NEW ASSESSMENT OF THE ECONOMIC IMPACTS FROM TEN WINTER SNOWPACK AUGMENTATION PROJECTS

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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 beginning on February 2, 1948. As the years evolved, additional programs funded by water agencies, municipalities and hydroelectric interests were organized over many California locales. During the 1995/96 winter season, thirteen operational programs were active. A broad range of statistical evaluations have been applied to many of these programs. In addition to statistical methods applied to precipitation and streamflow data, these evaluations have more recently focused on substantial radar data collected by operational 3cm and 5cm weather radar systems. The combined benefits are explored using ten programs in California which have been active for varied periods since 1950. The results from this study strongly suggest that beneficial increases in water supplies have been produced by these long-term cloud seeding programs.

1. HISTORIC BACKGROUND

For many years cloud seeding programs designed to enhance the mechanisms of rain and snow have been conducted at various sites in California (Dennis, 1980). 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 of continuous operations. Evaluations have been extensive (Orville, 1967; Malone, 1973). Some of these early projects, along with their initial year of operation, are listed below:

- 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).

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 (Hall, F., *et al.*, 1953a and 1953b). The Bishop Creek program is no longer active as an individual entity because the target area watershed now falls within the boundaries of the Eastern Sierra Program, a cloud

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Another program in the Sierra which has received extensive evaluations is the Kings River Weather Resources Management Program. It has an operations background beginning in 1954. The evaluations have produced apparent positive results significant to the 0.01 confidence level (Henderson, 1966; Malone, 1966). By 1974 a physical basis for seeding orographic clouds was reasonably well established (Grant and Kahan, 1974) and cloud seeding programs in California continued to expand.

2. 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 have 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, radiometers, supercooled liquid water detectors, pyrotechnic and liquid fuel aircraft delivery systems, ground-based ice nuclei generators, radar systems for program supervision and evaluations, plus computerized radar data collection 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.

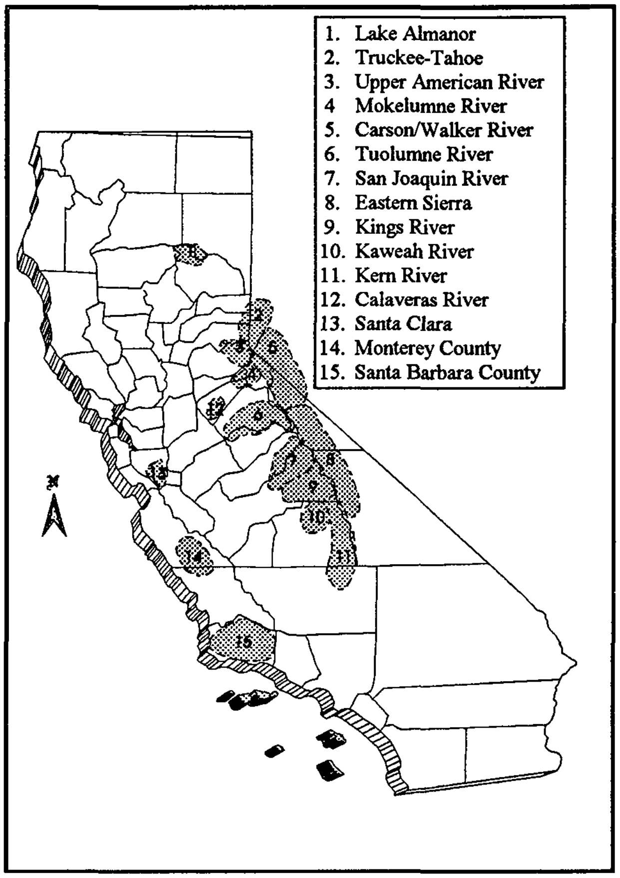

Figure 1. Rain and Snow Enhancement Programs in California, 1994/95 Season.

Ten cloud seeding programs were chosen for inclusion in this study. All were active during some portion of the 1994/95 water year. The choices included criteria such as geographic location, design features, length of operations, available data, multiple water use aspects, previous evaluations, and the author's knowledge of 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 that the ten programs have logged 246 seasons of cloud seeding experience.

Several of the programs received support from groups in addition to those listed. 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 the East Bay Municipal Utility District.

The major storage reservoirs, their capacities, and relevant watershed areas are listed in Table 2.

Table 1. Cloud Seeding Projects - Basic Information.

