THREE RAINFALL AUGMENTATION PROGRAMS IN TEXAS

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Abstract Three rainfall augmentation programs were initiated during the summer of 1985 in response to drought conditions affecting Texas in 1984. These programs were supported by two municipalities (San Angelo and Corpus Christi) and one water district (Edwards Underground Water District of San Antonio). Suitable clouds were seeded for dynamic response according to FACE techniques. Two of the programs (San Angelo and Edwards) were operated during the summer of 1986. An assessment of the potential effectiveness of the San Angelo project indicated approximately a 26 percent surplus in the target based on a target/ control analysis for the two seeded seasons. A similar assessment for the Edwards project indicated approximately a 5 percent surplus for the 1986 seeded season.

1. INTRODUCTION

North American Weather Consultants (NAWC) was contracted by three different entities in Texas to conduct rainfall augmentation programs during the summer of 1985. Weather Modification Inc. (WMI) of Bowman, North Dakota served as a major subcontractor to NAWC furnishing weather radars, seeding aircraft and pilots to the programs. The projects were conducted for the City of San Angelo, the City of Corpus Christi, and the Edwards Underground Water District. These programs resulted from a dry summer in 1984 which reduced water supplies in many parts of Texas. Two of these programs (San Angelo and Edwards) continued operations during the summer of 1986. The Corpus Christi program was not conducted in 1986 since the City determined adequate water supplies existed in the spring of 1986. The goal of the San Angelo and Corpus Christi programs was to increase surface reservoir storage. The goal of the Edwards program was to increase underground water storage in the Edwards Aquifer, which underlies much of the area west through north of San Antonio. Figure 1 provides the locations of the three areas.

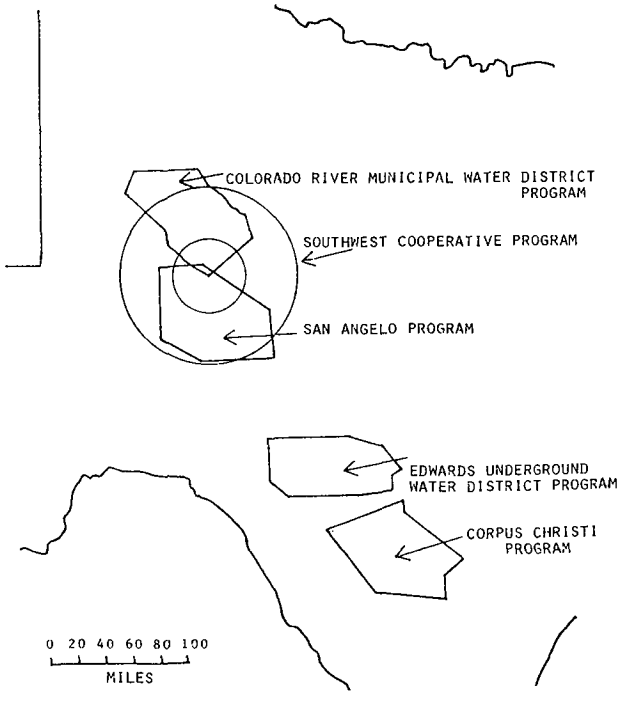

Figure 1 NAWC and Other Program Areas

2. PROJECT DESIGN

The "dynamic" seeding approach as developed on the Florida Area Cumulus Experiment (FACE) (Woodley, **et al.**, 1981) was utilized on these programs. In this approach growing cumulus towers with their tops reaching through the -10°C level are penetrated by specially equipped seeding aircraft. The pilot of the aircraft drops from one to several silver iodide flares into the updraft region of the tower. The expected chain of events with dynamic seeding summarized by Riggio 1983 are as follows:

- Heavy AgI seeding within the updraft region at the -5 to -10°C level of a convective cell leads to freezing of much of the available cloud liquid water;
- The latent heat release by freezing of liquid water and by condensation and deposition of water vapor produces positive buoyancy and leads to intensification of the updraft;
- The intensified updraft causes greater inflow of environmental air into lower cloud levels, increasing the water mass ingested by the cell;
- The intensified updraft carries a greater mass of precipitation to higher levels in the cell;
- The greater mass of precipitation descends and produces an enhanced downdraft which penetrates more vigorously into the lower-cloud- and sub-cloud layers; and
- More precipitation is carried to the ground within the more protected and favorable environment of the enhanced downdraft (Simpson, 1980).

