"REVIEWED"

AN EVALUATION OF A WEST TEXAS CLOUD-SEEDING PROGRAM

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Abstract. The Colorado River Municipal Water District has sponsored a summertime West Texas cloud-seeding program to increase rainfall in each year since 1970. Because of the program's longevity, it was evaluated utilizing established statistical techniques.

Based on a double-ratio test, Student's t-test, regression analysis and Wilcoxon Matched-Pairs Signed-Ranks test, results suggest that the District realized an increase in seasonal rain during the normal and wet seasons. This may have produced an economical benefit to the District and the Big Spring community.

1. INTRODUCTION

The Colorado River Municipal Water District (hereinafter termed the District) with headquarters in Big Spring, Texas, has sponsored a summertime cloud-seeding program to increase rainfall--and particularly runoff into Lake J. B. Thomas and E. V. Spence Reservoir--in each year since 1970. The target area--or the region of intended effect--is located in the upper reaches of the Colorado River Basin of West Texas. The District's weather modification effort has been an operational project based upon the assumption that ice-phase cloud seeding, using silver iodide (AgI) dispersed by aircraft at cloud base to increase rainfall, could be productive and beneficial.

Because the District's cloud-seeding program is the longest ongoing weather modification program in the State, the Texas Water Commission staff examined the program utilizing established statistical techniques as part of the Commission's statutory responsibility to promote research in weather modification in the State of Texas.

2. OPERATIONAL PROCEDURES

The primary objective of the District's cloud-seeding program is to increase runoff into the Thomas and Spence reservoirs. The operational cloud-seeding procedures for reservoir runoff dictate that the larger storm systems be given preferred emphasis.

The District's technique has involved seeding inflow areas at cloud base using 20-gram and/or 30-gram silver iodide flares attached to the wings of an Aztec aircraft. The vigorous cloud-base updraft carries the silver iodide nuclei up into the supercooled region of the cloud. Assuming a lack of natural ice nuclei in the supercooled region of the cloud and assuming wide distribution of the seeding agent, the nuclei are expected to produce ice particles by deposition, condensation-freezing, or freezing of cloud droplets or raindrops. The additional ice particles would result in a more efficient production of rainfall through the early initiation of the Bergeron process.

The District's seeding technique is designed to seed periphery cells that develop after a primary cell (or cells) appears on radar, causing them to be more microphysically efficient rain-producing cells leading to additional rainfall.

Target clouds were selected by the District's staff meteorologist. No restrictions were imposed on the meteorologist's seeding decision by the District's weather modification permit granted by the Texas Water Commission.

Seeding records indicate that a typical treatment of a cloud complex consumes approximately 206 grams of silver iodide. With respect to the larger amounts used in the Florida Area Cumulus Experiment (FACE) program to produce dynamic effects (Woodley, personal conversation), this amount is considered light.

3. PROCEDURES OF ANALYSIS

The approach to determine statistically the effects of the Colorado River Municipal Water District's cloud-seeding program on total rainfall within the Thomas and Spence watersheds relies upon rainfall measured by NWS observers located in the watershed and upwind of the District's watershed. The Thomas and Spence watersheds were defined as the "target area" for this study, and the outside stations comprised the "control" area.

A map shows the target area and control area rainfall-measuring stations used in the statistical analyses (Figure 1). These stations were all NWS cooperative weather-observing stations. The selection process considered station's proximity to the target area and continuity of rainfall records.

Because the approach was to draw inferences about rainfall amounts within the target area by using data from outside the target area, it was important to select the control stations as close as possible to the target area. A recent study (Haragan, 1978) looked at space correlations of monthly rainfall totals measured in and around the Big Spring area. Since the summertime rainfall events are typically localized, mean monthly summertime precipitation correlations decrease rather quickly with distance (Figure 2).

To better utilize the strength of the higher expected correlation coefficients, the control stations closest to the target area having a complete data set were used in this study. Also, the control stations were to be upwind of the target area to ensure that the control-area data were not contaminated by the cloud-seeding program during the seed years.

Because NWS stations in West Texas are few in number, only four control stations satisfied the selection criteria. Eight target stations were selected.

