"REVIEWED"

RESULTS OF OPERATIONAL SEEDING OVER THE WATERSHED OF SAN ANGELO, TEXAS

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Abstract: An assessment of five years of warm-season cloud seeding over the watershed of San Angelo, Texas is presented. The goals of the seedings were the replenishment of surface reservoirs, channel dams and surface aquifers and increased precipitation over the residential areas to reduce demand for municipal water. It was recognized that increased rainfall also would benefit the farming and ranching communities.

During the program a total of 125 kgm of AgI were expended during the course of 2,315 separate seeding events at cloud top or at cloud base. Most of the seedings took place within 30 n.mi. of San Angelo as intended, primarily to the west and southwest of the City.

Assessment of the effect of seeding made use of target-control regressions that had been derived from historical rainfall records. Historical monthly precipitation data were accumulated for long-term rainfall stations within the target and outside to the west and to the south. The period of record was 1960 through 1984 inclusive. Six control stations and nine target stations were used in the analysis.

The analysis suggests a positive effect of seeding (i.e. more rainfall) in each of the five years. The probability of this happening by chance may be a low as 3%. An overall effect of seeding of about +17% for the target for all years of operation is indicated. Sensitivity testing supports the interpretation that seeding was responsible for a sizeable portion of this apparent increase in rainfall.

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1. INTRODUCTION

During the latter stages of the 1982-1984 drought that affected San Angelo, Texas, the Council and Manager of the City investigated the potential of cloud seeding for mitigating the drought over the city's watershed. Aware of the results of the long-term program of the Colorado River Municipal Water District (CRMWD) (see Jones, 1985; 1988) and of continuing progress in cloud seeding research, the Council issued a solicitation for a qualified weather modification contractor. North American Weather Consultants (NAWC) answered this solicitation and was selected to conduct the operational cloud seeding program through the summer of 1988. Atmospherics, Inc., conducted the program in 1989. Annual reports on the seeding operations have been prepared by Girdzus and Griffith, (1986); Griffith and Girdzus, (1987); Risch and Griffith, (1988); Girdzus and Griffith, (1989); and Woodley et al.(1989).

The San Angelo program was based initially on dynamic seeding concepts and results from Florida (Woodley, et al., 1982; Gagin, et al., 1986). Later positive research results for West Texas (Rosenfeld and Woodley, 1989), obtained during the course of the Southwest Cooperative Program (SWCP), provided additional justification for the operational seeding effort. In both the SWCP and the CRMWD efforts, however, it appeared that "static" seeding effects might have been operative as well to increase the precipitation. ("Static" and "dynamic" seeding concepts are discussed briefly in the next section.)

The San Angelo rain enhancement program was designed to use state-of-the-art aircraft, radar and instrumentation systems to recognize and act upon seeding opportunities for rain enhancement over the target area shown in Figure 1. The primary objective of the program was the enhancement of rainfall over the watershed that feeds San Angelo's two main reservoirs, Twin Buttes to the southwest and O.C. Fisher to the northwest of the city. Seedings were to be concentrated in suitable clouds within 30 n.mi of these reservoirs to increase runoff in streams and channel dams supplying the reservoirs and to increase precipitation directly into the reservoirs themselves. Seedings at greater radii were approved in instances when the seeded cloud systems were expected to move toward the storage reservoirs. In meeting the primary objective, recharge of the area's shallow aquifers would be accomplished as well. A secondary objective of the program was to increase the rainfall in residential areas in order to decrease the demand for municipal water.

The program sponsors understood clearly that cloud seeding in West Texas would not "break" droughts, but that it likely would be effective in augmenting the rainfall during periods of natural rainfall. Whether this has been the case during the five-year seeding program is the focus of this paper.

2. THE SCIENTIFIC BASIS FOR CLOUD SEEDING

One major general premise of cloud seeding is that the introduction of ice nuclei into a nuclei-deficient supercooled cloud will improve its precipitation efficiency, leading to more precipitation. Relatively small numbers of ice nuclei (1 to 10 per liter) are thought to be needed to improve precipitation efficiency. This approach to seeding has been called "static" because the seeding concept is to add small concentrations of ice nuclei to clouds that are deficient in such nuclei. The nucleated ice crystals will then grow in size by diffusion and deposition until they fall from the cloud as

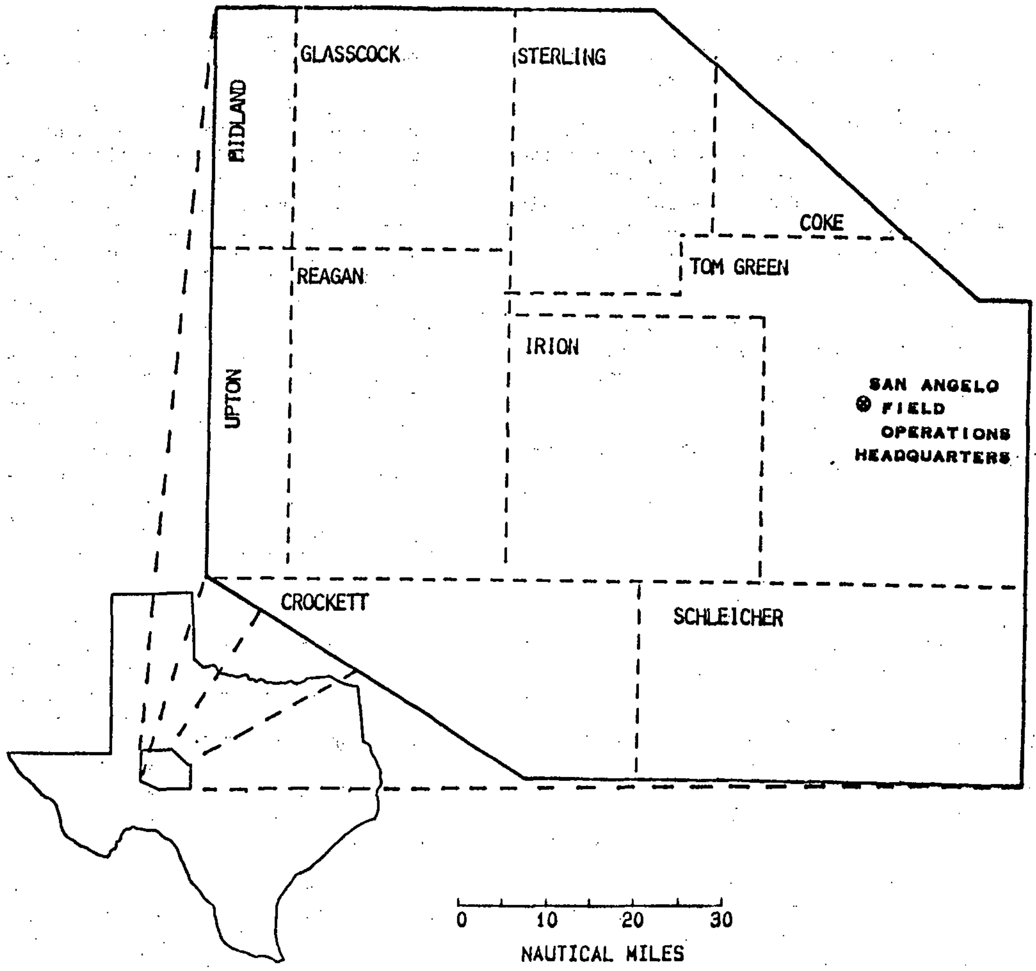

Figure 1. The target area for the San Angelo Rain Enhancement Program

precipitation. The release of fusion heat during the gradual glaciation process is thought to be comparatively small and unimportant. An excellent discussion of the "static" approach to seeding is provided in a review paper by Silverman (1986).

