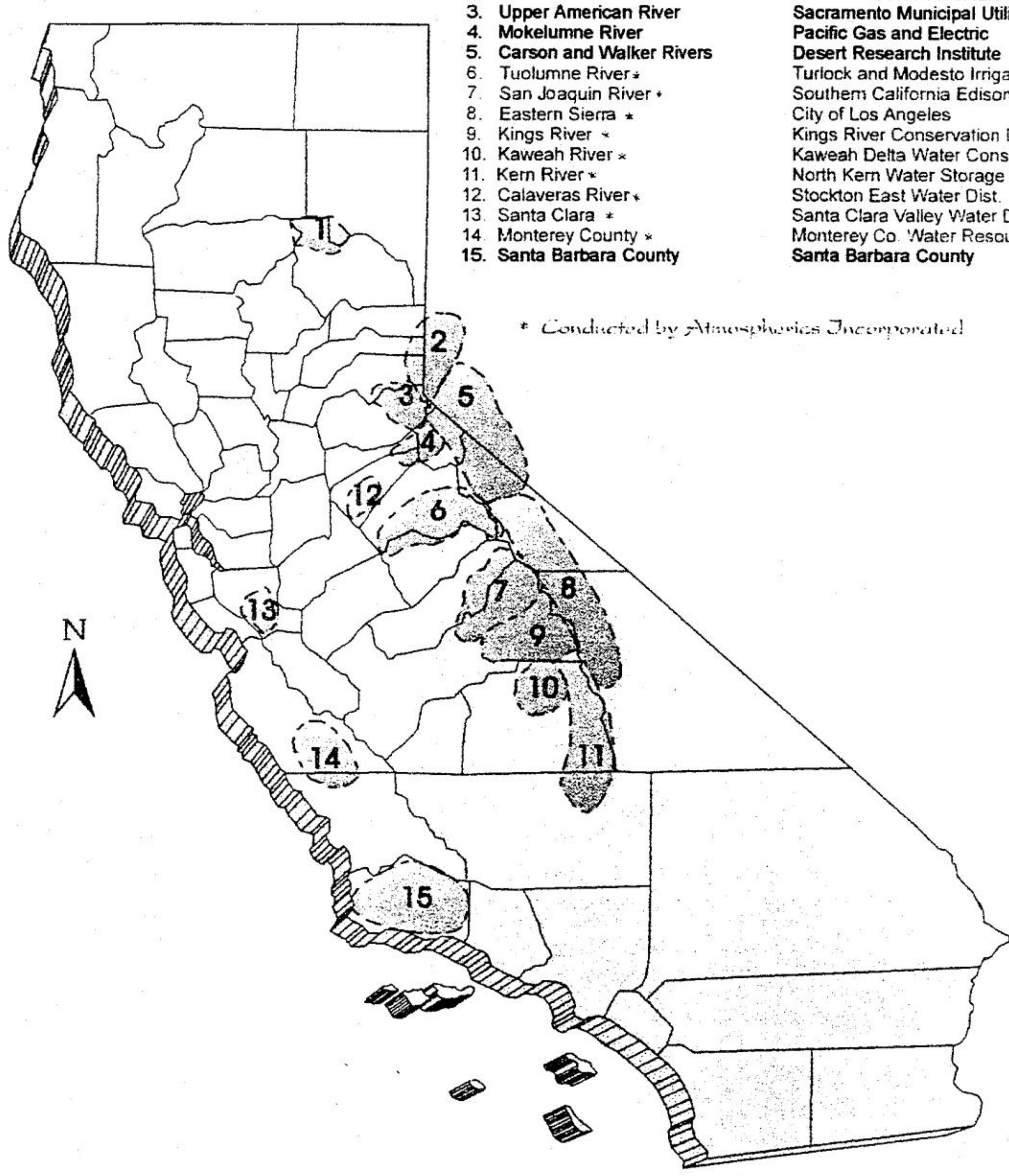
FIGURE 1.

