THE KINGS RIVER WEATHER RESOURCES MANAGEMENT PROGRAM

Thomas J. Henderson
Atmospherics Incorporated
Fresno, California

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. With the exception of a few suspension periods due to high runoff and the construction of a hydroelectric facility, the program has been operated for 6-7 months each year since its inception. 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 the cloud seeding activities. When applied to the subsequent operational periods, his analysis indicated an apparent increase in streamflow amounting to 6% of the total predicted by the regression analysis. The apparent increase was significant at the 0.005 level. During the years following this first analysis, a number of studies have been conducted including a continuation of the statistics work plus an analysis of data from 3cm and 5cm project radar data.

1.0 BACKGROUND AND INTRODUCTION

The Kings River is one of several streams which originates in the high snowfields along the western slope of the Sierra Range in California and flows from its 1,600 square mile watershed to the rich San Joaquin Valley. Emerging from the foothills east of Fresno, as noted in Figure 1., the total annual flow has ranged from a minimum of less than 400,000 acre feet (1977) to a maximum of more than 4,000,000 acre feet (1969). The average annual natural flow is about 1.5 million acre feet.

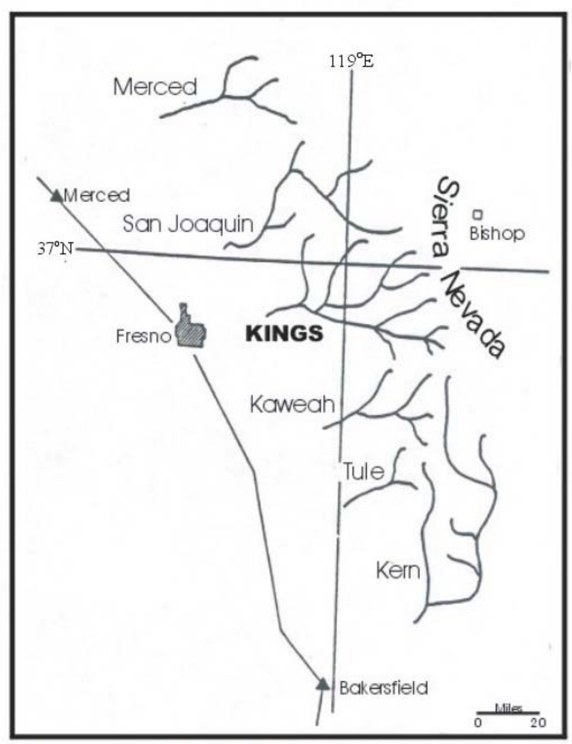

Figure 1. Watersheds of the Southern Sierra

Hydroelectric power production, agricultural interests, and domestic requirements provide the major interests in the overall water supply. In years of average runoff, no water from the river reaches the ocean. Present estimates indicate it requires nearly 150% of average snowmelt runoff before surplus water would be available for other uses. Of course, this depends on the condition of the watershed, the amount of carryover storage, the manner in which the water runs out of the basin, plus other hydrologic and meteorological factors governing the flow of the river. There are presently three main dams on the watershed. All of these are storage reservoirs for flood control and for power generation. Pine Flat Dam at the western outflow side of the watershed, is a 5 million cubic yard concrete structure built by the Army Corps of Engineers. Power generation and irrigated agricultural land are the primary users of the total water supply. Ground water recharge basins are active during years of high flow.

During its long history, the Kings River Conservation District (KRCD) has been the major funding source for this program. Other contributors include the Kings River Water Association, the Pacific Gas and Electric Company and the California Department of Water Resources. KRCD is a political subdivision of the State of California covering an area of about 2,000 square miles in Fresno, Kings and Tulare Counties. The entire service area of the Kings River is included within its boundaries. The district was formed by the California Legislature in 1951 with the passage of the "Kings River Conservation District Act".

Irrigation development in the San Joaquin Valley has been extensive which explains, in part, why Fresno County remains one of the richest agricultural counties in the United States, and probably one of the richest farming areas in the world. There are presently more than 1,300,000 acres of irrigated land in the area serviced by the Kings River.

In the 1954/55 water year, KRCD initiated an operational weather modification program designed to increase the annual flow of the Kings River into Pine Flat Reservoir. During the subsequent years of this historic program, a number of serious evaluation approaches were applied. These included streamflow statistical procedures, target-control precipitation comparisons, and the examination of radar reflectivity from seeded and non-seeded storm systems and post-frontal individual cumulus cells. These early investigations all suggested strong apparent positive results (Orville, H.T. 1957).

2.0 GENERAL OPERATIONS

During the operational period since 1955, the Kings River Conservation District Program has focused on five major components. In general, these are summarized in the following sub-sections.

