A BRIEF HISTORY OF EVALUATIONS PERFORMED ON THE OPERATIONAL KINGS RIVER WINTER OROGRAPHIC CLOUD SEEDING PROGRAM

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ABSTRACT: An operational winter orographic cloud seeding program has been conducted in the Kings River Drainage located in the southern Sierra Nevada Mountains of California most winter seasons since water year 1955. Both ground-based and airborne seeding modes have been used to disperse silver iodide into naturally occurring winter storms. Several evaluations have been performed to estimate the effectiveness of this seeding program. These evaluations have considered different seeded time periods dependent upon when the evaluation work was published. Since the program has not been randomized, these evaluations have all been based upon the historical target/control technique. Most of these evaluations have used annual streamflow as the response variable. One recent analysis was based upon April 1st snow water content. Control sites were selected from the Yosemite National Park region, an unseeded area, and southern Sierra Nevada sites located south of the Kings River Drainage. Linear regression equations were developed relating the control and target areas annual streamflow values during historical periods without any seeding. High correlations were obtained with r^2 values ranging from 0.90 to 0.98. Both linear and multi-linear equations were developed for April 1st snow water contents. High correlations were obtained with r^2 values ranging from 0.91 to 0.93. When these equations were used to <u>predict</u> the amount of natural streamflow or snow water contents during seeded years and then compared to the <u>observed</u> values during the seeded years, the average estimated increases in annual streamflow ranged from +3.3 to +6.1%. Similarly, the estimated increases in April 1st snow water content ranged from +4.9% (linear regression) to +5.7% (multi-linear regression).

1. INTRODUCTION AND BACKGROUND

An operational (non-randomized) winter cloud seeding program began in the 1955 water year for the Kings River drainage, which is located in the southern Sierra Nevada Mountains of California. This program has operated nearly continuously to the present time and is the second longest duration winter cloud seeding program in the world. The longest winter cloud seeding program is located immediately adjacent to this program; the upper San Joaquin River program that began in the 1951 water year and has been operated continuously since that time. The Kings River program has one period without any seeding, the 1981-1987 water years during which the Pine Flat Power Plant was being constructed. These water years were predominately very wet and even if a cloud seeding program had been contracted for these years, it is likely there would have been numerous seeding suspensions or even cancellation of the program during some of these years.

Both ground-based and airborne silver iodide treatment modes have been utilized to perform the seeding. The goal of the program is to increase winter precipitation above Pine Flat Dam in order to increase the streamflow into Pine Flat Dam, plus the flows of Hughes and Mill Creeks which flow into the Kings River below Pine Flat Dam.The drainage basin above Pine Flat Dam is approximately 1545 square miles. Figure 1 provides a map of the intended target area.