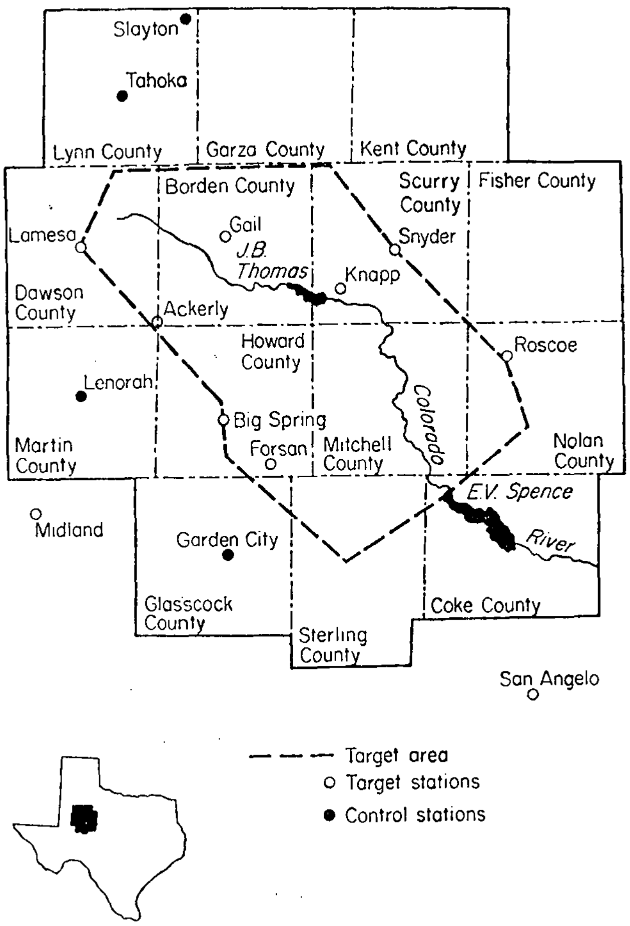

Figure 1. Target and Control Rainfall-Measuring Stations

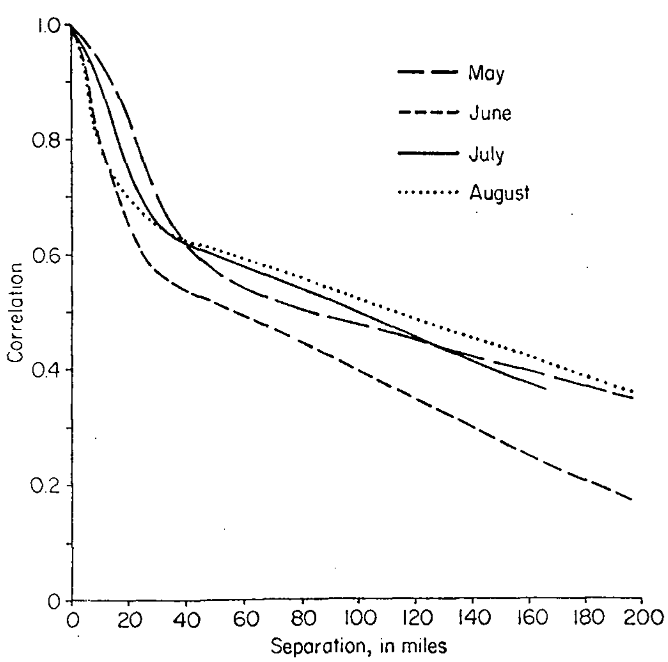

Figure 2. Mean Monthly Precipitation Correlation (May-August)

Seasonal rainfall amounts of each of the eight stations in the target area were added together to represent the target area seasonal rainfall. The same procedure was carried out with the control stations to formulate the control area seasonal rainfall.

Since there were twice as many target stations as control stations, the target rainfall was divided by two for ease of analyses' interpretation. This simple data transformation will not effect the statistics nor the conclusions of this study.

The analyses used rainfall data for the period 1951 through 1984. No stations had complete data prior to 1951. (Precipitation data for 1985 and 1986 were not available in time for this study.) Within that period of record, the unseeded years were from 1951 through 1970, and the seeded years were from 1971 through 1984.