A second premise of cloud seeding is that massive glaciation of a supercooled cloud will lead to substantial releases of the latent heat of fusion, leading to increased cloud buoyancy and greater cloud growth. These larger clouds will last longer and process more water, leading to more precipitation on the ground. This approach is commonly called "dynamic seeding", because the intention is to invigorate the cloud's internal circulations (updrafts and downdrafts) to promote larger clouds. Orville (1986) provides a comprehensive discussion of the "dynamic" approach to cloud seeding.

A complication for both approaches to cloud seeding is the tendency for secondary ice production in supercooled clouds with base temperatures warmer than about 10°C (see Hallet and Mossop, 1974; Mossop, 1976; Mossop, 1978a, 1978b; Vardiman, 1978 and Mossop, 1985). In warm-based clouds, the coalescence of water drops is a dominant precipitation-forming mechanism. When these precipitation-sized water drops are carried to the supercooled portion of the cloud, a few of them freeze, releasing ice splinters in the freezing process. Silverman (1986) points out that other factors, such as liquid water content, cloud droplet concentration, cloud depth, and updraft speed are also important factors in this secondary ice production. The major determining factor, however, apparently is cloud base temperature. Johnson (1982) indicates that +10°C is the critical cloud-base temperature threshold for natural ice multiplication.

Artificial nucleation may be counterproductive in clouds with an active coalescence process because the cloud may already contain enough natural ice for maximum precipitation efficiency. This may be a greater problem for the "static" approach to cloud seeding than for the "dynamic" approach. Large effects of dynamic seeding have been shown in both Florida (Simpson and Woodley, 1971; Gagin et al., 1986) and Texas (Rosenfeld and Woodley, 1989), and in virtually every instance the seeded clouds had base temperatures > +10°C.

Both the "static" and "dynamic" approaches likely are relevant to the clouds of West Texas. The static seeding approach may work best on cold-based cumuli and on highly organized convective systems, while the dynamic seeding approach will be most applicable to warmer-based convective clouds that have not yet developed massive stature. In most cases, the response of a cloud to seeding is a mixture of both static and dynamic effects. Which effect dominates probably depends on the initial conditions of the cloud and environment when seeding is initiated and on the amount of nucleant introduced into the cloud.

3. DESIGN AND IMPLEMENTATION OF THE PROGRAM

The San Angelo rain enhancement program made use of twin-engine, turbo-charged aircraft, silver iodide (AgI) pyrotechnic flares, solution-burning seeding generators, C-band operational radars, and rain gages. All seedings were conducted over the target area in Figure 1.

The primary function of the aircraft was to accomplish the seeding of suitable convective clouds using fixed or droppable 20-gm silver iodide pyrotechnics and/or seeding generators. The base of aircraft operations was Mathis Field in San Angelo, Texas. The cloud seeding aircraft were a Cessna 340 (in 1985, 1987 and 1988), a Beechcraft Duke (in 1986) and a Cessna 421 (in 1989).

All seeder aircraft had weather radar and seeding systems. The former was used primarily to ensure the safety of the aircraft and crew during seeding penetrations and the latter were used to carry out either on-top or cloud-base seedings of convective clouds. Under the belly or tail sections, the seeder aircraft carried flare racks that held up to 200 20-gm silver iodide pyrotechnic flares (TB-1 formulation). These flares normally burn for about 45 sec and fall up to 4,500 ft when ejected at altitudes of 20,000 ft in still air. In addition, the seeder aircraft had either wing-tip, AgI-acetone generators (1985 through 1988) or AgI flares affixed to racks on each wing (in 1989). Each generator usually produced about 2 gms of AgI per minute of operation, while the fixed flares produced about 3 gms of AgI per minute for each 20-gm flare that was burned. Total burn time for each fixed flare was about 6 minutes.

The San Angelo operational radar was a C-band Enterprise system in all years. In 1985 through 1988 the radar was an Enterprise WR-100-2 and in 1989 it was an Enterprise WR-100-5. In some years the radars had L-band aircraft transponder display capability, which was used for coordination of the seeding flights. The radars were located at Mathis Field near San Angelo, Texas at 31^{o} 21.5'N and 100^{o} 29.7'W. The airport elevation is 1916 ft.

Rainfall information for this study was obtained from long-term rain gage sites that included Garden City, Sterling City, Cope Ranch, Funk Ranch, Water Valley, Water Valley 10NNE, San Angelo, Mertzon, Mertzon 10NE, Eldorado and Ozona. It should be noted that the Eldorado gage site was 11 mi. NW of the city through June of 1981 and 2 mi. SE of the City from September 1981 to the present. The Mertzon site ceased operation in 1987, whereas the Mertzon 10NE site began its operation in 1977. These stations figure prominently in the assessment of seeding effects. The gage observations are discussed extensively by Woodley and Solak (1989).

In conducting the seedings, all suitable clouds were to be treated with a silver iodide (AgI) nucleant while they were over the watershed shown in Figure 1. Primary seeding emphasis was placed on clouds within 30 n.mi. of Twin Buttes and O.C. Fisher reservoirs located immediately southwest and northwest of the city, respectively.

Many of the seedings were at cloud top using droppable AgI flares. The number of flares used was a function of the suitability of a particular cloud system. Some of the seedings, particularly those at night, took place at cloud base, using either wing-tip AgI-acetone generators (1985 through 1988) or AgI flares affixed to racks on each wing (in 1989). The AgI-acetone generators produced more effective nuclei per gram of AgI at -10^{o}C, averaging between 10^{14} and 10^{15} nuclei per gram of nucleant, than the droppable or fixed flares, which averaged between 10^{12} and 10^{13} effective nuclei per gram of nucleant. Cloud-base seeding was the preferred mode of treatment, when large highly-organized cloud systems traversed the target area. Woodley and Solak (1989) discuss the rationale and scientific basis for each approach to seeding as a function of the initial conditions of the cloud and its environment.

4. OPERATIONAL RESULTS

During the 5-year program, the wettest May through September period, both within and outside the target area, occurred in 1986. The May through September periods in the remaining four years, ranked by decreasing wetness, were 1987, 1988, 1985 and 1989. The rainfalls in all years, except 1989, were above the May through September seasonal normals. It was dry in 1989, especially in the southwestern portion of the target and to the south and west of the target.

A summary of seeding operations for the five-year operational program is presented in Table 1. The number of seeding days and the number of seeding flights are not correlated with the total rainfall. For example, 1989 ranked #2 in the number of seed days, #1 in the number of seeding flights, and #1 in the amount of seeding agent expended. It ranked last, however, in total rainfall. Seeding activity alone does not guarantee high rainfall totals.