Similar technology transfer operational programs had been conducted previously in Jamaica (Griffith and Brown, 1976) and Georgia (Griffith, 1982). Suspension criteria were developed as part of the operational plan required through the Texas permit process. These criteria are summarized in Table 1.

Table 1
Seeding Suspension Criteria

1. Tornadoes, and funnel bearing clouds were not intentionally seeded.

2. Based upon radar reflectivity measurements, systems that had the potential for producing excessive rainfall in a short period of time were not seeded.
   a) Stationary storms which radar indicated were producing in excess of 2 inches rain per hour were not seeded (1 inch per hour for Edwards).
   b) Storms that were not stationary were tested against a graph relating rainfall rates and storm movement to determine whether or not excessive rainfall was possible. If the threshold was exceeded, the storm was not seeded.

3. Storm complexes were not seeded that were expected to produce hail to the ground. The criteria that was used is the observation of a 45 dBz radar reflectivity level (5 cm radar) at or above 1.5 km above the freezing level (Foote and Knight, 1979; Mather, **et al.**, 1976; and Waldvogal **et al.**, 1979). These criteria were developed to distinguish between clouds which produced hail and those that did not.

4. Seeding was not conducted within the target area whenever the National Weather Service issued a Severe Weather Warning that affected any part of the target area. (Note: this criteria was modified for the 1986 operations in the San Angelo area to allow seeding in portions of the target area unaffected by the severe weather warning).

5. Excessive soil moisture - This condition was determined by the sponsoring agencies and, if requested, seeding was not conducted on any storms in the designated area.

6. Hurricanes. No seeding was conducted within the target area when hurricane warnings (not watches) were in effect for any part of the target area.

7. Operations were suspended, when, in the meteorologist's opinion, a hazardous condition existed.

8. Suitable clouds that were expected to exit the target area boundary within 60 minutes were not seeded. The 700 mb wind along with radar observations were used to predict cell movement.

3. OPERATIONS

It was originally planned to conduct six month programs during 1985 in all three areas (April 1 through September 30 for Edwards and Corpus Christi and April 15 through October 15 for San Angelo) but this did not come to pass because of the time required to obtain the required permits. The San Angelo program began on April 17th and terminated on October 15th. The Corpus Christi project ran from May 9th through September 30th, and the Edwards project from July 9th through September 30th. Six month programs were conducted for the San Angelo and Edwards areas during the summer of 1986.

Project offices were established at the municipal airports of San Angelo and Uvalde, Texas. Project personnel (meteorologists and pilots) operated out of these offices. Weather radar (5 cm) were utilized at both locations to direct seeding operations. Specially equipped turbo-charged twin engine aircraft were used as seeding aircraft. These aircraft (one used in each seeding program) were equipped with both belly mounted droppable pyrotechnic flare racks and Lohse acetone-silver iodide generators. The Lohse generators were used in situations where logistical or meteorological restraints prohibited cloud top penetrations.

"The Southwest Cooperative Program (SWCP) is a cooperative effort by the Bureau of Reclamation and the states of Texas and Oklahoma to demonstrate an operational technology for rain enhancement for the arid regions of the Southwest" (Johnson, **et al.**, 1986). This program was conducted for the first year in the summer of 1986. The program operated from April 22 through July 31. The SWCP is a randomized seeding program designed to test the effects of dynamic silver iodide seeding on small multiple-cell convective systems. This program is rather unique since it is conducted in conjunction with two other operationally oriented programs. One of these programs is a long-term effort (15 years) sponsored by the Colorado River Municipal Water District in the Big Spring, Texas area. The other project is one of the project areas discussed in this paper - the San Angelo project. Figure 1 provides the locations of the respective program target areas. The SWCP target area consisted of an area defined by two concentric circles centered on Sterling City where the research radar was located. The inner circle was excluded from the target area to avoid ground clutter and high elevation angles in the radar volume scans.