Rainfall amounts used in the study were totalled over the period April 1 through October 31, which was the time of year coincident with the District's cloud-seeding season. Therefore, a "seasonal" rainfall total amount, as used in this study, consisted of the amount of rainfall accumulated during the April through October time period.

The year-to-year variability of the seasonal rainfall in both the target and control areas is quite large. The standard deviation in the target area during the unseeded years is 14.79 inches (Table 1). Clearly, when average seeding increases are expected to be on the order of 5.44 inches (10 percent increase) to 10.89 inches (20 percent increase), the high variability can easily mask the seeding effects.

By using established statistical techniques, some of the variability can be predicted, improving the overall confidence in the results.

4. RESULTS

4.1 Double Ratio

A straightforward test of the District's cloud-seeding program is the double ratio (DR). The double ratio is the ratio of the seeded years' mean target area rainfall with the mean control area rainfall divided by the ratio of the unseeded years' mean target area rainfall with the mean control area rainfall, or:

Eq (1) $DR = (Ts/Cs)/(Tns/Cus)$ where

T is the mean target rainfall,
C is the mean control rainfall,
s implies seed years, and
us implies unseed years.

The effect of seeding on the target area rainfall will be reflected in the numerator of the double ratio. Any effect on the target rainfall by causes other than seeding should be removed, to a large extent, from the double ratio by the unseed term in the denominator.

A double-ratio value of one suggests no seeding effect. A double-ratio value greater than one suggests a positive seeding effect and a value less than one suggests a negative seeding effect.

The double ratio for the District's 14-year cloud-seeding program is 1.074, suggesting a 7.4 percent increase of rainfall in the target area during the seeded years.

4.2 Student's t-test

The Student's t-test is often used to compare the means of two samples.

In this analyses, the two-tailed Student's t-test was used to first compare the seeded years' mean rainfall with the unseeded years' mean rainfall, and second, to compare the seeded mean rainfall measured in the target area with the regression estimated mean rainfall in the target area had seeding not occurred.

The mean rainfall for the seeded years was greater than that for the unseeded years in both the target and control areas (Table 1). A two-tailed Student's t-test was performed on the seeded years' mean rainfall versus unseeded years' mean rainfall in both the target area and the control area to determine if the observed differences in both areas were the result of chance or some other cause.

Table 1. Descriptive Statistics of Accumulated Seasonal Rainfall for Seeded and Unseeded Years

	Mean (in)	Std Dev (in)	Range (in) Min	Max
		Target Area (total rainfall divided by 2)		
Unseeded	54.44	14.79	30.41	81.85
Seeded	69.13	18.65	36.15	94.32
		Control Area		
Unseeded	53.33	16.45	26.96	85.85
Seeded	63.25	15.27	36.64	86.37

If there is evidence of significant difference between seeded and unseeded rainfall in the target area then it can be inferred that the difference was the result of some cause and not merely chance. Causes may include a climatic change, observer error, or the effects of the District's cloud-seeding program.

P-values were formulated for both the target and control areas (Norusis, 1984). In this study p-value is the probability that observed differences of seeded versus unseeded rainfall were due to chance.

The .015 p-value for the target area (Table 2) suggests that the observed increase of seeded rainfall in the target area was likely due to some cause other than chance. Since the .085 p-value for the control area is nearly six times greater than the target area p-value, the observed rainfall increase in the control area has a greater likelihood of being the result of chance.

Table 2. Two-Tailed Student's t-test Statistics of Differences in Mean Seasonal Rainfall in Control and Target Areas

	t-value	Degrees of Freedom	p-value	F-value
Target	-2.56	32	.015	1.59
Control	-1.78	32	.085	1.16

Because of the small p-value, it is inferred that the increase of seasonal rainfall observed in the District's watershed during the seeded period was not likely due to chance.