2.1 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 over the Pacific Ocean. As each of the systems move southeastward over Oregon and in California, the weather activity in the frontal zone may diminish. The Kings River watershed usually marks the southern boundary of any intense weather activity. Precipitation amounts usually diminish rapidly further south over the extreme southern Sierra. (Henderson, T.J. 1962).

The second weather pattern, one which is less common but can produce large amounts of precipitation in the southern Sierra, is associated with a high pressure center in British Columbia. This shunts the low centers further south off the coast of northern or central California. In this situation, the freezing levels move upward from the usual 4,000 feet to around 7,000 feet.

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. The pattern usually produces large amounts of precipitation in the Las Angeles basin and far less amounts over the downslope regions along the western portions of the Sierra. This weather system is often enhanced by warm moist tropical air from the area around the Hawaiian Islands.

The 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, during each precipitation period there is a tendency toward "bands" of precipitation to move across the area and seldom do the radar systems show long periods of unbroken continuous precipitation. A feeling persists at the operational level that the apparent maximum seeding effects can be found early in the most intense portion of all storms. This feeling is supported by radar data and much information from aircraft penetrations within the general storm systems. By the same observations there is a further indication that seeding is ineffective when the 500-mb temperatures are colder than about -22^{o}C. (Henderson, T.J. 1963).

2.2 Ground Generators

The evolution of the individual silver iodide ground generator has progressed through a number of experimental periods and design changes. At the moment, a standard unit includes a special stainless steel spray nozzle equipped with either manual or remotely operated valves which control the use rate of silver iodide solution. The finely divided mixture is burned in a 3-inch diameter flame chamber at about 1800^{o}F. The chemical solution strength is presently fixed at 2% silver iodide (by weight) in acetone. Each generator consumes about 19 grams of silver iodide per hour when the propane pressure is regulated at 6 psi. The propane source is used to pressurize the silver iodide solution tank as well as provide the heat source for producing the finely divided silver iodide ice nuclei.

A total of 12 manual operated units and 6 remote control silver iodide generators are installed at select locations within or adjacent to the Kings River Target area.

From year to year the actual locations of the individual generators have been shifted in a number of cases. These modifications have resulted from measurements of surface wind flow characteristics throughout the watershed and from silver iodide plume tracking during operational periods. The main line of units is along the south and southwest border of the target boundary with additional generators scattered in certain sections of the western and northwestern areas. Insofar as possible, the general method of operation involves ignition of the units located along a path perpendicular to the direction of surface windflow.

2.3 Aircraft

In the first few years of program operations, there were eight different types of cloud seeding aircraft tried on the Kings River Project. These were the P-40 (War Hawk), F-51 (Mustang), F8F (Bearcat), T-28 (Trainer), Cessna 180, Cessna 421 (Golden Eagle), Piper PA-21 (Aztec) and Piper PA-31 (Navajo). All aircraft have been equipped with turbo chargers and most included de-icing equipment. At present, the turbo charged Piper Aztec serves as the primary cloud seeding aircraft on the Kings River Program. The primary reason for this choice has been the aircraft's ability to handle substantial icing conditions during actual seeding flights. There continues to be substantial evidence that the aircraft is essential for any full-scale efficient cloud seeding program focused on mountain areas.

2.4 Radar

The original radar system used on the Kings River Project was designed and built by Atmospherics Incorporated. The system operated on a frequency of 9375-9400 megacycles (3.2cm wavelength) and produced a peak power of 50kw. In more recent years the 3cm radar system has been replaced by an Enterprise Electronics 5cm system operating at 250kw peak power. For the past three years the system has been equipped with the relatively new TITAN software package.

The radar system has two important functions within the application of the total cloud seeding program. As an operational tool, it provides much of the meteorological information necessary for proper direction of aircraft and the operation of silver iodide 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.

2.5 Research

Early in the history of the Kings River Program, the National Science Foundation provided modest funding for several supplemental meteorological tools considered basic to the total effort. The actual equipment included such items as time-lapse cameras, temperature measuring devices, calibrated cold boxes, microscopes, potential gradient recorders, small particle detectors, ice crystal counters, icing rate detectors and miscellaneous laboratory equipment. These ground-based and airborne measurement systems have provided a more definitive examination of storms and seeding effects within and beyond the boundaries of the Kings River watershed.

Through the years, additional research projects over the Kings River watershed have been funded by the Bureau of Reclamation (Project Sierra Cumulus), National Science Foundation (Physical Studies of Sierra Storm Mechanisms), Atmospherics Incorporated (Surface Wind Flow Characteristics in Mountainous Areas), and Atmospherics Incorporated (Methods for Evaluating Cloud Seeding Programs in Mountain Areas).