Table 1. SUMMARY OF SEEDING OPERATIONS
May through September
1985 through 1989

Year	# Seed Days	# Seeding Flights	Amt. AgI (kmg)
1985	31	39	18.0
1986	26	35	31.4
1987	34	37	28.3
1988	27	35	9.4
1989	33	50	37.9
Totals:	151	196	125.1

A plot of each seeding event in the May through September period since the program began in 1985 is provided in Figure 2, where a seeding event is defined as the activation of at least one flare (ejectable or end-burning). In the case of a solution-bearing generator, the generator burn time was divided into 6-minute segments and a seeding location was determined for each 6-minute time segment. Each 6-minute segment was then defined as a seeding event. Examination of Figure

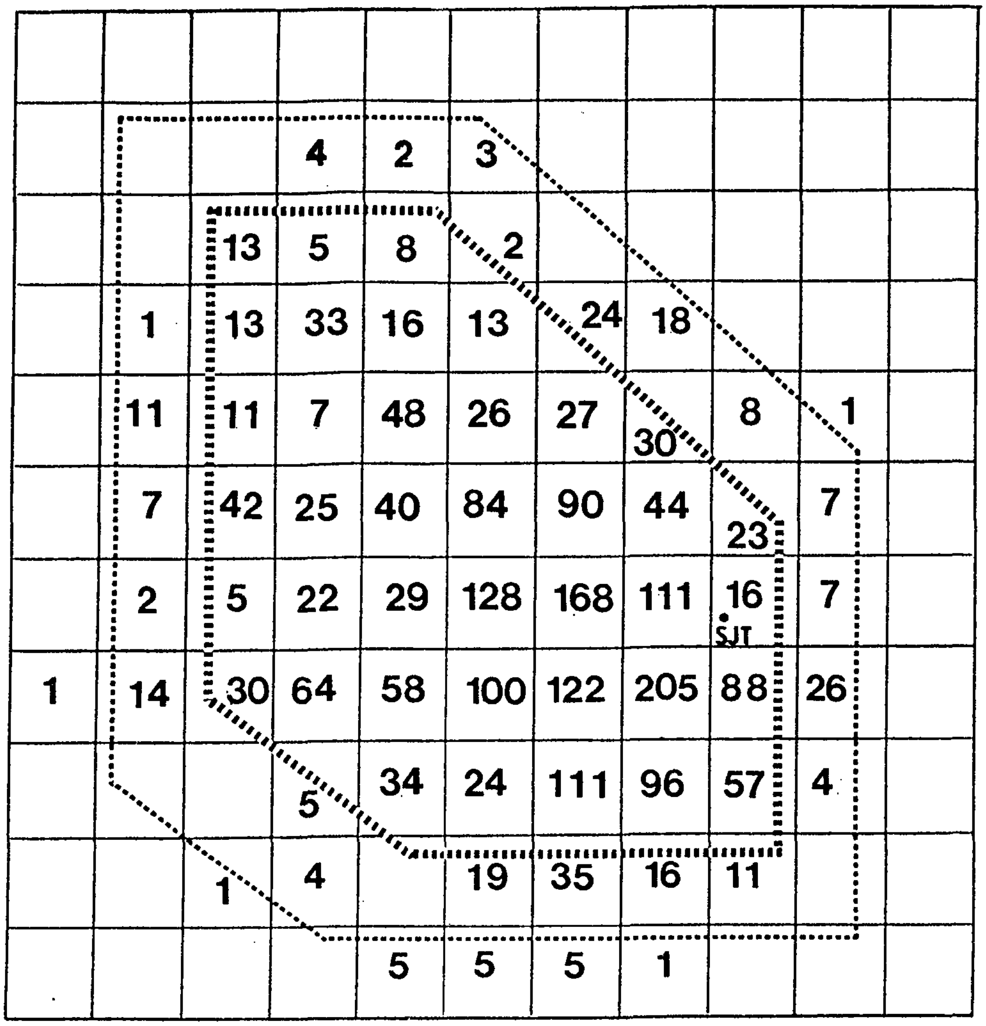

Figure 2. Location of seeding events during the San Angelo Rain Enhancement Program (May through September 1985 through 1989). A seeding event is defined as the activation of at least one flare or the ignition of the AgI-acetone generator. In the latter instance, the generator burn time was divided into 6-minute segments and a seeding location was determined for each 6-minute time segment. The outer figure is the operational area for the program while the inner area is the target. Each grid square is 10x10 n.mi. San Angelo (SJT) is identified in the extreme eastern portion of the target.

2 reveals that most of the 2,315 plotted seeding events took place within 30 n.mi of San Angelo, primarily to the west and southwest.

5. ASSESSMENT OF THE EFFECT OF SEEDING

Evaluating the effect of seeding in an operational seeding program is essential if the effort is to have long-term credibility. Unfortunately, this is not an easy proposition. The treatment has not been done on a random basis, and there are no control days to serve as an objective basis of comparison for the days that have been seeded. It is possible, however, to make an assessment of the effect of seeding, using target-control regressions that have been derived from historical rainfall records. Flueck (1976) outlines this procedure and discusses its advantages and its limitations. The basic requirements are that the target and control rainfalls be correlated, that the rainfall at the control stations not be contaminated by the seeding in the target and that the derived relationship between the control and target stations is valid for the period of seeding.

Gabriel and Petrondas (1983) add an additional requirement that there be no correlation between the departures from a regression line in successive years. Their studies suggest that such serial correlations may take place and result in misleading P-values for operational/historical comparisons. A suggested means for accounting for this tendency is to double the derived P-value (e.g. a 5% significance level or P-value is adjusted upward to 10%). We will return to this point later in the text.

Our approach to the assessment of seeding effects is similar --- at least initially --- to that of Girdzus and Griffith (1989). Historical monthly precipitation data were accumulated for long-term rainfall stations within the target and outside to the west and to the south. The period of record was 1960 through 1984 inclusive. These stations are shown in Figure 3. Six control stations (Midland Airport, Penwell, McCamey, Bakersfield, Ozona and Sonora) and nine target stations (Garden City, Sterling City, Cope Ranch, Water Valley, Water Valley 10 NE, Funk Ranch, San Angelo, Eldorado (11 NW and 2 SE), and Mertzon and/or Mertzon 10 NE were used in the analysis. Most of these stations were selected at the end of the first year of operations. Sonora, Sterling City and Eldorado were added at the end of the 5 years of seeding. Sheffield, Texas, was considered as a control station, but its record had too many gaps to permit its use (see Woodley and Solak, 1989).

It must be emphasized that all possible control and target stations were used. Stations were rejected only if their record was too intermittent to justify their use. In no case was a station record examined and then discarded because of its potential effect on the analysis.

