"REVIEWED"

FEATHER RIVER BASIN CLOUD SEEDING FEASIBILITY

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Abstract. North American Weather Consultants performed a feasibility study of a cloud seeding program, on behalf of the California Department of Water Resources, for portions of the Feather River drainage in the northern Sierra Nevada. The primary objectives of the study were: 1) determine areas that would present the greatest opportunity for runoff enhancement; 2) determine the seeding agent and delivery system that will maximize enhancement with minimal adverse social and environmental effects; 3) estimate the increase in runoff to Lake Oroville that enhancement would have produced during years when unused storage in the reservoir would have been available; and 4) determine the feasibility of proceeding to a design study and an Environmental Impact Report. Apparent results from other cloud seeding projects in the Sierra Nevada were used to simulate the effects of cloud seeding upon precipitation in the proposed Feather River target area. The modeled increased precipitation was then used as input for the WRENSS hydrology model to estimate the runoff increases due to the seeding. Benefit cost ratios were formulated to assess whether or not a cloud seeding project would be economically feasible. The study demonstrated that there is a technological basis for the successful performance of an operational weather modification program. A preliminary project design was prepared with a cautionary note that a full design should be completed with more detailed investigations in areas that were beyond the scope of this feasibility study; e.g., suspension criteria, evaluation procedures, equipment needs and siting, to name only a few.

1. BACKGROUND

Because of the ever increasing demands upon water supplies in the state of California, the California Department of Water Resources (CDWR) initiated a study to determine the feasibility of augmenting water supplies in the Feather River drainage area, located in the Northern Sierra Nevada (refer to Figure 1). This feasibility study had as its objectives the following:

1) determine areas that would present the greatest opportunity for runoff enhancement;
2) determine the seeding agent and delivery system that will maximize enhancement with minimal adverse social and environmental effects;
3) estimate the increase in runoff to Lake Oroville that enhancement would have produced during years when unused storage in the reservoir would have been available; and
4) determine the feasibility of proceeding to a design study and an Environmental Impact Report.

Individual tasks that went into the completion of the study included: review and summarize other relevant Sierra Nevada programs; prepare climatological and hydrological descriptions of the area; describe physical characteristics, frequencies and seedability of storm types by month; recommend operational procedures, seeding agents and delivery systems;

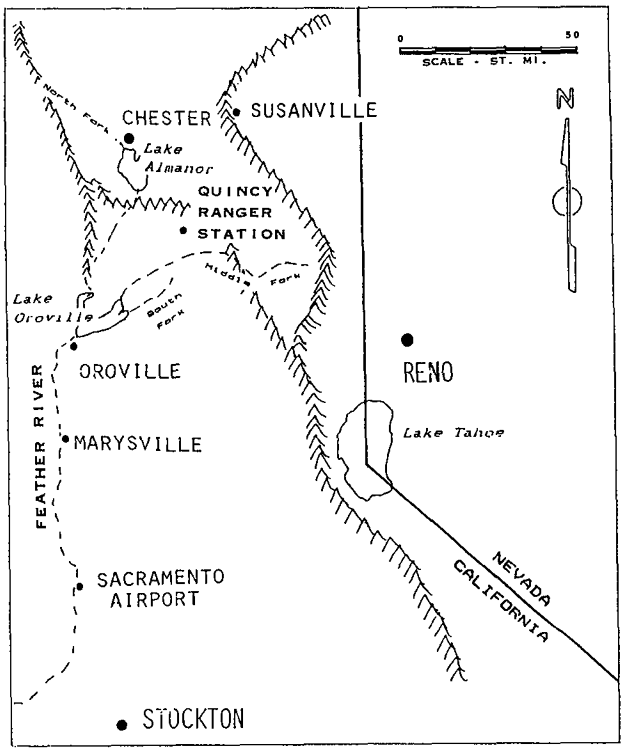

Figure 1 Schematic representation of the Feather River drainage and the Sierra Nevada.

recommend target areas; estimate increases and identify storm types to be seeded; recommend operational season; develop suspension criteria; recommend suspension criteria monitoring requirements; estimate downwind effects and monitoring requirements; estimate storage available at Oroville; recommend evaluation criteria for estimating increases in runoff; estimate the percentage of annual increase in runoff for dry, normal, and wet years; prepare a general description of the precipitation enhancement program; and describe considerations (financial, legal, environmental, and benefits and detriments) involved in implementing the precipitation enhancement program.

1.1 Hydrology of the Feather River Basin

The Feather River Drainage is rather unique when compared to other Northern Sierra catchments. The Feather is somewhat of an over-the-barrier catchment rather than having primarily windward catchments as do the American and Yuba catchments.