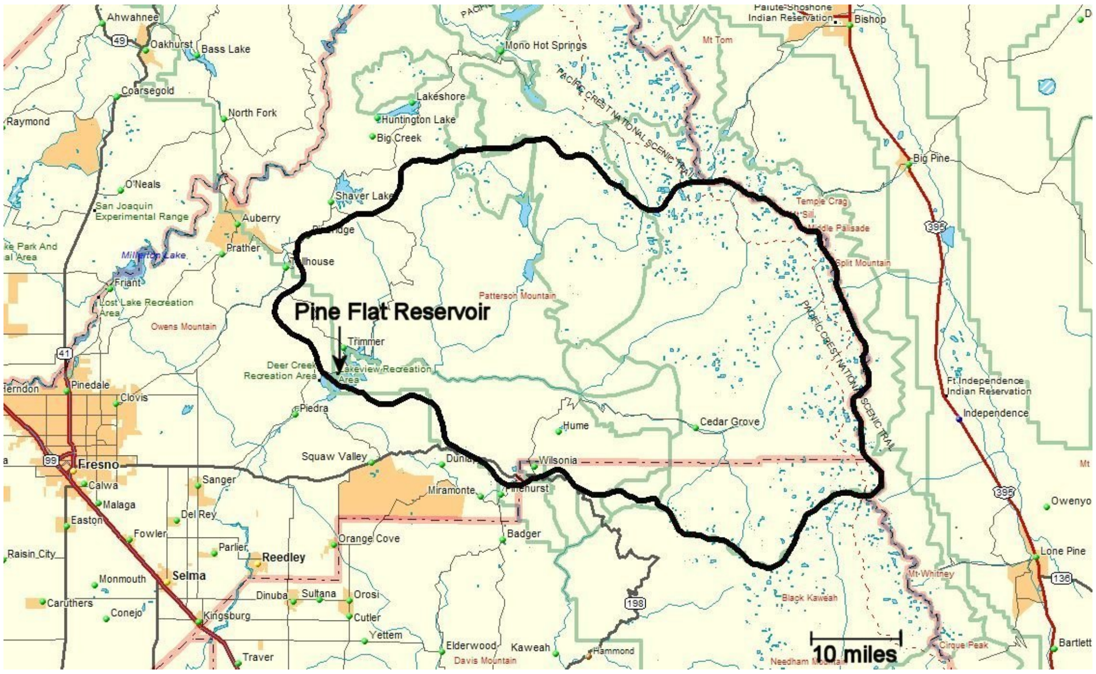

Figure 1: Kings River Program Cloud Seeding Target Area

Since this has been a non-randomized program throughout its lifetime, methodologies other than comparison of seeded and unseeded precipitation amounts (as would be done in a randomized program) have been employed in various attempts to estimate the impacts of the seeding program. For various reasons most of these evaluation attempts have been based upon annual streamflow amounts rather than precipitation, which is the most commonly utilized response variable. The use of streamflow to evaluate this program does entail some special considerations. For example, Pine Flat Dam construction began in 1947 and was completed in 1954 (a year prior to the beginning of the cloud seeding program). There are natural flow streamflow records available dating back to 1895 (in the present Winton Park area). This measurement site was moved upstream to a site near Piedra in 1930. In 1955 this site was moved approximately 500 yards upstream following the completion of the Pine Flat Dam.

There are also two storage reservoirs located on the North Fork of the Kings River (Courtwright and Wishon). As a consequence, the streamflow reporting station KGF, which is located below Pine Flat Dam, is one in which the unimpaired runoff amounts are calculated and used in place of the observed values since 1955. There was one higher elevation observation station on the North Fork of the Kings River (KGC, on the North Fork near Cliff Camp) that was apparently discontinued in 1995. This means that there are no unimpaired streamflow measurements on the Kings River that can be used to evaluate the seeding effectiveness. Unimpaired measurements are preferred since they are not subject to calculation errors.

Two different contractors have conducted these seeding programs under contract to the Kings River Water Conservation District: Atmospherics, Inc., AI (water years 1955-1980, 1988, 1994-2007) and North American Weather Consultants, NAWC (water years 1989-1993 and 2008-present).

2. KINGS RIVER EVALUATIONS

Over its history several evaluations of the program's effectiveness have been performed, with the first published in 1966. Brief summaries of some of the evaluations follow. The summaries are in chronological order from earliest to latest. The typical types of evaluations that have been performed are known as historical target/control evaluations (Dennis, 1980). They do not involve randomization (a technique frequently employed in the performance of research programs), where approximately one-half the seedable cases are left unseeded to facilitate rigorous statistical evaluation techniques. The target/control evaluation technique involves mathematical correlations (regression equations) of streamflow or precipitation in target and nearby non-seeded control areas during historical periods without any seeding conducted in either the target or potential control areas during the historical period, nor the likelihood of seeding impacts in the control areas during seeding periods. These linear or multi-linear regression equations are then used during seeding periods to predict the expected natural amount of streamflow from the target area. These predicted amounts are then compared to the actual streamflow values to determine if there are any systematic differences. Locations of the stream gaging stations used in the following publications are provided in Figure 2. For clarification, the streamflow measurement locations and confluence of streams entering the Kings River below Pine Flat Dam are: 1) Kings River stream gage below Pine Flat, approximately ¼ of a mile downstream from Pine Flat Dam, 2) Mill Creek confluence with the Kings River approximately 2 miles downstream of Pine Flat Dam, 3) Hughes Creek confluence with the Kings River, approximately 2½ miles downstream of Pine Flat Dam and 4) Piedra stream gage, approximately 3½ miles downstream from Pine Flat Dam.