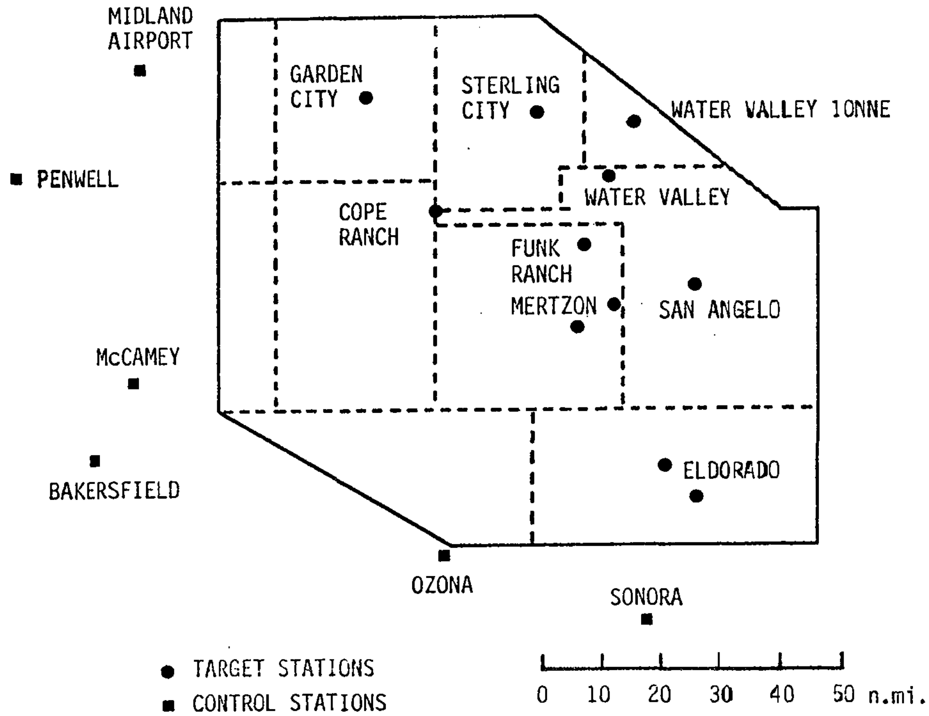

Figure 3. Map showing the location of the target and control stations used in the analysis. Two stations (i.e. Mertzon and Eldorado) have multiple sites. This is addressed in the text.

Having selected the target and control stations, the analysis proceeded along the following steps:

1. A linear regression relationship between the average, seasonal (May through September) target and control rainfalls was derived. In a variation of this basic analysis, regression equations between mean seasonal control rainfall and the total seasonal rainfall for each target station were derived.
2. The regression equations were then used to evaluate the five years of seeding. The observed mean May-September rainfall for the six control stations was substituted into the regression equations, and the overall target rainfall and the rainfall for each station was predicted.
3. The predicted rainfalls were compared to the observed rainfalls to obtain an estimate of the effect of seeding. This was done for each year and for all five years of the program.

This analysis is only as good as the input data; the quality of the rain gage records had to be addressed before any analyses could begin. All rainfall observations, except for those from the Mertzon 10 NE station, were provided by the National Climate Data Center in Asheville, North Carolina. Overall, the station record is fairly complete, but missing records were a problem for some stations. Table 2 lists the data availability for the target and control stations for the base period (1960 through 1984) and for the project period (1985 through 1989). It is based on the number of station-months that had to be edited. Each station-month requiring any intervention, whether one day or the entire month, is noted.

Study of Table 2 reveals that four stations (San Angelo, Water Valley, Cope Ranch and Midland) had a perfect record. With the exception of Sheffield (and perhaps Mertzon), the interpolations for missing data were minimal for the other stations. Sheffield was dropped from consideration because of large gaps in its record. Mertzon appeared to be acceptable. All of the editing necessary to complete the study with the remaining stations is documented by Woodley and Solak (1989).

In the cases of Eldorado and Mertzon, the gage sites at each location changed during the report period. Eldorado had no overlapping record for its two sites. The records for Mertzon and Mertzon 10NE, however, overlapped from 1977 through 1986. It was possible, therefore, to determine the relationship between the two

Table 2. NUMBER OF STATION-MONTHS* EDITING NECESSARY PRIOR TO REGRESSION ANALYSIS

Stations	Base Period (1960-1984; 130 months)	Project Period (1985-1989; 25 months)
	Control Stations	
Midland	0	0
Penwell	6	0
McCamey	1	0
Bakersfield	1	0
Sheffield	17	2
Ozona	3	0
Sonora	0	3
	Target Stations	
Garden City	1	0
Sterling City	4	5
Water Vly	0	0
Water Vly 10NNE	4	1
Cope Ranch	0	0
Funk Ranch	3	0
San Angelo	0	0
Mertzon	9	1 (record ends in 1987)
Mertzon 10 NE	-	0 (1987 through 1989)
Eldorado**	2	0

* A station is said to have one station-month of editing, if the record for only one day or as many as all days for that month was (were) missing.

** The record for Eldorado included Eldorado 11NW from 1960 through most of 1981 and Eldorado 2SE from September 1981 through the project period.

stations. The results, which are presented by Woodley and Solak (1989), indicate that the rain measurements at the new Mertzon site (i.e. Mertzon 10NE) are low relative to the old site. Use of the new site for a portion of the treatment period will tend to underestimate the apparent effect of seeding. The alternative is to use the regression relationship discussed by Woodley and Solak (1989) to adjust the readings at the new site to the old. In view of the uncertainties involved, we decided to pursue a conservative course of action and make no adjustments.

A listing of the data used for this analysis of seeding effect is provided in the Appendix. These are the input data for the regressions to be discussed in this paper. Documentation of all data editing and interpolations is presented by Woodley and Solak (1989).

5.1 Results

A listing of the regression equations relating target to control rainfalls and the resulting correlation coefficients is presented in Table 3. Note that the correlations range from a maximum of 0.84 to a minimum of 0.58. The overall target vs control correlation is 0.77. A complete correlation matrix among all stations can be found in the report by Woodley and Solak (1989).

Again, it must be emphasized that no search was made to find the "best" stations or "best grouping of stations" for this analysis. Such a search must have a physical basis, and we could find no physical reason to modify our initial selection of stations. In truth, we have used all of the candidate control stations that had a long-term rainfall record. In the case of the target stations, we used all stations within the target that had a complete or nearly complete record for the period of analysis.

The equations of Table 3 were used to predict the overall target rainfalls and the rainfall at each target station for each of the five years of seeding operation. The results in terms of ratios of observed to predicted rainfalls are presented in Table 4 and in terms of differences between observed and predicted rainfalls (units: inches) are presented in Table 5. If seeding has increased the rainfall during the program, there should be a preponderance of ratios and differences > 1. That they do, in fact, exceed 1 does not of itself prove the effectiveness of seeding in increasing rainfall. It is, however, a big step in that direction.

The real challenge is interpreting the results of Tables 4 and 5. The regression equations for individual stations have correlations that range between 0.84 and 0.58, so they are not perfect predictors of target rainfalls. It would be a mistake, therefore, to interpret the results as proving that seeding either increased or decreased the rainfall at a particular station in a particular year.