The Feather River Basin as defined by this study encompasses the complete Feather River watershed above Oroville Dam with the exception of the West Branch Feather River. Elevations within the basin range from the 275-m, mean sea level elevation of Oroville Reservoir to 3200 m at the top of Lassen Peak. Generally, the basin slopes southwesterly from the Sierra Nevada Range and southeasterly from Lassen Peak in the Cascade Range down to the Sacramento Valley floor. The upper portion of the basin is crossed by three mountain ridges running in a northwest-southeast direction. These ridges are responsible for a series of high mountain valleys which contain streams of moderate slope. As the gradients of these tributaries increase, and as they join, the main water courses form.

The three main water courses are the North, Middle, and South Forks of the Feather River. As the rivers flow from the high mountain valleys to the Sacramento Valley floor, gradients as high as 1200 m within 22 km (as in the South Branch, Middle Fork) are achieved. This has resulted in the formation of deep canyons and steep walls where average slopes often exceed 45 degrees.

Runoff exiting the entire 8880 sq. km^2 drainage area is funneled through a single narrow channel at the site of Oroville Dam. Oroville Reservoir has a capacity of approximately 3.5 million acre-feet and an average annual inflow around 4.3 million AF. This compares to an average annual flow of 1.0 million acre-feet for the Middle Fork Feather River. Due to the high demand for water and energy, there are numerous diversions, canals, and reservoirs within the study area.

1.2 Precipitation

The annual average precipitation in the Feather drainage area varies from as low as 15 inches (southeast of Portola) to 90 inches in the Bucks Lake region with an annual average basin precipitation of approximately 45 inches. Distribution of this precipitation, during the primary water-months (October-April), shows a single peak in the January-February period.

2. SEEDING SIMULATIONS

The primary questions raised by a potential project sponsor is, how effective will the seeding be; in the case of the Feather River project, how much runoff can be attributed to the seeding? The first step in answering that question is to estimate the increased precipitation in the target area. That data can then be used as input into a hydrological model. In estimating the potential increases in precipitation, results from post hoc analyses of the Pacific Gas and Electric's (PG&E) Lake Almanor project were used (Mooney and Lunn, 1969; Bartlett **et al.**, 1975; Marler and Scott, 1983). These analyses of randomized seeding events were stratified according to various rawinsonde parameters indicating whether the storm was "cold" or "warm" and whether it was "westerly" or "southerly." This stratification procedure led to a possibility of four "storm" types as defined by:

Parameter	South	West	Warm	Cold
Winds between 6000' and the -10°C level	145-234	235-305		
Height of the -5°C level (feet)			>7500	<7500

In the case of Marler and Scott (1983), the warm westerly storms were further restricted to those cases where the -5°C level was lower than 9500 feet. Using the above cited results and the corresponding "storm" classifications, the estimated precipitation increases used in the seeding simulations were as follows:

Storm Type	Percent Increase	Percentage Total of Occurrence (October-April)
Cold/West	35%	5
Cold/South	3%	5
Warm/West	20%	32
Warm/South	0%*	58

*Note: The warm southerly storms are considered to be nonseedable.

Detailed seeding simulations were restricted to four water years; a water year being defined as the period October through April. These four water years (1976-77 through 1979-80) were selected since during this period a wide range of conditions (critical, dry, and wet) for the Sacramento Drainage were represented. For each of these years, hourly precipitation data from eight stations within and in the vicinity of the target area were used to determine the natural precipitation. Oakland rawinsonde data were then used to define storm types and associate a storm type with the natural precipitation. The natural precipitation was then adjusted by the factors shown above, for each of the storm types. To simulate the seeding effects as closely as possible to an actual seeding project, suspension criteria were also incorporated into the simulations. A review of conditions during these four years showed that during the 1979-80 season there were two periods in which seeding probably would have been suspended due to the excess spill at Oroville (Roos, 1985) resulting from excess rain. Consequently the precipitation during these two periods were not augmented in the simulation. From the preceding, the average estimated increases for the target area (all stations averaged), by season were:

Season	Percent Increase
76-77	10
77-78	6
78-79	7
79-80	5

The above percentage increases in precipitation are rough indications of the potential benefit of a Feather River seeding project, but more important is the amount of runoff this precipitation represents. It should be pointed out here, that the modest increases are direct results of the low frequency of occurrence of the more "seedable" storm types, as shown in the previous table. The precipitation amounts, natural and augmented, were used in a hydrological model, a discussion of which follows.

3. HYDROLOGIC MODELING

The Water Resources Evaluation of Non-Point Silvicultural Sources (WRENSS) hydrologic technique (Troendle and Leaf, 1980; Troendle, 1979), was employed to determine the hydrologic impacts of the simulated prescription increases. WRENSS was developed from Subalpine Water Balance Model simulations (Leaf and Brink, 1973a and 1973b), of baseline water balances for small catchments in the Western United States. The Subalpine Water Balance Model was previously used by Jones, Leaf & Fischer (1975) in the evaluation of a weather modification program. WRENSS contains regional response functions, relating to evapotranspiration and precipitation, which vary according to aspect and season of the year. A more detailed discussion of the WRENSS methodology is included in the original feasibility study report (Swart **et al.**, 1986).