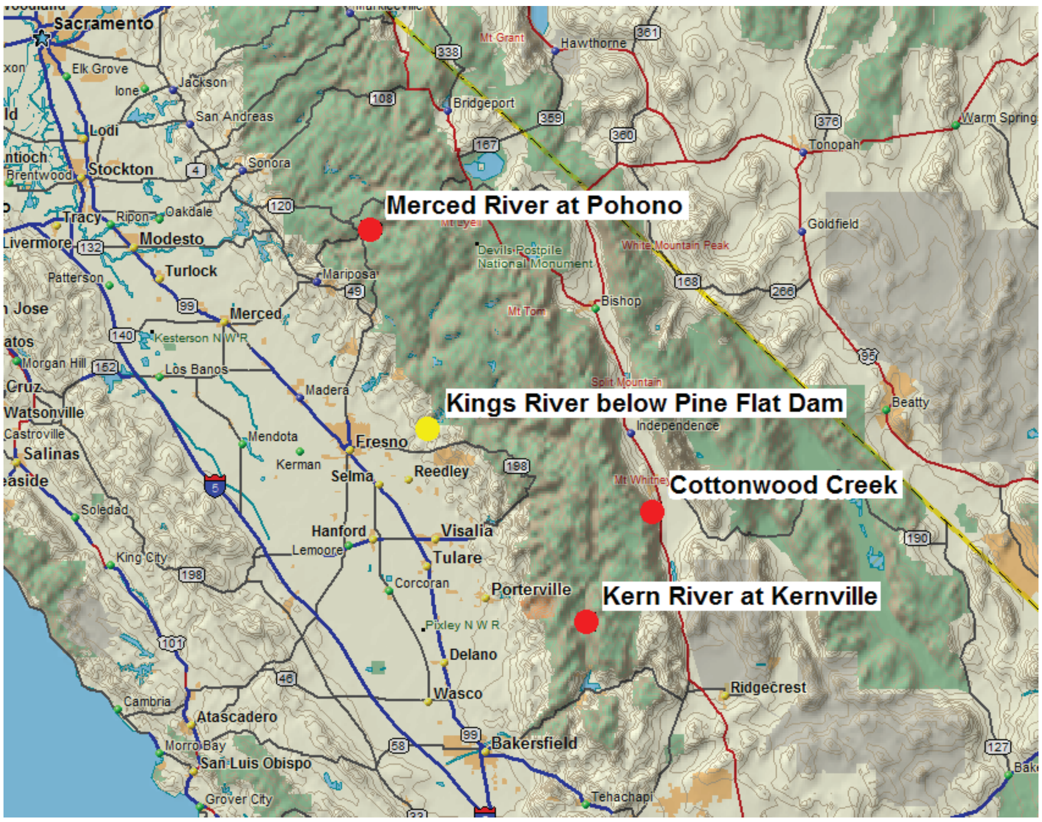

Figure 2: Target and Control Stream Gage Locations (red circles are control stations and the yellow circle is the target station)

2.1 Henderson, 1966

Henderson (1966) appears to be the first published study on the Kings River cloud seeding program. An annual streamflow evaluation was performed using two control stations: 1) the Merced River at Pohono Bridge and 2) the Kern River at Kernville. Annual streamflow amounts from these stations were correlated with the target station, Kings River below Pine Flat. The historical period includes water years 1926 to 1950. The seeded period was water years 1955 to 1964 (10 years). The correlation coefficient was 0.947 (r^2 = 0.90). The indicated average increase in the Kings River (KGF) was + 6.1% or an average annual increase in streamflow of 83,090 acre-feet. Later analysis by Atmospherics, Inc (AI) included the flows of Hughes and Mill Creeks (mid-elevation tributaries to the Kings River) added to the KGF values. This does not appear to be the case in this early analysis. Adding the flow of these two creeks, which historically entered the Kings River above the Piedra stream gaging site, to the KGF calculated values would more closely match the Piedra records before the construction of Pine Flat Dam. Recall that the correlations for the historical period (1926 to 1950) were based on the unimpaired Piedra measurements.