Project facilities in San Angelo were shared between the two projects. The projects were designed such that the research and operational seeding aircraft could be used to either conduct non-randomized seeding or randomized seeding depending upon whether suitable small multiple-cell convective systems were present or not.

Limited seeding opportunities occurred over the Edwards and Corpus Christi target areas during their respective operational periods in 1985. The reasons for the lack of opportunities were primarily two-fold: 1) clear skies and 2) suspension criteria. The months of July and August were dominated by clear skies. When clouds did occur they were often associated with severe weather watches or warnings that either restricted or curtailed any cloud seeding activities.

The situation was considerably different over the San Angelo target area. One difference between this program and the other two was that it started in mid-April and ran nearly the planned six month period. The Corpus program ran a shorter period and the Edwards a significantly shorter period of time. Table 2 contains seeding activity information for the San Angelo program. There were several occasions on the San Angelo program that cloud seeding activities were restricted or curtailed due to severe weather watches and warnings.

Table 2
1985 Seeding Activity on the San Angelo Project

Month	Number of Seeded Days	Silver Iodide Usage (g)
April	4	2667
May	7	2412
June	4	1870
July	8	5134
August	4	1470
September	8	7130
October	1	440
Totals	36	21,123

There were a number of seeding opportunities in both the San Angelo and Edwards target areas during their respective six month operational periods in 1986. Suspensions were also relatively common occurrences especially in the Edwards target area early in the season. Table 3 provides a summary of the seeding activity for the San Angelo project. This table includes seeding conducted by the SWCP research aircraft within the San Angelo target area. Table 4 contains similar information for the Edwards target area.

Table 3
1986 Seeding Activity on The San Angelo Project

Month	Number of Seeded Days	NAWC Silver Iodide Usage (g)	SWCP Silver Iodide Usage(g)	Total Silver Iodide Usage(g)
April	2	505	120	625
May	6	5123	3720	8843
June	6	12166	3840	16006
July	4	586	620	1206
August	4	794	---	794
September	6	4554	---	4554
October	2	672	---	672
TOTALS	30	24,400	8,300	32,700

Table 4
1986 Seeding Activity on the Edwards Project

Month	Number of Seeded Days	Silver Iodide Usage (g)
April	3	197
May	5	2000
June	1	1740
July	3	3917
August	7	6180
September	10	5334
TOTALS	29	19,368

4. ASSESSMENT OF SEEDING EFFECTS

Weather modification for precipitation enhancement is best not viewed as strictly a drought relief tool. It should be viewed as one of several water management tools available for potential application in a given area. Longer term weather modification activities beyond possible drought relief operations provide a better opportunity for assessment of the effectiveness of the seeding. The assessment of operational programs encounter two major obstacles: natural variability in precipitation and the lack of a random sample with which the seeded data can be compared. Several years of seeding are often necessary to develop a reasonable assessment of an operational seeding program. With the above precautions in mind, limited target-control assessments of precipitation during a portion of the 1985 and 1986 seeded periods were conducted.

4.1 San Angelo Assessment

A limited assessment of this program was conducted following the 1985 season. The same procedures were utilized to examine the effectiveness of the 1986 season. Historical monthly precipitation data were accumulated for long-term precipitation stations within and upwind of the San Angelo target area. The data were accumulated for the period of 1960-1978. Upwind was considered to be west through south of the target area. Figure 2 provides the locations of the target and control stations utilized in the assessment. All available target area stations were utilized. Unfortunately, there were a limited number of historical stations (seven) within the target area. Initially, more control stations were examined although some were dropped since they did not improve the correlations between target and control.