The general area hydrological investigation covered the North, South, and Middle Forks of the Feather River. Within this area three watersheds were selected for detailed analysis:

(1) The Middle Fork of the Feather River above the gaging station near Merrimac, California.

(2) Butt Creek below the Almanor-Butt Creek Tunnel near Prattville, California.

(3) Antelope Lake above the gaging station just below Antelope Lake on Indian Creek.

These were selected primarily because of their relative location in the potential target area; also published streamflow data for the first two of the catchments are not seriously impacted by diversions and upstream storage.

The additional runoff that could be attributed to weather modification in the target area (excluding the Lake Almanor project area) was computed using the index watershed analysis and the projected increases in precipitation for the climatic stations previously discussed. The projected increases in precipitation were weighted using the Theissen Polygon techniques. Based upon the location of the polygons with respect to the index watersheds and on subjective judgement, an index watershed weighting was given for each area within the target area.

Increased runoff for the four years of interest were computed as follows:

Year	Runoff Volume (acre-feet)
76-77	51,000
77-78	221,900
78-89	136,100
79-80	143,700

Rather than limiting the seeding simulating to the four years, rough estimates of seeding effects on a longer-term data base were calculated. Four stations, within the target area, with long term precipitation records were investigated. Listed below are the stations, the period of record and the average seasonal increased precipitation for each.

Station	Period	Seasonal Increase (inches)	(%)
Brush Creek	1948 - 83	4.02	6.5
Plumas Eureka	1964 - 83	4.04	8.0
Downieville	1948 - 83	4.36	8.7
Portola	1955 - 83	1.46	7.8

To put these increases in proper perspective, runoff volumes were estimated using a linear regression of increased precipitation vs. increased runoff obtained from the detailed analysis of the years 1976-1980. This translated to an average increased runoff of approximately 77,500 AF per year.

4. BENEFIT-COST ANALYSIS

Estimates of the annual operating budget, including the amortized cost of equipment acquisition, were made in order to assess the economics of conducting a Feather River cloud seeding program. These annual costs were:

Equipment (amortized over a 5-year period)	$ 45,600.
Annual operating expenses	$215,000.
TOTAL	$260,600.

Assuming an average annual increased runoff volume of 80,000 AF and a value of $30 per AF, the total value of the increased water would be $2,400,000. The benefit-cost ratio would then be:

$$\frac{\text{Benefit}}{\text{Cost}} = \frac{\$2,400,000}{260,000} = 9.2$$

Even though a 9-to-1 benefit-cost ratio would be adequate justification for initiating a program, it is suspected that these results are on the conservative side. Since the increases in runoff are driven by the occurrence of the more seedable storm-type (i.e., cold westerly, with 35% increases), the number of occurrences of these, from historical records, if underestimated could cause the underestimation of potential precipitation increases. In fact, the frequency of occurrence of the cold westerly storm type, from the Oakland sounding was very low (approximately 5%). When compared to soundings taken at Sheridan, for the Sierra Cooperative Pilot Project, and with icing data at Squaw Peak (50 miles south of the proposed target area) the frequency of this type may be higher than estimated from the Oakland soundings.

5. DISCUSSION

Given these encouraging results, NAWC prepared a preliminary design for a Feather River cloud seeding program. This preliminary design includes the following elements:

- Target area: southern portion of the Feather River drainage (primarily the Middle Fork and South Fork). This is with the assumption that the PG&E's Lake Almanor project continues, since runoff into Lake Oroville also benefits from that area.

- Operational season: November through March. The seeding simulations indicated these five months to be the most productive.

- Storm types to be seeded: Cold-west; cold-south; and warm-west. This procedure is based upon the apparent seeding results from the Lake Almanor project.

- Seeding Agent: Silver iodide (again, based upon past success of the Lake Almanor project).

- Delivery Systems: ground-based, silver iodide dispensers. Approximately ten, high-elevation, remotely-controlled units would be needed to seed the warm and/or stable storms. Aerial seeding could be investigated, but may not be cost effective.

- Suspension Criteria: at minimum, excessive snowpack should preclude seeding. Thresholds that have been suggested by the CDWR are defined by the percentages of normal April snowpack water content:

January 1	110%
February 1	130%
March 1	150%

  Further studies need to be done to arrive at an adequate suspension criteria dealing with the potential of "subsequent" flood events. A reservoir storage threshold can be used provided the overall seeding project would not be too restricted.

- Additional Equipment:
  - Rawinsonde system
  - Weather data satellite downlink acquisition system
  - Remote-controlled seeding devices
  - Manual seeding devices

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