RAIN AND SNOW ENHANCEMENT PROGRAMS IN CALIFORNIA 1994/95 SEASON

Project	Sponsor
1. **Lake Almanor**	**Pacific Gas and Electric**
2. **Truckee-Tahoe**	**Desert Research Institute**
3. **Upper American River**	**Sacramento Municipal Utility Dist.**
4. **Mokelumne River**	**Pacific Gas and Electric**
5. **Carson and Walker Rivers**	**Desert Research Institute**
6. Tuolumne River *	Turlock and Modesto Irrigation Dists.
7. San Joaquin River *	Southern California Edison
8. Eastern Sierra *	City of Los Angeles
9. Kings River *	Kings River Conservation Dist.
10. Kaweah River *	Kaweah Delta Water Conservation Dist.
11. Kern River *	North Kern Water Storage Agency
12. Calaveras River *	Stockton East Water Dist.
13. Santa Clara *	Santa Clara Valley Water Dist.
14. Monterey County *	Monterey Co. Water Resources Agency
15. **Santa Barbara County**	**Santa Barbara County**

* Conducted by Atmospherics Incorporated



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HISTORIC BACKGROUND - CALIFORNIA PROGRAMS

Cloud seeding programs designed to enhance the mechanisms of rain and snow have been conducted somewhere in California during each of the past 47 years. Two of these programs have operated almost every year for more than 40 of those years and one has an unbroken record of 45 years continuous operations. Some of these early projects, along with their initial year of operation, can be listed as follows:

- The California Electric Power Company program over the Bishop Creek watershed in the eastern Sierra, (1948)
- The Southern California Edison Company program over the Upper San Joaquin River watershed, (1950).
- The Pacific Gas and Electric Company program over the Lake Almanor watershed, (1953)
- The Kings River Conservation District program over the Kings River watershed above Pine Flat Dam, (1954)

Perhaps one of the earliest and most comprehensive evaluations of a cloud seeding program in the United States was focused on the Bishop Creek Program. Dry ice seeding operations began on February 2, 1948 over the 125 square mile watershed of this hydroelectric power system in the eastern Sierra near Bishop, California. The program was funded by the California Electric Power Company (now Southern California Edison Company) and remained active for 11 years. The initial evaluation began in 1950 and was guided by Dr. Ferguson Hall of the Department of Commerce. The study considered precipitation and snow survey data but eventually settled on annual streamflow totals as the most powerful approach. Various combinations of control streams, both north and south of the target watershed, were examined using a range of statistical techniques. A final multiple regression analysis suggested a 9% increase in streamflow from the seeded watershed. The extensive study was eventually published as Research Paper No. 36, Cloud Seeding Operations in the Bishop Creek, California Watershed, Ferguson Hall, T.J. Henderson and Stuart A. Cundiff, Department of Commerce, Washington, DC, January 1953. The program is no longer active as an individual entity, but the Bishop Creek watershed presently falls within the boundaries of the Eastern Sierra Program, a cloud seeding project funded by DWP, City of Los Angeles.

THE CLOUD SEEDING PROGRAMS

Throughout the history of cloud seeding in California, as many as 20 programs have been active in a single year. Most of these have been designed to increase snow in the mountain watersheds of the Sierra for enhanced hydroelectric power generation. Others were focused on the important California agriculture or supplemental water for municipalities. The scientific design of modern cloud seeding programs may include such hardware as computerized satellite weather data acquisition systems, pyrotechnic and liquid fuel aircraft delivery systems, ground-based ice nuclei generators, radar systems for program supervision and evaluations, computerized radar data collection systems, plus a broad range of artificial ice nuclei formulations and dispensing systems. Operational design features of every program include certain suspension criteria focused on the possibility of extremely severe storms, high reservoir storage levels, excessive streamflow which may produce flooding, unusual snowpack conditions, emergency search and rescue missions, avalanche hazards, and a broad range of overall water supply considerations. Fifteen programs were active in California during the 1994/95 season. The names and locations of these programs are shown in Figure 1.

Ten cloud seeding programs were chosen for inclusion in this study. All were active during some portion of the present 1994/95 water year. The choices included such criterion as geographic location, design features, length of operations, available data, multiple use aspects, previous evaluations, and the author's knowledge about the program. The names of the chosen programs, the primary supporting groups, and their individual years of operation are listed in Table 1. One of the most impressive aspects of this list is simply that the ten programs have logged 246 seasons of cloud seeding experience.

Several of the programs received support from groups in addition to the ones shown on the list. For example, the Kings River Program includes support from the Kings River Water Association, Pacific Gas and Electric Co., and the California Department of Water Resources. The Kern River program also receives support from the Kern Delta Water District, Buena Vista Water Storage District, and the City of Bakersfield. Modesto Irrigation District is a partner in the Tuolumne River Project, and the Mokelumne River Project receives support from East Bay Municipal Utility District.