2.2 Henderson, 1981

This analysis used annual streamflow amounts from the same controls as the 1966 study above: 1) the Merced River at Pohono Bridge and 2) the Kern River at Kernville. The same historical period was used (water years 1926 to 1950). The seeded period was water years 1955 to 1979 (25 years). It again appears that just the KGF streamflow values were used (e.g., Hughes and Mill Creek flows were not added). This report took an unusual course of action; it only considered the years with an indicated positive seeding effect to calculate an average seeding increase which was ~ 6%. This is not standard procedure, since normally all calculated values are added together (whether any individual year is positive or negative) and then compared to the total observed flow. If this approach had been followed in this report, the average indicated increase would be +3.3%, not the reported 6%. This seems to be the only paper or report that adopted this approach although NAWC does not have access to all the annual project reports so this may not be the case.

2.3 Atmospherics, Inc., 1986

This report (though printed in 1986) covers nearly the same period as section 2.2; with just the 1980 water year added, resulting in a seeded period of water years 1955 to 1980 (26 years). The historical period remained the same; water years 1926 to 1950. There were two changes made in this evaluation. First, the Kern River at Kernville was dropped as a control since AI began a winter cloud seeding program for the Kern River in water year 1977. Several alternate controls were examined with the combination of Cottonwood Creek (east slope drainage in the southern Sierra Nevada) along with the previously used Merced River at Pohono Bridge used as controls. Second, the flows of Hughes and Mill creeks were added to the Kings River (KGF) flows. The resulting correlation coefficient was 0.981 (r^2 = 0.96). The estimated average annual increase in streamflow was +5.5% or an average increase in streamflow of 89,342 acre-feet. It is interesting to speculate about this average increase of 5.5% versus the earlier 6% in section 2.2 above but with the more correct number for comparison being ~3.3% as explained earlier. In other words, for approximately the same time period, evaluations based upon one control common to both evaluations (Merced at Pohono Bridge) but using two stations as the second control (either Kern River near Kernville or Cottonwood Creek) results in two rather different answers; either approximately +3.3% versus +5.5%. This might be partially explained by a somewhat higher correlation coefficient for the Merced/Cottonwood controls (0.981) versus the Merced/Kern controls (0.947) and the addition of the flows from Hughes and Mill Creeks.

2.4 Henderson, 2003

This was a rather short update on previous evaluations which AI had performed. The Merced River at Pohono Bridge and Cottonwood Creek were again used as the controls. It is unclear whether Hughes and Mill Creek flows were included but this is likely the case. The calculated average increase in the Kings River annual flows for the water years 1955 to 2001 (47 years) was 5.5%. It is not stated in this paper but it appears the non-seeded water years of 1981 to 1987 were included in this analysis based on the stated total of 47 seeded years.

2.5 Silverman, 2007

As stated in the paper's title, Silverman (2007) used the Ratio Statistics method to evaluate the Kings program. Silverman used the same controls as in sections 2.3 and 2.4 in the above; Merced River at Pohono Bridge and Cottonwood Creek. Silverman used an historical period of water years 1935 to 1954. This is a different historical period than some of those used by Henderson. Silverman used the KGF flows as the target station which apparently did not include the Hughes and Mill Creek flows. The seeded years were the water years 1955 to 2004. He included the non-seeded water years of 1981 to 1987 in his analysis. The correlation coefficient of his regression equation was 0.988 ($r^2 = 0.98$), a similar number to Henderson's value in section 2.3 (0.981). Silverman estimated the average annual increase in the Kings River flow was +5.1%.