Another worthwhile statistical approach is regression analysis. This approach identifies a relationship between natural rainfall measured by the NWS rain-gage stations in the control area and that measured by NWS stations in the District's target area. The relationship is then used to estimate the seasonal rainfall amounts that would have occurred in the target area during the seeded years had seeding not taken place. Next, comparisons of the seeded target rainfall with the estimated target rainfall had seeding not occurred can be made to infer the success of the District's cloud-seeding program.

The equation of the regression line, developed using the theory of least squares (Norusis, 1984), is:

Eq (2) $Y = 12.16 + .793(X)$ where

X is the seasonal total of the control-area stations, and
Y is the estimated seasonal total of target-area stations.

Correlation coefficient (R) is .88.

Since the control stations were selected in close proximity to the target area, the correlation coefficient is quite good. Therefore, the regression line is expected to provide useful estimates of the seasonal rainfall amount that likely would have occurred in the target area had cloud seeding not taken place.

To observe the estimated effects of the District's cloud-seeding program using the regression line, it is necessary to plot the regression line and the observed target rainfall along with the corresponding observed control-area rainfall measured during the seeded years 1971 through 1984 (Figure 3). The years plotted above the regression line imply the seeded, target rainfall to be greater than the estimated unseeded, target rainfall. The years plotted below the regression line imply the seeded, target rainfall to be less than the estimated unseeded, target rainfall.

Based on the regression results, eleven of the 14 consecutive years of the District's cloud-seeding program showed positive rainfall increases in the target area (Table 3). The most successful seed year appeared to be 1980, when seeded target rainfall measured 34.6 percent more than the best estimate of target rainfall in the absence of seeding.

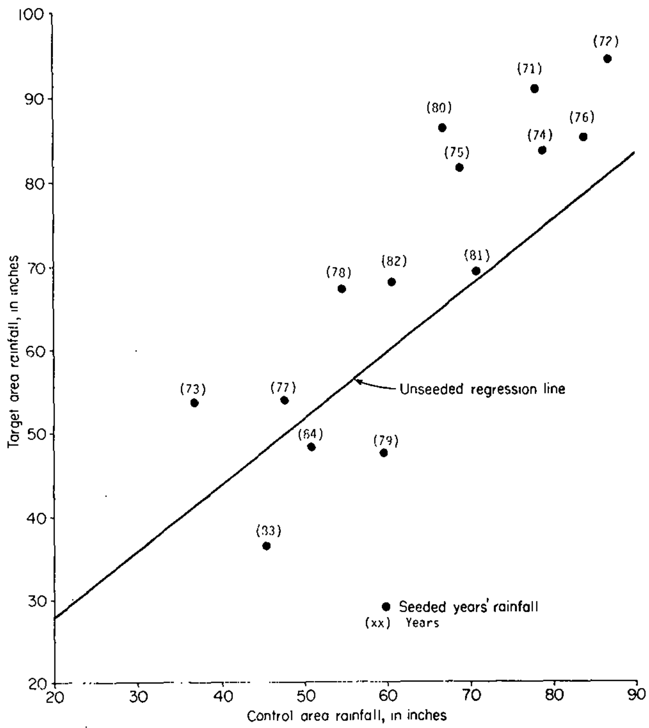

Figure 3. Unseeded Target/Control Regression Line

Overall, the apparent average increase of the accumulated seasonal rainfall amounts measured in the District's two watersheds was 10.26 percent per year.

Table 3. Apparent Yearly Results of the District's Cloud-Seeding Program, 1971-1984

Year	Percent Departure ( )*	Net Increase	Net Decrease
1971	23.2	X	
1972	17.0	X	
1973	30.1	X	
1974	12.9	X	
1975	23.0	X	
1976	8.9	X	
1977	9.0	X	
1978	21.4	X	
1979	(19.5)		X
1980	34.6	X	
1981	1.9	X	
1982	13.9	X	
1983	(24.5)		X
1984	(8.2)		X
Yearly Average	10.26		
TOTAL		11	3

* ( ) indicates negative departures

A look at the means shows that the mean observed seeded, target rainfall is greater than the regression estimated mean unseeded, target rainfall by 10.1 percent (Table 4).