The major storage reservoirs, capacities and their relevant watershed areas, are listed in Table 2. These are only shown to illustrate the magnitude of the total areas and water volumes associated with the overall drainage basins, within which the cloud seeding programs are geographically focused. It is worth emphasizing the watershed areas total nearly 11,000 sq. miles and the storage capacity of the major reservoirs alone is about 8.0 million acre ft. Not listed are the many upstream reservoirs which also account for substantial storage. In some cases the actual effect from the associated cloud seeding program is focused on smaller areas within these major watersheds. These figures, as well as streamflow totals relevant to the actual seeded areas, are discussed in a subsequent section which deals with benefits.

TABLE 1.

CLOUD SEEDING PROJECTS - BASIC INFORMATION

	Project name	Primary Support Group*	Total seasons of Cloud Seeding
1.	Lake Almanor	PG & E	42 (1953)
2.	Upper American	SMUD	27 (1968)
3.	Mokelumne River	PG & E	42 (1953)
4.	Tuolumne River	TID/MID	5 (1990)
5.	Monterey County	MCWRA	5 (1990)
6.	Eastern Sierra	DWP	9 (1977)
7.	San Joaquin River	SCE	45 (1950)
8.	Kings River	KRCD	36 (1954)
9.	Kaweah River	KDWCD	18 (1975)
10.	Kern River	NKWSD	17 (1977)
		TOTAL:	**246 SEASONS**

* PG&E Pacific Gas and Electric Company
SMUD Sacramento Municipal Utility District
TID/MID Turlock and Modesto Irrigation Districts
MCWRA Monterey County Water Resources Agency
DWP Los Angeles Department of Water and Power
SCE Southern California Edison Company
KRCD Kings River Conservation District
KDWCD Kaweah Delta Water Conservation District
NKWSD North Kern Water Storage District

TABLE 2.

CLOUD SEEDING PROGRAMS

MAJOR RESERVOIRS, CAPACITIES, WATERSHED AREAS

	Project Name	Major Storage Reservoir	Capacity (AF)	Watershed Area (mi^2)
1.	Lake Almanor	Lake Almanor	1,143,000	491
2.	Upper American, S.F.	Folsom	977,000	250
3.	Mokelumne River	Pardee/Camanche	627,000	169
4.	Tuolumne River	New Don Pedro	2,030,000	1,500
5.	Monterey County	Nacimiento/ San Antonio	340,000 330,000	330 323
6.	Eastern Sierra	Crowley	321,000	2,000
7.	San Joaquin	Millerton	521,000	1,600
8.	Kings River	Pine Flat	1,000,000	1,500
9.	Kaweah River	Terminus	143,000	680
10.	Kern River	Isabella	568,000	2,100
		TOTAL:	**8,000,000**	**10,943**

EVALUATIONS

Because of the natural and artificial water courses in California, supplemental water from many cloud seeding programs has extensive multiple uses and related benefits. For example, an acre foot of water in the snowpack at 10,000 ft. elevation may eventually move through several hydroelectric generating plants, then contained in downstream reservoirs for flood control and recreational purposes, move on to the valley floor for use by agricultural interests, industry and municipalities and sometimes finding its way to ponding basins for ground water recharge.

This paper does not specifically focus on evaluations of individual weather modification programs. However, cloud seeding programs in California have been evaluated, re-evaluated, and re-re-evaluated more than any other similar programs in the world. At present, there are no less than 260 references dealing with evaluations of cloud seeding programs in California. It is enough to say that data used in these historic and current evaluations have included files from several rain gage networks, various cooperative snow survey programs, USGS published streamflow records, and radar data sets obtained during many cloud seeding operations. For the benefit of the statistical community, the ranges of R^2 values within these evaluations are listed in the following Table 3.

It is worth emphasizing that the statistical analyses which produced the ranges of R^2 values in Table 3, and utilized the four parameters in the data set column, have ultimately noted apparent increases in the range of 4% to 16%, significant at the 0.05 level.

TABLE 3.