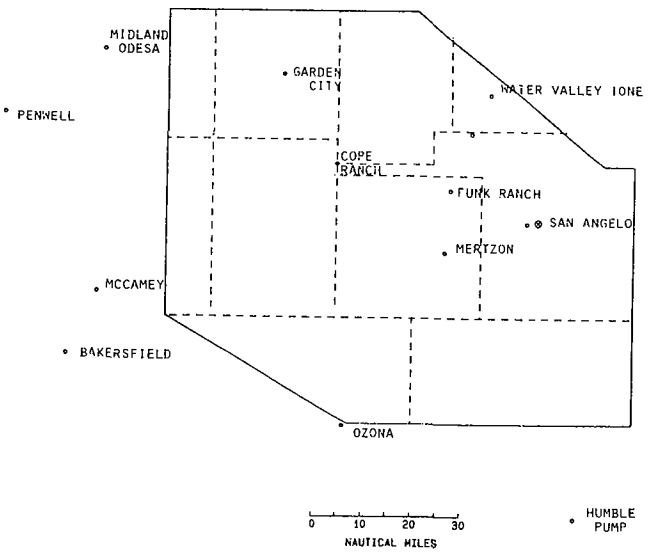

Figure 2 Locations of Long-Term NWS Precipitation Stations Used in Target-Control Assessment

Linear correlations were calculated between different groupings of target and control data. Only the months which were operational for the whole month (i.e., May through September) were included in the assessment. Types of correlations included:

- o Average precipitation in all target versus all control stations for the entire seeded period (May-September)
- o Average precipitation for each target station versus the average of the control stations by month and for the period of May through September.

These historical target-control regression equations were utilized to predict the expected target precipitation for the 1985 and 1986 seasons.

Table 5 provides the linear correlation information, the observed and predicted precipitation, ratios of observed over predicted precipitation and the one tailed statistical probabilities from the student's t and Mann Whitney U tests. The correlation coefficients (r) were generally in the range of .75 - .85 although the month of June had an extremely poor correlation. The application of statistical tests to non-randomized data such as these is tenuous as described in Gabriel, 1979 and Changnon, 1981.

4.2 Edwards Assessment

No assessment of the 1985 operations was attempted due to the limited amount of seeding that was conducted. A target-control assessment was developed, however, following the 1986 season. Similar procedures to those described in the San Angelo assessment were utilized. A historical period of 1960-1984 was used in the development of target-control regression equations. Figure 3 provides the locations of the NWS target and control precipitation stations. Target stations were even more restricted in the Edwards area than the San Angelo area. Three stations were available for the 1960-1984 period. A fourth station (Medina) became available in 1967. Five control stations were available south through west of the target area.

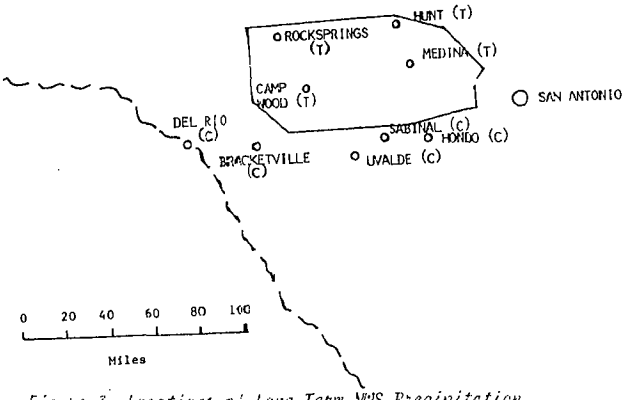

Figure 3 Locations of Long-Term NWS Precipitation Stations Used in Target-Control Assessment.

Linear regression equations were developed for the months of April, May, June, July, August, and September as well as for the entire seeded period of April through September. Two sets of equations were developed for the three target stations (1960-1984) and for the four target stations (1967-1984). Table 6 provides the correlation information, observed precipitation, predicted precipitation ratios of observed over predicted precipitation, and the student's t and Mann Whitney U test probabilities.