Table 4. Descriptive Statistics on the Apparent Increase in Seasonal Rainfall within the District's Watersheds

Variable	Number of Cases	Mean (in)	Std Dev (in)
Seeded Target	14	69.13	18.65
Estimated Unseeded Target	14	62.29	12.10

The Student's t-test of the two means suggest the apparent rainfall increase in the target area (Table 5) was not the result of chance.

Table 5. Statistical Significance of the Two-Tailed Student's t-test on Apparent Increases in Seasonal Rainfall in the District's Watersheds

Difference Mean	Std Dev (in)	t-value	p-value
6.84	10.28	2.49	.027

The lower the p-value the greater the probability that the observed departure from the regression-estimated target rainfall was due to some other cause, conceivably the District's cloud-seeding program. The .027 p-value (Table 5), suggests once again an overall positive seeding effect of the District's 14-year cloud-seeding program.

A second regression line was developed for the seeded years. Rainfall estimated by this regression line can be viewed as the best estimate of seeded rainfall that occurred in the target area.

The equation of the seed regression line is:

Eq (3) $Y = 2.59 + 1.05(X)$, where

X is the seasonal total of the control-area stations, and
Y is the estimated seasonal total of target-area stations.

Correlation coefficient (R) is 0.86.

A plot of the two regression lines along with the 95 percent confidence band about the unseeded line was made to determine if both lines were significantly different and under what conditions (Figure 4). Because the seeded regression line falls outside the confidence band during the wetter than normal years, it infers that the District's cloud-seeding program is most efficient during the normally wet years. This supports the view held by many atmospheric researchers that cloud-seeding activities for rainfall enhancement must be viewed as long-term endeavors and not short-term, drought-relief projects.

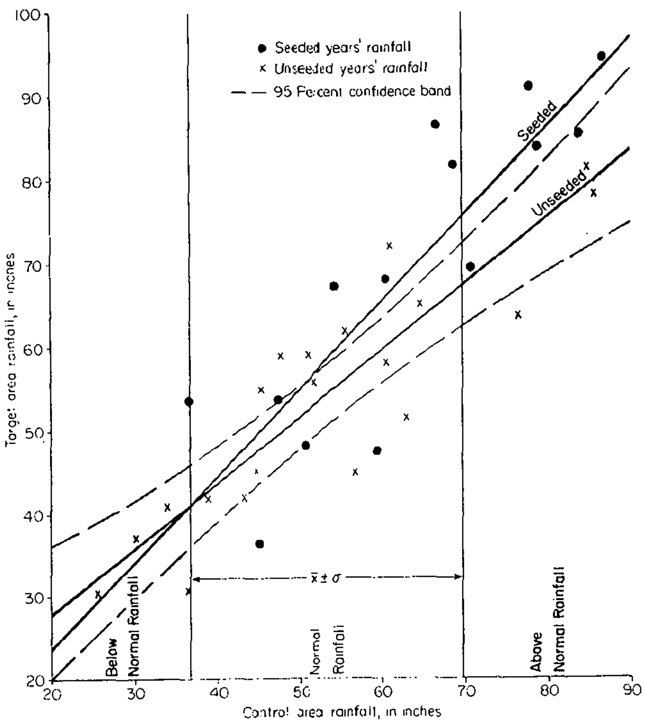

Figure 4. Seeded and Unseeded Regression Lines

Because of the absence of seeded years' rainfall in the below-normal rainfall range (Figure 4), and because the seeded regression line is within the confidence band during the drier than normal years, no conclusions can be drawn about seeding effects during the normally dry years of the District's program.

4.3 Non-parametric Test

In those statistical tests discussed heretofore, there exist limitations inherent in assuming a normal distribution of meteorological data. There are statistical techniques, however, that test the significance of differences between samples without assumptions about the frequency distributions. Known as non-parametric, the tests unfortunately do not have quite the same power of the parametric techniques, but they do not require assumptions that are rarely met. Since there is a lack of knowledge on how seeding changes the distribution of rainfall, these tests are frequently preferred and employed.

A Wilcoxon Matched-Pairs Signed-Ranks test was performed to determine if the observed target rainfall was significantly different from the regression-predicted target rainfall had seeding not taken place.