Overall impressions, however, may have validity. Approaching the results in this way, one notes immediately that there is a preponderance of ratios and differences > 1 in both tables. This is especially true for the stations closest to San Angelo (i.e. San Angelo and Mertzon), where most of the seedings took place (see Figure 2), and for all years combined. The overall target variable has ratios and differences > 1 for all 5 years of operation. Assessment of the significance of this result is possible if one views the result for a particular year as a random event, much like the flip of a coin. The probability that a particular year will have a target ratio or a rainfall difference > 1 is 1/2 or 50%. This is the same probability of

Table 3. REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS RELATING TARGET TO CONTROL RAINFALLS FOR THE SAN ANGELO RAIN ENHANCEMENT PROGRAM (Period of Record 1960 through 1984)

	Correlation Coefficient	Equation
Control vs Target	0.77	$T_R = 3.67 + 0.814C_R$
Control vs Garden City	0.65	$G_R = 3.83 + 0.738C_R$
Control vs Sterling City	0.64	$S_R = 4.32 + 0.774C_R$
Control vs Cope Ranch	0.66	$C_R = 4.03 + 0.735C_R$
Control vs Water Valley	0.63	$(WV)_R = 4.19 + 0.826C_R$
Control vs Water Valley 10NNE	0.60	$(WV^*)_R = 4.64 + 0.806C_R$
Control vs Funk Ranch	0.67	$F_R = 3.75 + 0.817C_R$
Control vs San Angelo	0.63	$(SA)_R = 2.70 + 0.832C_R$
Control vs Mertzon	0.58	$M_R = 4.51 + 0.734C_R$
Control vs Eldorado	0.84	$E_R = 1.05 + 1.067C_R$

Table 4. RATIOS OF OBSERVED TO PREDICTED RAINFALLS FOR TARGET STATIONS BY YEAR AND FOR ALL FIVE YEARS OF OPERATIONAL SEEDING

Station	1985	1986	1987	1988	1989	All Years
Grdn Cty	1.21	0.94	0.84	1.42	1.33	1.12
Strlng Cty	0.98	1.13	1.14	1.15	0.93	1.07
Wtr Vly	0.78	1.23	1.39	0.94	1.56	1.16
Wtr Vly 10NNE	0.75	1.72	1.46	0.89	1.53	1.28
Cope Ranch	0.94	2.09	0.78	1.09	0.47	1.16
Funk Ranch	1.04	1.00	1.03	0.92	0.92	0.99
San Angelo	1.14	1.41	1.56	0.84	1.40	1.27
Mertzon	1.86	1.17	0.97	1.82	1.35	1.42
Eldorado	1.02	0.92	1.22	1.09	1.17	1.07
Target	1.07	1.29	1.16	1.13	1.19	1.17

Table 5. DIFFERENCES BETWEEN OBSERVED AND PREDICTED RAINFALLS FOR TARGET STATIONS BY YEAR AND FOR ALL FIVE YEARS OF OPERATIONAL SEEDING (Units are inches)

Station	1985	1986	1987	1988	1989	All Years (avg. value)
Grdn Cty	2.35	-0.92	-2.08	5.34	2.49	1.43
Strlng Cty	-0.25	2.05	2.02	2.09	-0.62	0.93
Wtr Vly	-2.77	3.77	5.74	-0.87	4.72	2.12
Wtr Vly 10NNE	-3.21	12.01	6.75	-1.64	4.69	3.77
Cope Ranch	-0.70	16.37	-2.86	1.16	-4.17	2.96
Funk Ranch	0.45	0.00	0.36	-1.10	-0.65	-0.18
San Angelo	1.50	6.26	7.36	-2.01	2.83	3.19
Mertzon	10.21	2.56	-0.44	11.07	2.88	5.26
Eldorado	0.27	-1.29	3.18	1.26	1.12	0.91
Target Average	0.87	4.54	2.23	1.70	1.47	2.16

obtaining "heads" (or "tails") upon a single flip of the coin. The probability of two years in a row > 1 is 25%. Finally, the probability that 5 years in a row will be > 1 is about 3% (i.e. $(0.5)^5$). Thus, there are 3 chances in 100 that the results for the San Angelo operational seeding program are due to chance and a 97% probability that they are due to seeding intervention. Remembering the admonition of Gabriel and Petrondas (1983) that the P-values for operational/historical comparisons be increased by a factor of two to account for the possibility that the departures from the regression might be serially correlated, the P-value or significance level for our study becomes about 6% --- not as impressive as 3% but still suggestive of an effect of seeding.

Figure 4 shows a "scatter plot" of the seasonal (May through September) target and control values that went into the base period regression. In addition, the points for the five seeded seasons have been added to the plot (i.e. the larger dark circles). Note that all five points lie above the base-period regression line. Further, there is no obvious relationship between the size of the effect and the amount of control rainfall. This is in contrast to the results for the CRMWD effort (see Jones, 1985 and 1988) in which the effect of treatment seemed to increase with an increase in the control rainfall.

These results certainly suggest an overall effect of seeding of about +17% for the target for all years of operation. If the Eldorado gage is eliminated entirely from this analysis as a sensitivity test because of its 13-mile change in location during the seeding period, the apparent overall effect of seeding becomes 18%. This station is not pivotal, therefore, to the analysis.

Plots of the all-years results of Tables 4 and 5 are provided in Figures 5a and 5b. The obvious "clinker" in the results are the ratio and rain-difference values for Funk Ranch. No effect,either positive or negative, is indicated at this site, even though the stations around it suggest appreciable effects of seeding.

The explanation for the anomaly at Funk Ranch lies in its 5-year rainfall record. The average rainfall at this station for the 5 years is 12.52 in., but the average 5-year rainfalls at the 4 surrounding stations to the northwest (Cope Ranch), northeast (Water Valley), southeast (San Angelo) and south (Mertzon), are 14.04, 15.36, 15.01 and 17.81 in., respectively. Clearly, the 5-year mean rainfall at Funk Ranch is low relative to the values at the surrounding nearby stations. It is unlikely that such a disparity over 5 years is real, and it explains why the estimate of the apparent seeding effect is inconsistent with the estimates for the nearby stations.

It is interesting to note that the area closest to San Angelo (San Angelo and Mertzon) had apparent overall effects ranging between 27% and 42%. The mean increases in rain amount for this region closest to the San Angelo reservoirs average between 3 and 5 inches per season (May through September). This is the region over which most of the seeding was done (see Figure 2). Funk Ranch does not fit this nice picture for the reasons discussed above.

5.2 Sensitivity Tests

Sensitivity tests are an important component of any analysis. To test the sensitivity of the San Angelo results the following procedure was applied:

1. The 25-year base period (1960-1984) was divided into five 5-year blocks.
2. Linear regression equations relating control to target rainfalls were derived for the five 20-year base periods. With the derivation of each regression equation, a 5-year period was set aside as a hypothetical period of seeding. As an example, the period 1965 through 1984 was used to derive the target vs. control relationship and the period 1960 through 1964 was set aside as a period of hypothetical seeding.
3. A seeding effect was then calculated for each 5-year period of hypothetical seeding and for the 5-year period (1985 through 1989) of actual seeding. The "seeding effects" were then compared.

If seeding indeed has been responsible for increased rainfall, one would expect the apparent seeding effect to be evident in each of the five sensitivity tests. Further, one would expect the apparent effect in the period of actual seeding, to be greater than the "effect" for each 5-year period of hypothetical seeding. These expectations are realized as is obvious by examining the presentation in Table 6.

Note that in each 5-year period, the apparent effect of actual seeding for the years 1985 through 1989 exceeds the "effect" in each 5-year period of hypothetical seeding. In every instance the ratio of observed to predicted rainfall for the actual period of seeding is > 1, while only three of the five years is > 1 for the period of hypothetical seeding.