Table 6

Regression Equations, Daily Precipitaion Stations

Regression Equ.	r	1986 Obs.(O) Ave. Precip.	1986 Obs.(P) Ave. Precip.	Ratio O/P	Student's t Sign.	U test Sign.
$y_1 = 4.05+.82(x_1)$	.818	17.37	16.60	1.046	.36	.32
$y_2 = 5.60+.80(x_2)$	.818	18.39	17.78	1.034	.42	.37

WHERE:

y_1 = ave. precip. for target stations (Camp Wood, Hunt, Rocksprings).

x_1 = ave. precip. for control stations (Bracketville, Del Rio, Hondo, Sabinal, Uvalde).

AND

y_2 = ave. precip. for target stations (Camp Wood, Hunt, Medina, Rocksprings).

x_2 = ave. precip. for control stations (Bracketville, Del Rio, Hondo, Sabinal, Uvalde).

Table 5
San Angelo Regression Equations and Results for the 1985 and 1986 Seasons

			1985			1986			1985 and 1986				
Period	Equation	r	Obs. (O) Precip	Pred. (P) Precip	O/P Precip	Obs. (O) Precip	Pred. (P) Precip	O/P Precip	Mean Obs(O)	Mean Pred(P)	Mean O/P	t Test	u Test
May	y=.50+1.04(x)	.73	3.75	2.18	1.72	5.32	3.74	1.42	4.54	2.96	1.57	.023	.029
June	y=1.18+.39(x)	.26	2.67	2.34	1.14	4.88	2.38	2.05	3.77	2.36	1.59	.074	.143
July	y=-.08+.92(x)	.84	2.23	1.17	1.90	2.00	.50	4.04	2.12	.83	2.97	.030	.043
August	y=.35+1.14(x)	.84	.56	1.76	.32	5.24	5.34	.98	2.90	3.55	.65	.217	.171
September	y=1.08+.71(x)	.84	3.63	3.54	1.02	4.28	3.35	1.28	3.95	3.45	1.15	.267	.305
May-Sept.	y=3.25+.82(x)	.78	12.84	11.93	1.08	21.73	14.98	1.45	17.28	13.46	1.26	.022	.119
May, July-Sept.	y=2.77+.82(x)	.84	10.17	9.04	1.12	16.85	12.01	1.40	13.51	10.53	1.26	.024	.057

5. SUMMARY

Three rainfall augmentation programs were conducted during the summer of 1985. The programs were conducted for the Cities of San Angelo and Corpus Christi and the Edwards Underground Water District with headquarters in San Antonio, Texas. The programs were designed to operate in a manner responsive to public awareness of possible flash flood events with the implementation of seeding criteria safeguards to avoid seeding during such events. The projects can be considered a technology transfer of the dynamic seeding hypothesis from FACE. There were limited seeding opportunities in the Corpus Christi and Edwards target areas during the 1985 operational period. This was the result of dry weather dominating this area interspersed with a few storm days several of which exceeded the project safeguard criteria. Substantially more seeding opportunities occurred over the San Angelo target area which was at least partially due to the longer operational period in this area.

Two of the projects were re-established in 1986 (San Angelo and Edwards). A number of seeding opportunities occurred in both project areas. A Bureau supported research project (Southwest Cooperative Program) was conducted concurrently for a portion of the San Angelo project. The two programs were operated in a cooperative fashion.

A limited target control precipitation assessment was performed for the San Angelo target area during the 1985 and 1986 seeded periods. A similar assessment was performed for the Edwards project for the 1986 season. These assessments were limited by the small number of long term National Weather Service precipitation stations within and near the two target areas.

The two year assessment of the San Angelo program indicated an average of a 26 percent surplus of observed to predicted precipitation. One-tailed statistical significance probabilities were low (.02 to .11) that these results were due to chance but the application of these tests to non-randomized data is tenuous. Significant runoff into City reservoirs occurred during the 1986 operational period (39,580 to 152, 653 acre feet from April 15th to October 15th).

A one year assessment of the Edwards program indicated a surplus of approximately 3 to 5 percent of observed to predicted precipitation. Statistical significance probabilities were high (.32 to .42).

The initial indications from these short-term assessments are in line with the expectations of effects on area-wide precipitation. Additional seeded seasons would be required before the effectiveness of these programs can be assessed with any degree of confidence.

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