2.6 Silverman, 2010

Silverman evaluated eleven long-term operational winter Sierra Nevada cloud seeding programs in this paper. This included an analysis of the Kings program which he termed an update on the previous results reported in 2007 (2.5 above). Apparently the historical period was 1935-1954. The seeded period was water years 1955-2006 (two more seeded years than his 2007 evaluation). Silverman again included the non-seeded water years of 1981-1987 in his analyses. Silverman used the ratio statistics methodology he had used in 2.5 above and added some Monte Carlo permutation tests which can be used with non-randomized data sets to estimate significance and confidence intervals. He again used the Merced at Pohono Bridge and Cottonwood Creek as controls. The analysis for the Kings included the standard KGF site with same correlation coefficients as in section 2.5; 0.981. It is unclear whether Silverman's data included the flows of Hughes and Mill Creeks. The end result was a calculated average increase in the annual Kings River flow of 6.1%.

2.7 Update on Atmospherics, Inc. Streamflow Evaluation

For this paper NAWC used the evaluation procedures developed by Atmospherics, Inc. in 1986 (section 2.3) to update the calculated predicted annual streamflow for the entire seeded period; water years 1955 through 2012. The equation developed by Atmospherics, Inc. was:

$$\text{Kings} = 2.639\ (\text{Merced}) + 34.258\ (\text{Cottonwood}) - 95{,}581\ \text{AF}.$$

NAWC's calculations included the flow of Hughes and Mill Creeks but excluded the not-seeded water years of 1981-1987 contrary to Silverman's 2010 analysis. When the actual streamflow values were compared to the predicted values the average estimated increase was 4.5% equivalent to an average estimated increase in annual streamflow of 72,431 acre-feet. The difference between this 4.5% value and the 6.1% value calculated by Silverman, 2010 may be due to Silverman's inclusion of the non-seeded water years of 1981-1987 which were predominately very wet years.

2.8 Yorty, Flanagan, Solak, Weston and Griffith, 2013

Following the first season of operations (water year 2008) on a three year contract between the Kings River Conservation District and NAWC, NAWC developed an additional evaluation for the Kings River program based upon upper elevation snow water content observations. This seeding evaluation utilized April 1 manually collected snowcourse data. Snowcourse data were collected for sites in both the Kings River Basin (the target area) and the Merced Basin (used as a control area). Data were obtained through the California Data Exchange Center (http://cdec.water.ca.gov). Sites were selected with records going back to approximately 1930 in order to have as many historical (non-seeded) years as possible for use in the evaluations, prior to the beginning of the seeding program in 1955. Some later non-seeded years were also included in the historic base period, as discussed in more detail below. The non-seeded base period was used to establish regression equations representing the relationship between the control and target areas in the absence of seeding.

Target and control site selection was based on correlation (between target and control groups), elevation, and reasonable distribution of the target sites within the Kings River Basin. Average site elevations are similar (8883' for control sites, 9210' for target sites) which should yield equivalent conditions in terms of temperature and melt potential. Three control sites and five target sites were identified. Locations of these sites are provided in Figure 3. Table 1 provides information on the target and control sites.