The "effect" of hypothetical seeding in the period 1980 through 1984 presents the biggest challenge to the period of actual seeding with a ratio of observed to predicted rainfall of 1.13 as compared to 1.20 for the actual seeding period. A year-by-year closer look at this five-year period produced ratios of observed to predicted rainfalls for the period of hypothetical seeding of 1.30, 1.08. 1.39, 0.98, and 0.71. The ratios for the actual period of seeding are 1.10, 1.32, 1.20, 1.15 and 1.21. Again, all of the yearly ratios are > 1 for the actual seeding period, whereas only three of the five yearly ratios are > 1 for the period of hypothetical seeding. As discussed earlier in the text, the probability of obtaining ratios > 1 five years in a row is between about 3% and 6%, suggesting that seeding might have been responsible for the apparent effect. On the other hand, the probability of obtaining three of five ratios > 1, as is the case for the 5-year period of hypothetical seeding, is about 13%.

This sensitivity analysis supports the interpretation that AgI seeding is responsible for at least a portion of the apparent increases of rainfall over the San Angelo watershed for the period 1985 through 1989. It does not, however, prove that is the case. Only by evaluating all of the evidence might one be justified in reaching such a conclusion.

6. DISCUSSION

Assuming that the suggested seeding effects are real, the question becomes how the increases were produced. A good start to answering this question are the research results presented by Rosenfeld and Woodley (1989), which indicate that AgI seeding of convective cells in West Texas was effective in increasing the areas, durations and rain volumes of the cells. The radar-estimated rainfall volume at the bases of the AgI-treated cells was more than double (i.e. increases exceeding 100%) the rain volume from the cells that received simulated treatment. This result is significant at the 3% significance level using re-randomization procedures. The apparent effect of seeding and its significance increases slightly when control cells are incorporated into the analysis. The effect of treatment on maximum cell height, as measured by radar, generally averaged less than 5%.

It must be pointed out, however, that the results discussed by Rosenfeld and Woodley (1989) do not appear to fit the "classic" dynamic-seeding response whereby the AgI-treated cell first grew explosively in the vertical before expanding laterally. Although the seeded cells were

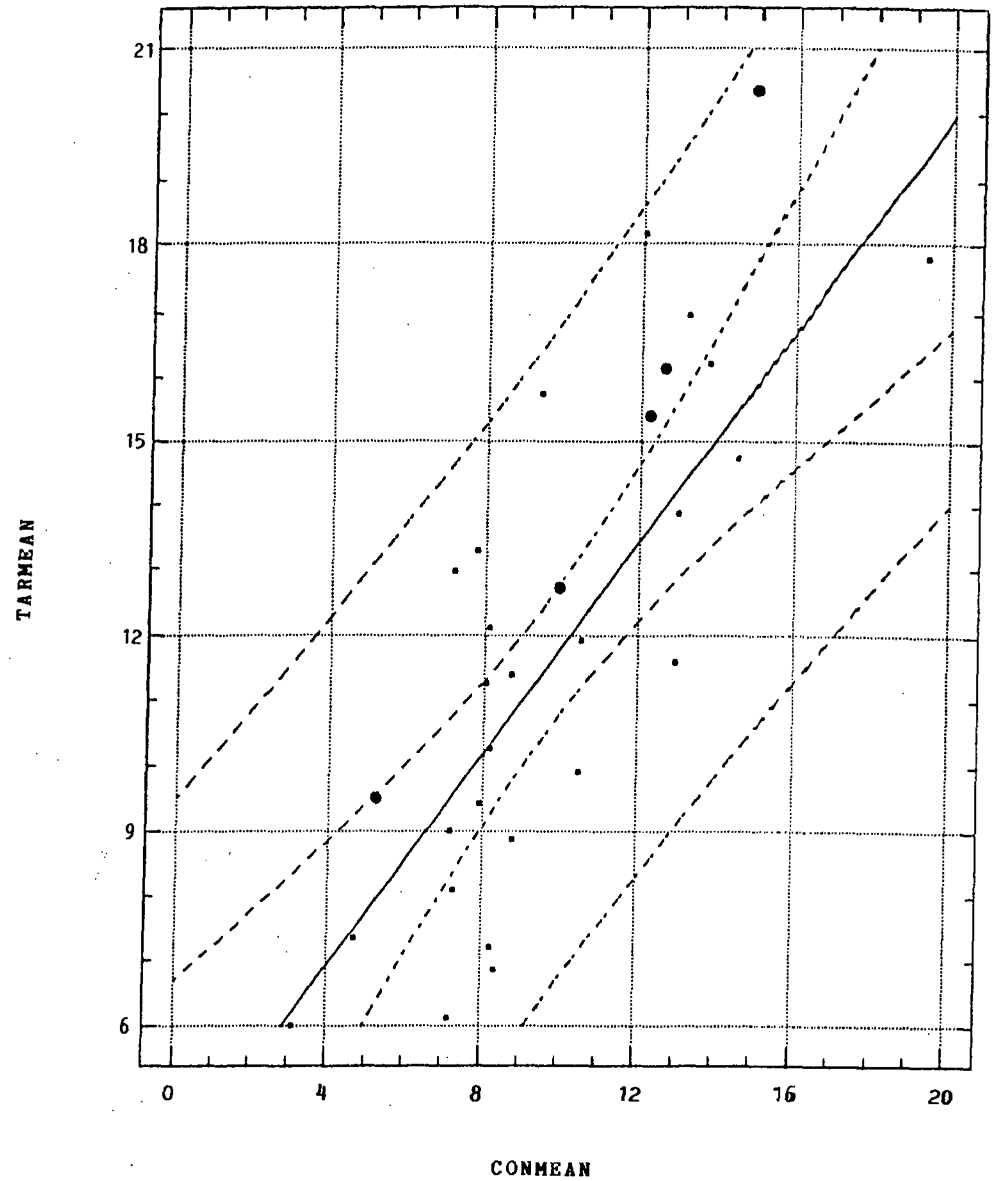

Figure 4. Scatter plot between the seasonal (May through September) mean control and mean target rainfalls for the base period 1960 through 1984. The solid line is the least-squares best fit. The dashed lines are 90% and 95% confidence intervals. The values for the five seeded seasons are plotted as large black dots.

slightly taller in the mean than those cells that did not receive treatment, vertical growth of the cells was not the dominant response.

In moving from the cell scale to the larger scales, it was found that cell merger occurred twice as often in the AgI-treated cases. Merging was most pronounced for cells treated early in their lifetimes with 9 or more AgI flares. The merger results are highly significant.

If one accepts the results of Rosenfeld and Woodley (1989) indicating a large effect of seeding on the convective cells of West Texas, the next question is how this effect spreads to the larger scales during the operational seedings. It is expected that cell mergers, leading to larger and more clustered areas of precipitation, play a major role in this transfer. The strong evidence for increased merging of the seeded cells in West Texas supports this speculation, as do the results of other investigators. It has been well documented, for example, that the merger of convective cells or elements can affect the future development of a cloud mass, leading to taller, larger and more intense convective systems that produce more rainfall (Simpson and Woodley, 1971; Lemon, 1976; Houze and Cheng, 1977; and Wescott, 1977).