3.0 STATISTICAL EVALUATIONS

The early 1963-64 season completed the tenth consecutive year of weather modification operations on the Kings River watershed. During that 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 gauge figures. As in almost all cases using rain gauge data, the figures did not produce relationships with high significance levels. In addition, the network concentration of established rain gauges was too small to give adequate sampling of the areas within and beyond the target boundaries. (Malone, T.F. 1966; Henderson, T.J. 1966).

During these early stages of the program an investigation of all snow survey courses and compiled data was initiated. This vigorous investigation produced a more significant relationship between seeded and non-seeded 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 less than desirable. It is important to note that much of the 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 special local effects.

As the years evolved, an examination of the streamflow records along the western slopes of the Sierra Range produced much basic data which were considerably more meaningful than either the snow survey data or the precipitation data. Additionally, it seemed appropriate to deal directly with the amount of runoff inasmuch the program was designed to increase this figure and any numbers dealing with the volume of water are much more meaningful to the actual water users for hydro generation and agriculture. An important publication was now indicating that statistical studies suggested apparent increases 6 to 10 percent in streamflow from cloud seeding over the Kings River. Further, these statistical calculations on the data from the West Coast orographic cloud seeding programs, "estimate the odds to be 1,000 to 1 against this increase having been by the natural variability alone in the precipitation". (Malone, T.F. 1973; Dennis Arnett S. 1980).

By 1986 the application of statistical methods were focused on many of the flow figures from streams along both the western and eastern slopes of the Sierra. The results of these new analyses continued to indicate that a very high confidence level could be placed on results from comparison between the flow of the Kings River and the combination of flows from adjacent streams not affected by the cloud seeding program. The use of control streams from areas both north and south of the target areas seemed appropriate in any search for methods of eliminating bias from years which contained a predominance of either northerly or southerly type storms. (Henderson, T.J. 1986).

The possible bias from persistent storm directions was not the only item investigated in this evaluation search. For example, the total number of acres covered by forest fires was tabulated in both control and target areas, methods of streamflow measurements were checked, types of measuring devices and locations of measuring points were investigated, surface evaporation from the newly constructed reservoirs was considered, and the historic record of streamflow itself was repeatedly checked. Most of the possible items which may have had some abnormal effect on the natural flows of either the control or target area streams were ultimately 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 a long list of controversial methodologies. Consequently, a straightforward multiple regression analysis has been used to indicate any possible change in the flow of the Kings River. (Hacking, Ian 1965; Edwards, A.L. 1979; Wegman, E.J. and DePriest, D.J. 1980; Epstein, E.S. 1985).

Combinations of possible control streams were examined and these included the Merced, San Joaquin, Kern, Kaweah, Tule, Owens, and Cottonwood. 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. In this case, the combination of streams which resulted in the highest correlation with the Kings River was found to be the Merced River (north) measured at Pohono Bridge and Cottonwood Creek (south) as measured by the Department of Water & Power, City of Los Angeles. This multiple regression analysis ultimately produced the following predictor equation.

Kings= 2.639MER +34.258Cott – 95,581AF

When applied to the forty-seven years prior to 2002, this equation has suggested annual results which range from –9.5% to +25.6%. The statistical analyses in twelve of these years indicated small apparent negative results. However, the average percentage change in flow for the total period was +5.5%. The statistical probability of this apparent overall positive effect was 99.9%.

So, what does this statistical procedure indicate when applied to the most recent operational period. Substituting numerical values for water year 2002, we find the following.

Kings = 843,023 + 172,797 – 95,581 AF.
Kings = 920,239 AF (predicted)

The measured natural flow of the Kings River for WY2002 was 1,140,716 AF.

Therefore, the calculated apparent increase in Kings River streamflow due to cloud seeding during WY2002 is:

1,140,716–920,239 acre feet = +220,477 AF.

This suggests a 19.3% increase in Kings River annual flow due to the cloud seeding program as applied during the months of 1 October 2001 through 31 May 2002. It is interesting that this apparent increase in Kings River total *annual flow* has been exceeded during nine previous annual periods since statistical procedures were first applied to WY1955.

ACKNOWLEDGEMENTS

A sincere note of appreciation must go to the Kings River Conservation District of Fresno, California for its continued support of the total cloud seeding program. Throughout this historic period, the various Boards of Directors have displayed an unusual understanding of the uncertainties connected with this effort. The District is to be commended for its insistence the project be operated on a professional level and that all relevant data and results remain public information.

Additional recognition must go to Dr. William Finnegan, Desert Research Institute, Reno, Nevada, for his unusual insight to the chemical properties of both liquid and solid fuel cloud seeding formulations and the important related effects from these formulations.

Lastly, to all the many friends who have provided important scientific inputs and specific suggestions which continue to enhanced the apparent success of this historic program.

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