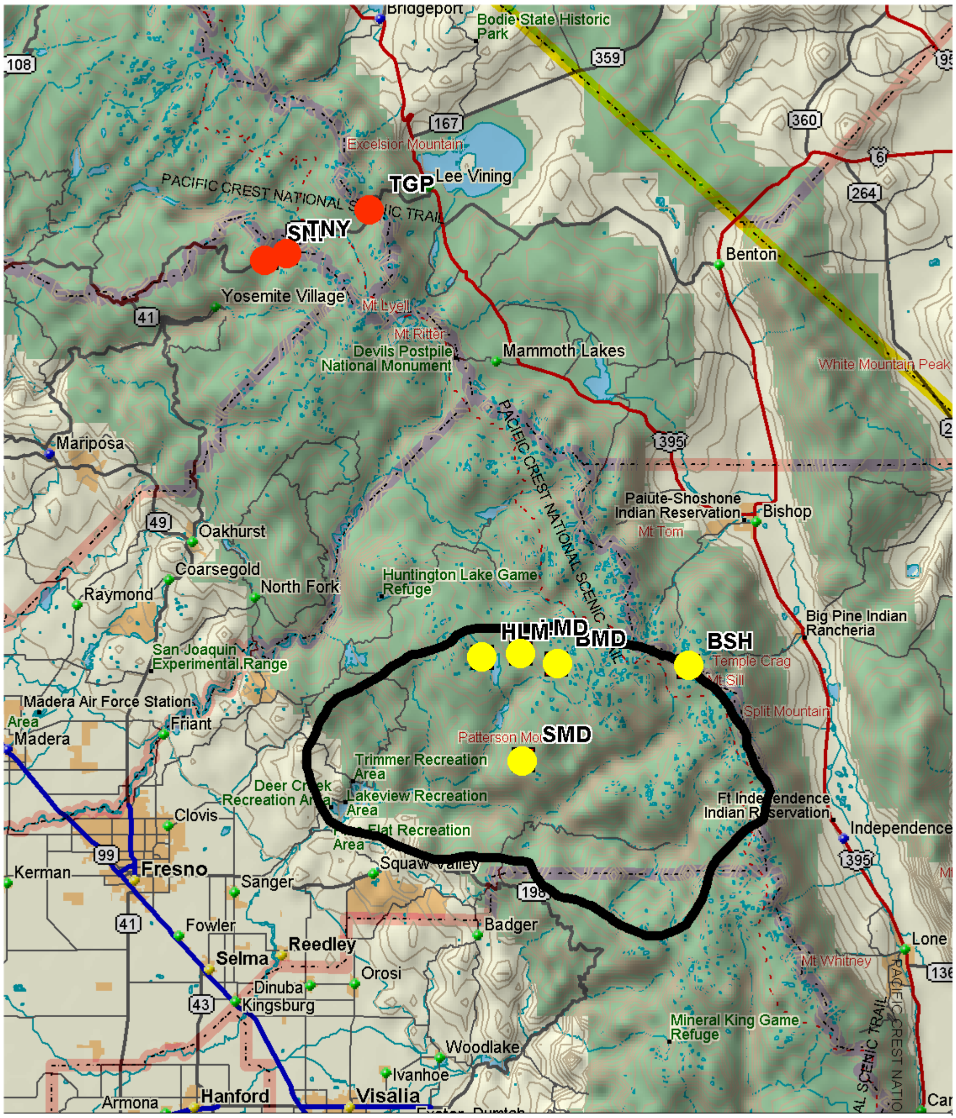

Figure 3: Kings River Target Area and Snow Water Content Target/Control Site Locations (red circles are control sites and yellow circles are target sites)

Target/control analyses were conducted for a 26-year regression period; water years 1930-1954 (excluding water years 1934, 1936-38, and 1952 due to missing data at one or more sites) and the water years 1981-1987 when there was no seeding due to construction activities at Pine Flat. Linear and multi-linear regression equations were developed based upon these data.

The linear regression equation was: $Y = 0.906 (X) – 2.20$ where X is the average of the three control sites. The r^2 value for this equation was 0.91.

The multi-linear regression equation was:
$Y = 0.363 (X1) + 0.209 (X2) + 0.349 (X3) – 1.45$; where X1 = Tioga Pass, X2 = Snow Flat, and X3 = Tenaya Lake. The r^2 value for this equation was 0.93.

These equations were used to predict the annual average April 1st snow water contents which were compared to the actual April 1st snow water contents for the seeded seasons. Both equations indicated higher April 1st water contents than predicted. The estimated average increase in April 1st snow water content using the linear regression equation for all prior seeded water years (1955 to 2012,excluding the non-seeded water years of 1981-1987 and five seasons with missing data, water years 1958, 1965,1967, 1969, 1986, 1998) was +4.9%. The estimated average from the multi linear equation for the same period was +5.7%. These estimated snow water content increases are quite similar to most of the stream flow evaluation increases percentage-wise.