CLOUD SEEDING PROGRAM EVALUATIONS -- CALIFORNIA

Data Set	Range of R^2 values
Rain gage networks	0.68 - 0.82
Snow survey programs	0.76 - 0.91
Streamflow compilations	0.87 - 0.98
Project radar data	0.83 - 0.92

BENEFITS

Based on the extensive statistical and physical evaluations, this study assumes that supplemental water has been derived from such cloud seeding programs and explores the potential benefits in terms of a range of effectiveness percentages and their values. In order to establish a broader view of these possible benefits on a cumulative scale in California, the average annual streamflow, hydroelectric generating capacity, and hydro production efficiency data were assembled and tabulated. For each of the ten programs included in the study, these values are shown in Table 4.

The average streamflow totals include only the flows which originate in the areas affected by the cloud seeding programs, then move downstream through various hydroelectric plants. Hydroelectric capacity is simply the maximum capacity of all hydro units affected by the cloud seeding program. These capacity values do not suggest the hydro plants are operating at this level and at all times throughout the water year. The efficiency column shows data expressed as the average number of kilowatt hours generated per acre foot of water through the hydroelectric plants as affected by the cloud seeding program. All of these figures must certainly have error ranges, but this aspect must be left to the fine-tuning in future years.

Taken as a whole, the totals shown in Table 4 tend to minimize any error ranges associated with basic data from individual projects, and probably come somewhat closer to establishing realistic benefits. It is enough to emphasize that the totals are large, and represent a remarkable and extremely valuable resource in California.

The study now moved to the actual benefits, which are derived by assuming the cloud seeding programs actually increase the average volume of available water by some range of percentages. For purposes of reaching some meaningful conclusions, the chosen percentages were 2%, 4%, and 6% increases, rather conservative figures when compared with the higher values concluded from more recent physical and statistical studies. A fourth column showing a 9% increase in runoff volume was added as a sort of personal speculative figure because of the results shown by the extensive statistical evaluation focused on the historic Bishop Creek Program as published in 1953.

The results from this range of percentage streamflow increases as applied to the average annual streamflow through the individual basin-related hydro powerplants are shown in Table 5.

TABLE 4.

CLOUD SEEDING PROJECTS - HYDRO GENERATION

	Project Name	Average Annual Flow (AF)	Hydroelectric Capacity (MW)	Efficiency Kwh/AF
1.	Lake Almanor	700,000	670	2,833
2.	Upper American	405,000	660	4,350
3.	Mokelumne River	330,000	208	2,400
4.	Tuolumne River			
	TID/MID	1,656,000	195	350
	Holm-Kirkwood	435,000	214	2,000
5.	Monterey County			
	Nacimiento	200,000	4	120
	San Antonio	70,000		
6.	Eastern Sierra			
	Bishop Creek	68,000	29	3530
	Rush Creek	35,000	11	1270
	Lee Vining Creek	26,000	11	1045
7.	San Joaquin River	1,776,000	1,190	8,630
8.	Kings River			
	PG&E	1,670,000	1,547	6,076
	KRCD	1,311,000	165	310
9.	Kaweah River	444,000	7	1,760
10.	Kern River	716,000	90	2,100
	TOTALS:	**9,842,000**	**5,009**	

TABLE 5.

CLOUD SEEDING PROJECTS - INCREASES IN STREAMFLOW

		Average Annual Flow Increases from Cloud Seeding (AF)			
		2%	4%	6%	9%
1.	Lake Almanor	14,000	28,000	42,000	63,000
2.	Upper American	8,100	16,200	24,300	36,450
3.	Mokelumne River	6,600	13,200	19,800	29,700
4.	Tuolumne River				
	TID/MID	33,120	66,240	99,360	149,040
	Holm-Kirkwood	8,700	17,400	26,100	39,150
5.	Monterey County				
	Nacimiento	4,000	8,000	12,000	18,000
	San Antonio	1,400	2,800	4,200	6,300
6.	Eastern Sierra				
	Bishop Creek	1,360	2,720	4,080	6,120
	Rush Creek	700	1,400	2,100	3,150
	Lee Vining Creek	520	1,040	1,560	2,340
7.	San Joaquin River	35,520	71,040	106,560	159,840
8.	Kings River				
	PG&E	33,400	66,800	100,200	150,300
	KRCD	26,220	52,440	78,660	117,990
9.	Kaweah River	8,880	17,760	26,640	39,960
10.	Kern River	14,320	28,640	42,960	64,440
	TOTALS:	**196,840**	**393,680**	**590,520**	**888,780**

Before moving on to the estimates of dollar values, the remaining calculations involved the conversion of average annual streamflow increases in acre feet to the total megawatt hours of generation. These amounts are shown in Table 6. Because the supplemental water provides multiple-use benefits, the total average annual volume of water attributed to the ten cloud seeding programs was required for estimating the benefits to agriculture, municipalities and the environment. These totals are shown in Table 7.