Project Name	Primary Support Group*	Total Seasons of Cloud Seeding
Lake Almanor	PG&E	42 (1953)
Upper American	SMUD	27 (1968)
Mokelumne River	PG&E	42 (1953)
Tuolumne River	TID/MID	5 (1990)
Monterey County	MCWRA	5 (1990)
Eastern Sierra	DWP	9 (1977)
San Joaquin River	SCE	45 (1950)
Kings River	KRCD	36 (1954)
Kaweah River	KDWCD	18 (1975)
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, Water Sheds

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

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 that the watershed areas total nearly 11,000 sq. miles and the storage capacity of the major reservoirs alone is approximately eight million acre feet.

Not listed are the many upstream reservoirs which also account for substantial storage. In some cases the 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.

3. EVALUATIONS

Because of the natural and artificial water courses in California, supplemental water from many cloud seeding programs has multiple uses and related benefits. For example, an acre foot of water in the higher snowpack at 10,000 ft. elevation may eventually move through several hydroelectric generating plants, then be 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 find 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 repeatedly re-evaluated more than any 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 based on correlations between target/control data are listed in Table 3.

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

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.

4. BENEFITS

Based on the extensive statistical and physical evaluations, this study assumes that supplemental water has been derived from 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 possible benefits on a cumulative scale in California, the average annual streamflow, hydroelectric generating capacity, and hydro production efficiency data were assembled and tabulated. These values are shown in Table 4 for each of the ten programs included in the study.

Table 4. Cloud Seeding Projects - Hydro Generation

Project Name	Average Annual Flow (AF)	Hydro-electric Capacity (MW)	Efficiency Kwh/AF
Lake Almanor	700,000	670	2,833
Upper American	405,000	660	4,350
Mokelumne River	330,000	208	2,400
Tuolumne River			
TID/MID	1,656,000	195	350
Holm-Kirkwood	435,000	214	2,000
Monterey County			
Nacimiento	200,000	4	120
San Antonio	70,000		
Eastern Sierra			
Bishop Creek	68,000	29	3530
Rush Creek	35,000	11	1270
Lee Vining Creek	26,000	11	1045
San Joaquin River	1,776,000	1,190	8,630
Kings River			
PG&E	1,670,000	1,547	6,076
KRCD	1,311,000	165	310
Kaweah River	444,000	7	1,760
Kern River	716,000	90	2,100
TOTALS:	9,842,00	5,009	

The historic average annual streamflow totals, as calculated for the benefit study period, 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 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 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 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 valuable resource in California.

The study now moved to the actual benefits, derived by assuming the cloud seeding programs actually increase the average volume of available water by some range of percentages. For purposes of reaching meaningful conclusions, the chosen percentages of increase were 2%, 4%, and 6%, 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 from an historic perspective because of results obtained by the extensive statistical evaluation, published in 1953, focusing on the Bishop Creek Program.

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.

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 5. Cloud Seeding Projects - Increases in Streamflow

Absolute increases in streamflow from individual watersheds corresponding to assumed percentage increases due to cloud seeding.

	2%	4%	6%	9%
Lake Almanor	14,000	28,000	42,000	63,000
Upper American	8,100	16,200	24,300	36,450
Mokelumne River	6,600	13,200	19,800	29,700
Tuolumne River				
TID/MID	33,120	66,240	99,360	149,040
Holm-Kirkwood	8,700	17,400	26,100	39,150
Monterey County				
Nacimiento	4,000	8,000	12,000	18,000
San Antonio	1,400	2,800	4,200	6,300
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
San Joaquin River	35,520	71,040	106,560	159,840
Kings River				
PG&E	33,400	66,800	100,200	150,300
KRCD	26,220	52,440	78,660	117,990
Kaweah River	8,880	17,760	26,640	39,960
Kern River	14,320	28,640	42,960	64,440
TOTALS:	**196,840**	**393,680**	**590,520**	**888,780**

Table 6. Cloud Seeding Projects - Increases in Generation

Increases in average annual generation (MWh x 10^3) produced by the assumed percentage increases due to cloud seeding.

	2%	4%	6%	9%
Lake Almanor	39.7	79.4	119.1	178.7
Upper American	35.2	70.4	105.6	158.4
Mokelumne River	15.8	31.6	47.4	71.1
Tuolumne River				
TID/MID	11.6	23.2	34.8	52.2
Holm-Kirkwood	17.4	34.8	52.2	78.3
Monterey County				
Nacimiento	0.5	1.0	1.5	2.3
San Antonio	--	--	--	--
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
San Joaquin River	306.5	613.-0	919.5	1,379.3
Kings River				
PG&E	202.9	405.8	608.7	913.0
KRCD	8.1	16.2	24.3	36.4
Kaweah River	15.6	31.2	46.8	70.2
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

5. 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 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 (Randerson, 1984). 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.

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.*

**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.*

Table 8. Total Value of Supplemental Water (x 1000) Ten Cloud Seeding Programs in California.

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

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