Table 1: Snow Water Content Target and Control Site Information

Site	Symbol	Elev.	Apr. 1 SWE Avg.	Lat.	Lon.
Control Sites					
Tioga Pass	TGP	9800'	26.8"	37°55.02'	119°15.18'
Snow Flat	SNF	8700'	44.5"	37°49.62'	119°29.82'
Tenaya Lake	TNY	8150'	33.6"	37°50.28'	119°26.88'
Control Avg		8883'	35.0"		
Target Sites					
Bishop Pass	BSH	11,200'	35.0"	37°6.00'	118°33.42'
Beard Meadow	BMD	9800'	33.3"	37°6.78'	118°50.22'
Long Meadow	LMD	8500'	29.3"	37°7.80'	118°55.20'
Statum Meadow	SMD	8300'	32.3"	36°56.58'	118°54.78'
Helms Meadow	HLM	8250'	26.7"	37°7.32'	119°0.30'
Target Avg		9210'	31.3"		

3.0 Summary

Numerous evaluations of the Kings River winter cloud seeding program conducted over the years have consistently indicated increases in annual streamflow (+3.3 to 6.1%) and in one analysis increases in target area April 1st snow water content (+4.9 to 5.7%). This information is summarized in Table 2. It should be recognized that the potential exists for increases in precipitation during the seeded water years in the control station records used in these evaluations due to cloud seeding programs being conducted in adjacent basins. This is especially true of streamflow on the Merced River at Pohono Bridge and the snow water control sites in Yosemite National Park. An increase in control stations values during the seeded water years would result in increases in estimated natural precipitation in the target area using the historical regression equations that were based on non-seeded water years. As a consequence, the estimated increases in streamflow or snow water content in the target area could be underestimated when the regression equations are used to make these estimates. Unfortunately there are very few choices of possible control stations in the Sierra

Nevada since there are numerous on-going winter cloud seeding programs throughout the entire length of the Sierra Nevada Range. The Merced River drainage is the only drainage in the Sierra that has never been directly seeded as a targeted drainage.

Table 2: Summary of Various Evaluations of the Kings River Winter Cloud Seeding Program

Evaluation	Year	Type	Controls	Historical Water Years	Seeded Water Years	Avg. % Increase
Henderson[1]	1966	Annual streamflow	Merced @ Phono Bridge and Kern @ Kernville	1926 - 1950	1955 - 1964	6.1
Henderson[1]	1981	Annual streamflow	Merced @ Phono Bridge and Kern @ Kernville	1926 - 1950	1955 - 1979	3.3[2]
Atmospherics[3]	1986	Annual streamflow	Merced @ Phono Bridge and Cottonwood Creek	1926 - 1950	1955 - 1980	5.5
Henderson[3, 4]	2003	Annual streamflow	Merced @ Phono Bridge and Cottonwood Creek	1926 - 1950	1955 - 2001	5.5
Silverman[1, 4]	2007	Annual streamflow	Merced @ Phono Bridge and Cottonwood Creek	1935 - 1954	1955 - 2004	5.1
Silverman[1,4]	2010	Annual streamflow	Merced @ Phono Bridge and Cottonwood Creek	1935 - 1954	1955 - 2007	6.1
NAWC[3]	2013	Annual streamflow	Merced @ Phono Bridge and Cottonwood Creek	1926 - 1950	1955 - 1980 1988 - 2012	4.5
Yorty[5]	2013	April 1st Snow water	Upper Yosemite area	1930 - 1954[6]	1955 - 1980 1988 - 2012	4.9 to 5.7

[1]Apparently did not include flows of Hughes and Mill Creeks during seeded seasons
[2]Number adjusted down from ~ 6% since only years with positive values were included in the average (years with negative values were dropped).
[3]Included the flows of Hughes and Mill Creeks.
[4] Apparently included the non-seeded years of 1981-1987.
[5]Evaluation methodology first developed in 2008 but applied to all seeded years through 2012.
[6]Some missing data.

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