TABLE 6.

CLOUD SEEDING PROJECTS - INCREASES IN GENERATION

	Average Annual Mwh ($x10^3$) Increases from Cloud Seeding			
	2%	4%	6%	9%
1. Lake Almanor	39.7	79.4	119.1	178.7
2. Upper American	35.2	70.4	105.6	158.4
3. Mokelumne River	15.8	31.6	47.4	71.1
4. Tuolumne River				
TID/MID	11.6	23.2	34.8	52.2
Holm-Kirkwood	17.4	34.8	52.2	78.3
5. Monterey County				
Nacimiento	0.5	1.0	1.5	2.3
San Antonio	--	--	--	--
6. Eastern Sierra				
Bishop Creek	4.8	9.6	14.4	21.6
Rush Creek	0.9	1.8	2.7	4.0
Lee Vining Creek	0.5	1.0	1.5	2.2
7. San Joaquin River	306.5	613.0	919.5	1379.3
8. Kings River				
PG&E	202.9	405.8	608.7	913.0
KRCD	8.1	16.2	24.3	36.4
9. Kaweah River	15.6	31.2	46.8	70.2
10. Kern River	30.1	60.2	90.3	135.5
TOTALS:	**689.6**	**1,379.2**	**2,068.8**	**3,103.2**

TABLE 7.

AVERAGE ANNUAL VOLUME OF WATER ATTRIBUTED TO CLOUD SEEDING

Total average annual flow from ten programs (AF)	**2% Increase (AF)**	**4% Increase (AF)**	**6% Increase (AF)**	**9% Increase (AF)**
9,842,000	196,800	393,600	590,400	885,600

CONCLUSIONS

The added power generation and values have been calculated for each of the percentage increases in streamflow due to the cloud seeding programs. Conservative estimates of supplemental water values to Agriculture, Municipalities and Environmental interests have also been compiled. These data are shown in Table 8.

The total values of the supplemental water produced by the ten cloud seeding programs each year in California are in the range of $26 million to $115 million. Based on a private sector estimated total operational cost of $1,798,000 for the ten cloud seeding programs, the benefit/cost ratios for the four percentage increases are in the range of 14:1 to 64:1.

The complexity of precisely calculating electrical energy amounts associated with multiple hydro plants within complex watersheds was beyond the scope of this study. Averages provide an adequate overview but individually they must certainly contain inaccuracies, both plus and minus. Additionally, the stated value of electrical energy at $20/Mwh is very conservative. During dry seasons, the actual value of supplemental water for hydro generation may be many times that figure depending upon modes of operation within specific projects. The total dollar values of supplemental water for agriculture, municipal and environmental uses are equally difficult to estimate. The $60/AF figure used in this study is considered very conservative, but these are starting points for future studies.

TABLE 8.
TOTAL VALUE OF SUPPLEMENTAL WATER (x 1000)
TEN CLOUD SEEDING PROGRAMS IN CALIFORNIA

	2%	4%	6%	9%
1. MWh	690	1,380	2,070	3,105
2. $20/MWh	$ 13,800	$ 27,600	$ 41,400	$ 62,100
3. Agriculture/ Municipal/ Environment ($60/AF)	$ 11,810	$ 23,620	$ 35,430	$ 53,150
4. TOTAL VALUE	**$ 25,610**	**$ 51,220**	**$ 76,830**	**$ 115,250**
5. BENEFIT/ COST RATIO*	**14:1**	**28:1**	**42:1**	**64:1**

* *Based on an estimated annual cost of $1,798,000 to operate eight of the programs for six-months each season (Nov-Apr) and the year-round operations for San Joaquin and Eastern Sierra. Cost includes full-time assigned personnel, in-house satellite derived weather data acquisition and weather forecasts, ground-based radar, aircraft seeding capabilities, ground generator networks on seven of the programs, evaluations and reports.*

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