The .026 p-value (Table 6) infers that there is only a 2.6 percent probability that the difference between the seeded sample and the estimated unseeded sample could be attributed to mere chance.

Table 6. Wilcoxon Matched-Pairs Signed-Ranks Test Statistics for Observed Seasonal Mean Target-Area Rainfall

Mean Rank	:	Number of Cases
8.00	:	11 (Observed $<$ Predicted)
5.67	:	3 (Observed $>$ Predicted)
		0 (Observed = Predicted)
Z-value = -2.2286		p-value = .0258

The non-parametric test supports the findings of the double-ratio test, Student's t-test and the regression analysis.

5. ECONOMIC IMPACT

During the mid to late-1970s, the Texas Department of Water Resources (TDWR) conducted a series of economic studies (Allaway et al., 1975; Lippke, 1976; and Kengla et al., 1979) to determine the economic effects of weather modification activities to increase rainfall on crop and rangeland production within and near the District's upper Colorado River watershed.

The study developed relationships between rainfall and yield using multiple linear-regression statistical techniques. A hypothetical 10 percent increase of monthly rainfall amounts was imposed on the relationship to determine the effects on yield and, subsequently, on the regional economy.

The results of the studies show that there could be substantial direct and indirect increases in agricultural incomes resulting from a 10 percent increase in average precipitation.

The total regional effects of a 10 percent increase in average April through October rainfall would expand regional annual output in 1977 dollars by approximately $3.86 million and regional income by $2.30 million.

Assuming the 10.26 percent increase in seasonal rainfall over the District's upper Colorado River watershed is due to seeding, and assuming a proportional increase of regional effects, it is estimated from the TDWR studies that the total annual economic net effect on the region would mean an expansion in average regional output of approximately $3.96 million and a similar expansion of regional income of $2.45 million. The cumulative impact of the District's weather modification program, begun in 1971, would be $34.30 million in 1977 dollars.

6. CONCLUSIONS

Given the limitations of the statistical analyses, the conclusions about the impact of the District's 14-year cloud-seeding program are as follows:

1. On the average, the District's target area received a significant increase in seasonal rainfall over the best estimate of target-area seasonal rainfall had seeding not occurred. Parametric and non-parametric statistical tests infer that the increase was likely the result of some cause other than chance, possibly the District's cloud-seeding project.

2. Clearly, some seeded years showed better results than others. Apparently the largest observed percent increase in rainfall occurs during naturally-wet seeded years. Therefore, these findings support the idea that, to maximize the usefulness of the technology, cloud seeding should be viewed as part of a long-term water management program that takes into account the fact that periods of drought are inevitable.

3. Based on previous economic studies, the District's cloud-seeding program may have realized an average overall annual expansion in regional output of approximately $3.96 million and a similar annual expansion in regional income of $2.45 million in 1977 dollars.

6. SUMMARY

Statistics is an evaluation technique that is best served in a controlled laboratory. Unfortunately for purposes of experimentation, the atmosphere is far from a controlled environment. To overcome some of the problems the atmospheric laboratory presents, cloud-seeding programs must run for relatively long periods of time to produce meaningful conclusions. The District's 14-year cloud-seeding project provides the State of Texas and the Southwest with such a program.

The statistical results from the analyses discussed in this paper clearly support the District's contention that its cloud-seeding project has provided a significant economic benefit to the District and the Big Spring community as well. The reader is reminded, however, that statistical techniques draw inferences about the total population of quantities by examining the behavior of a sample of the population. Sampling theory clearly dictates that the sample distribution be constructed using "random" observations of meteorological parameters. Unfortunately, in practice meteorological observations are not often selected in this manner. Because the data used in this study could not be selected randomly, the statistical analyses described herein are exploratory and only suggestive of a cloud-seeding effect.

In any event, longevity of cloud-seeding programs in Texas alone is testament of its technological progress in the Texas water community. This study offers yet another building block to that technology and it should provide the incentive for other water districts, river authorities, municipalities and agriculture groups to learn more about today's rainfall-augmentation technology as it relates to their particular water resource needs.

8. ACKNOWLEDGMENTS

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