Because vigorous cell mergers usually take place in regions of strong convergence of moist air beneath the clouds, one is left with the suspicion that seeding enhances the surface convergence. How this takes place is still a matter for conjecture, but the most likely process is enhanced downdrafts following seeding as postulated by Simpson (1980) and modeled later by

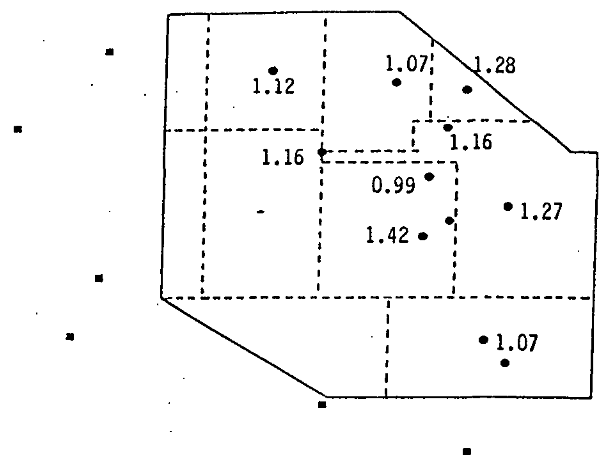

Figure 5a. Ratios of observed to predicted rainfalls for target stations for all five years of operational seeding.

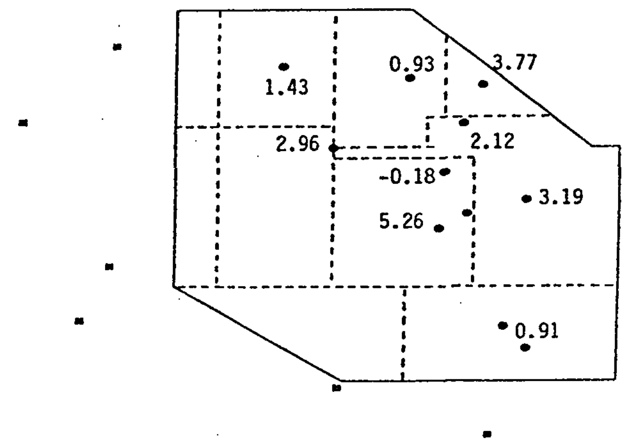

Figure 5b. Differences between mean observed and mean predicted seasonal rainfalls for the target stations. The values are in inches.

Table 6. APPARENT SEEDING EFFECTS[1] IN PERIODS OF ACTUAL AND HYPOTHETICAL SEEDING

Base Period	Regression Equation	Hypothetical Seed Period	Seeding Effect	Actual Seed Period	Seeding Effect
1965-1984	Y = 4.52 + 0.754X r = 0.805	1960-1964	0.87	1985-1989	1.15
1960-1964 + 1970-1984	Y = 3.03 + 0.862X r = 0.804	1965-1969	1.09	1985-1989	1.18
1960-1969 + 1975-1984	Y = 3.79 + 0.797X r = 0.656	1970-1974	1.02	1985-1989	1.18
1960-1974 + 1980-1984	Y = 3.32 + 0.876X r = 0.753	1975-1979	0.90	1985-1989	1.14
1960-1979	Y = 3.66 + 0.788X r = 0.784	1980-1984	1.13	1985-1989	1.20
1960-1984	Y = 3.67 + 0.814X r = 0.765	---------	----	1985-1989	1.17

1 The seeding effect is defined as the ratio of observed to predicted rainfall for particular period of real or hypothetical seeding.

Tao and Simpson (1988). Uncertainties such as this are the reason for continuation of research programs, such as the Southwest Cooperative Program (SWCP).

Rosenfeld and Woodley (1989) noted several other apparent effects of seeding that are of relevance to the interpretation of the San Angelo operational seeding effort. Their seeded cells showed at least two growth pulses during their lifetimes, while those that were not seeded typically pulsed only once. This means that the seeded cells lasted longer than the unseeded cells. This suggests that dynamic effects were operative.

On the other hand, there was a stronger "bright band" phenomenon near the freezing level in the AgI treated cells. This suggests more snow crystals with slower fall velocities in the seeded clouds relative to the unseeded clouds. This implies that static effects were operative in the seeded cells as well.

Based on the Rosenfeld and Woodley (1989) study, therefore, it seems likely that the response of the treated clouds in the San Angelo program was a mixture of static and dynamic effects. This makes sense, and it may explain why apparent seeding effects were evident in 1988 when most of the seeding was done at cloud base. Such seeding is normally used to produce static effects, although, as discussed earlier, one could certainly make the case that the high-output seeding generators used by North American Weather Consultants in 1988 may have produced dynamic effects as well. When conducting base seeding in regions of strong updraft, it is likely that fairly high concentrations (i.e. > 100 l^{-1}) of nuclei were carried upward in the strong updraft cores. Such concentrations of nuclei might have produced the rapid glaciation thought necessary for dynamic effects.

Without supporting physical measurements, one must be content with the circumstantial evidence for increased rainfall in the San Angelo program. Although this evidence is strong, it is not conclusive. The apparent positive effects in each of the five years of the program certainly suggest an effect of seeding. That the area of greatest apparent effect nearly coincides with the region that received the most seeding is a strong indicator of seeding effects. Finally, the finding that seeding effects are indicated after sensitivity testing also supports an interpretation of positive seeding effects in the San Angelo program.

The results of the San Angelo program are consistent with the convective cloud seeding program, sponsored by the Colorado River Municipal Water District (CRMWD) in Big Spring, Texas, which ran continuously from 1971 through 1988 (18 years). The twofold purpose of this program was to increase precipitation runoff for storage in the CRMWD reservoirs and to increase rainfall for use by agriculture. Seeding during this program was done primarily at cloud base using silver iodide (AgI) acetone generators.

In assessing the apparent effect of seeding in the CRMWD program, Jones (1985 and 1988) made use of the historical rainfall record (1936-1970) to calculate percent of normal rainfall at target and control stations. He also used these data to develop target-control regressions, which were used to predict rainfall in the seeded period (1971-1988). The predicted and observed target rainfalls were then compared. The percent-of-normal analysis indicates 30% above normal rainfall in the center of the target while the regression analysis suggests that seeding increased the rainfall about 11% in the target area.

A second analysis by Jones (1988) of the yields of unirrigated cotton in and around the target since seeding began in 1971 indicates increases of cotton production of 48% and 45% in the target and downwind of the target, respectively, while the increase in cotton production in the same time period in the counties upwind of the seeding was only 8%. If one assumes that rainfall has been the major control of cotton production over the entire region, this result might be interpreted as further evidence for seeding-induced rain increases.

Collectively, the San Angelo and Big Spring programs provide fairly persuasive evidence for seeding-induced increases in precipitation. It is crucial that these results be confirmed and that a major effort be made to gain physical insights as to how and why the rain increases were produced.

7. CONCLUSIONS

Upon assessing all of the evidence, we conclude that seeding has increased the rainfall over the San Angelo watershed. Among all the factors considered, we consider the following most convincing:

1. In the statistical analysis an apparent positive seeding effect is evident in each of the five years of operational seeding. Our analysis suggests that the probability of this happening by chance may be as low as 3%. The apparent overall area-wide effect is +17%.
2. The apparent effect of seeding appears to be strongest over regions where most of the treatment took place during the 5-year program, especially near and to the west and southwest (upstream) of the reservoirs serving San Angelo. One target station does not, however, fit this general picture, because of an unrepresentative rainfall record.
3. The apparent effect of seeding is still evident after sensitivity testing.
4. The results of research to date within the context of the Southwest Cooperative Program (SWCP) indicate that seeding in West Texas is effective in increasing the rainfall from individual convective cells by over 100% and that seeding promotes the merger of adjacent clouds, leading to larger and longer-lasting raining clouds (see Section 6.0). There is good reason to expect, therefore, that seeding will produce increases in rainfall when it is applied on an operational basis.
5. Analysis of the 18-year operational cloud seeding program of the Colorado River Municipal Water District (CRMWD) indicates that seeding has increased the rainfall by about 11%. This result is consistent with the results of the San Angelo program.

8. ACKNOWLEDGEMENTS

This paper is dedicated to Mr. Stephen Brown, Manager of the City of San Angelo, whose vision and perseverance made this program possible. The results of this five-year seeding effort suggest that his faith has been well-founded.

We thank also Mr. Art Talamantes, Meteorologist In Charge of the San Angelo Office of the National Weather Service, for his help and that of his forecasters (Jim Boyd, Bud Canfield, Jim Maxwell and Matt Sena). Whenever data and/or a forecast consultation was needed, they were there to help.

We also want to acknowledge that some of the analyses pursued in this report are based on initial analyses by Messrs. Girdzus, Griffith and Risch of North American Weather Consultants that were presented in their 4-year series of contract reports to the City of San Angelo. These contract reports are cited in the reference section of this report. We also appreciate the encouragement offered by Tom Henderson, President of Atmospherics, Inc., during the course of this study.

In addition, we recognize the efforts of Richard Jackson with the San Angelo rain gage network. His efforts were valuable in evaluating the program, as is obvious when reading this report.

Finally, we thank Mr. George Bomar and the anonymous reviewers for their critique of this report. Their comments were most helpful during its revision phase.

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MAY TO SEPTEMBER YEARLY RAINFALLS FOR TARGET AND CONTROL STATIONS

	Control Stations							Target Stations									
Yr	MAF	Pnwll	McCmy	Bkrsfld	Ozona	Sonora	Mean	Grdn Cty	Strlng Cty	Wtr Vly	Wtr Vly 10NNE	Cope Rnch	Fnk Rnch	SJT	Eldrdo	Mrtzon	Mean
								Pre-Treatment Period									
60	7.81	7.86	8.21	6.90	7.09	5.13	7.17	8.17	6.53	6.20	5.43	6.21	7.19	5.24	5.23	4.98	6.14
61	15.65	5.21	5.65	3.82	13.98	11.97	9.38	17.33	16.42	12.01	18.45	12.21	16.52	13.23	17.84	17.77	15.75
62	10.81	9.74	5.55	6.66	4.94	12.43	8.36	9.45	8.35	4.91	4.66	6.83	6.87	5.40	9.00	6.16	6.85
63	8.03	7.15	6.17	6.66	6.55	8.47	7.17	8.70	8.88	7.75	9.97	10.20	8.91	9.37	7.87	9.52	9.02
64	5.55	3.83	12.23	5.67	9.17	16.29	8.79	9.78	13.58	8.53	8.34	9.38	7.47	5.19	9.19	8.51	8.88
65	8.01	6.95	8.35	6.08	9.34	9.57	8.05	10.75	14.73	11.09	14.89	14.40	9.91	9.82	7.86	8.05	11.28
66	12.60	8.18	8.33	11.12	12.72	10.21	10.53	6.53	11.70	13.13	11.76	11.52	15.72	10.42	14.68	11.82	11.92
67	5.13	8.27	6.74	6.90	7.39	12.26	7.78	10.96	13.93	13.13	12.48	16.01	13.47	13.55	12.52	13.42	13.28
68	10.48	8.67	11.29	9.82	12.26	10.33	10.48	11.07	9.04	9.96	9.85	5.91	12.02	11.60	10.33	9.41	9.91
69	8.55	5.47	7.41	8.08	10.92	8.26	8.12	12.00	15.86	15.23	11.80	7.12	14.48	12.78	10.34	9.56	12.13
70	4.27	5.03	8.65	10.66	6.19	8.73	7.26	9.02	6.38	7.07	9.63	8.07	8.11	6.97	9.81	7.94	8.11
71	10.45	11.16	7.06	9.16	22.75	18.73	13.22	14.01	15.84	19.19	19.90	11.01	17.12	16.70	16.77	22.13	16.96
72	8.33	11.44	11.15	11.14	19.62	20.99	13.78	14.84	17.22	16.06	20.38	14.64	16.20	18.23	13.65	14.69	16.21
73	5.02	6.31	5.42	10.37	10.69	11.23	8.17	6.53	6.95	12.03	13.62	7.72	15.00	9.82	11.11	9.65	10.27
74	11.94	12.11	18.38	29.73	20.83	23.30	19.38	13.26	16.41	18.20	20.80	17.41	19.24	15.01	22.12	17.62	17.79
75	18.34	13.26	11.13	11.70	9.48	14.10	13.00	16.39	15.50	15.21	13.91	15.87	11.76	12.87	10.96	12.35	13.87
76	8.87	8.90	11.37	16.94	17.10	24.08	14.54	16.80	14.74	14.60	12.52	18.17	12.33	11.76	19.38	12.41	14.75
77	2.27	4.39	4.79	3.94	5.85	7.03	4.71	6.95	7.01	10.28	10.06	10.49	6.22	3.78	6.29	5.11	7.36
78	11.66	10.06	15.70	15.29	9.10	15.94	12.96	9.35	12.70	13.79	11.17	14.19	8.10	9.33	15.37	10.27	11.59
79	9.42	7.23	5.85	7.31	8.96	8.77	7.92	12.49	6.85	9.24	9.83	12.54	10.48	6.36	9.36	7.54	9.41
80	14.07	13.30	10.29	8.56	11.94	14.00	12.03	19.05	17.43	22.58	17.42	14.15	20.01	22.49	13.07	17.20	18.16
81	8.08	5.39	7.01	7.29	10.61	13.95	8.72	9.27	11.75	11.56	11.50	11.91	9.42	13.30	7.80	16.14	11.41
82	9.95	7.58	2.73	7.47	6.88	8.56	7.20	10.30	14.89	17.83	18.08	10.76	9.18	11.08	8.26	16.11	12.96
83	1.74	2.15	1.72	2.05	5.01	6.13	3.13	2.19	5.84	7.43	7.84	5.28	5.34	5.45	5.97	8.81	6.02
84	10.73	11.43	8.03	7.63	5.53	6.06	8.24	7.59	5.28	6.12	5.31	5.31	8.77	7.21	7.57	11.83	7.22
								Treatment Period									
85	8.08	7.29	10.00	7.20	15.63	11.98	10.03	13.58	11.82	9.70	9.51	10.70	12.39	12.54	12.02	22.08	12.70
86	19.49	17.36	12.88	7.07	13.88	18.67	14.89	13.90	17.88	20.26	28.65	31.34	15.92	21.35	15.65	18.00	20.33
87	9.32	12.49	9.99	15.00	13.50	15.03	12.56	11.02	16.05	20.30	21.51	10.40	14.37	20.51	17.63	13.29*	16.12
88	16.49	10.83	7.88	8.41	15.30	13.92	12.14	18.13	15.79	13.35	12.78	14.11	12.57	10.79	15.26	24.49*	15.25
89	5.87	6.65	5.29	5.91	3.39	3.95	5.18	10.14	7.70	13.19	13.51	3.67	7.33	9.84	7.70	11.19*	9.36

* The gage totals for 1988 through 1989 are from Mertzon 10NE (see Appendix A for details)