AN EXAMINATION OF THE RAINFALL DISTRIBUTION OVER THE TARGET AREA OF THE COLORADO RIVER MUNICIPAL WATER DISTRICT'S WEATHER MODIFICATION PROGRAM

John Girdzus
Colorado River Municipal Water District

and

George W. Bomar
Texas Water Development Board

1. INTRODUCTION

Although the application of weather modification technology has become increasingly widespread in this country over the past ten to 15 years, the effects of cloud seeding remain a source of controversy. The arguments for and against weather modification have been as stormy as the necessary atmospheric conditions themselves. The findings from one fairly recent survey of weather modification programs in the United States indicate that precipitation from some types of cloud systems can be increased if the systems are treated properly (National Academy of Sciences, 1973). However, many questions remain unanswered. Also of great concern is the matter of what effect seeding of clouds in one area may have on modifying precipitation in areas downwind.

Research conducted cooperatively by the U. S. Department of the Interior, Bureau of Reclamation and the Texas Water Development Board during the period 1971-73 focused on the potential for hygroscopic and ice-phase seeding of convective clouds in western areas of Texas. The "San Angelo Cumulus Project," which was conducted during the summers of 1971-73 on the Edwards Plateau of Texas, indicated that the potential for dynamic ice-phase seeding was not encouraging but also suggested that opportunities for light silver iodide seeding should be relatively frequent (Smith et al., 1974). The series of experiments revealed that, although the number of individual cloud opportunities in that area is rather small, the potential for utilizing weather modification in the area could be increased substantially if further attention were devoted to the treatment of mesoscale cloud systems.

Since 1971 the Colorado River Municipal Water District has conducted a precipitation enhancement program within a 3500 mi^2 (9065 km^2) area of the Texas High and Low Rolling Plains (Figure 1). This cloud-seeding program has been designed to supplement surface water runoff into a number of reservoirs located within or near this region of West Texas.

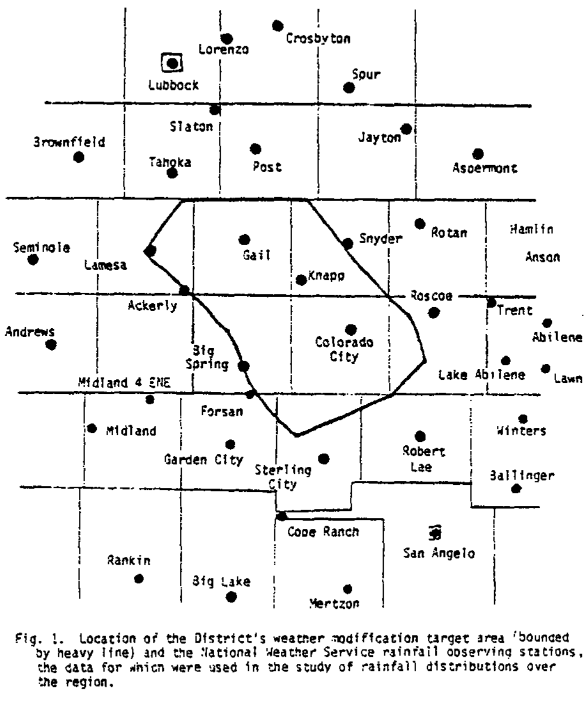

Fig. 1. Location of the District's weather modification target area (bounded by heavy line) and the National Weather Service rainfall observing stations, the data for which were used in the study of rainfall distributions over the region.

The region encompassing the District's cloud-seeding target area is partly in the Permian Basin of Texas. Mean annual rainfall over this region increases fairly uniformly from west to east, with Lamesa at the western end of the target area having an average annual rainfall of 16 inches and Maryneal at the eastern extremity having an average annual total of 22 inches.

Summertime thundershowers account for almost three-fourths of the mean annual rainfall total of the region. For this reason, it is quite common to find extremely high variabilities of monthly and annual precipitation amounts. For instance, the climatological history of Big Spring reveals that it has received annual rainfall totals varying from 4.68 inches to 34.25 inches during this century. The wet spring and summer seasons are usually characterized by a nearly continuous flow of warm, moist low-level tropical air from the Gulf of Mexico. Quite frequently during the wet season, cool air aloft creates sufficient instability to instigate scattered thunderstorms that often are moderate to heavy in intensity.

The District's cloud-seeding program incorporated the dispensation of silver iodide (AgI) into summertime convective cloud systems from an airborne platform. The program was in operation during the period April through October for each of the years 1971-75. The dispensing of the AgI was facilitated by flying an aircraft below cloud base, whereupon the AgI was released in the updraft regions of thunderstorm cells exhibiting, in the judgment of the project meteorologist, a potential for responding favorably to seeding. Light silver iodide seeding was performed on those clouds whose tops exhibited vertical growth and contained supercooled water. Seeding was not injected into cells which manifested dissipation or glaciation.

Prior to August, 1973 all seedable cells were treated. However, beginning in August, 1973 and continuing for the duration of the 1973 season, as well as all of the 1974 and 1975 seasons, randomized field experiments were carried out to accommodate an on-going evaluation of the District's program. The randomization scheme consisted of a 75 to 25 seed to no-seed ratio; that is, one fourth of all flares used in the program were of the "dummy" variety.

2. THE APPROACH

The aim of this paper is to present information on the rainfall distribution within and adjacent to the District's cloud-seeding target area during and prior to the time when the District's program was in operation. A survey of a limited nature such as this cannot provide conclusive evidence that either positive or negative effects on the occurrence of rainfall result from cloud seeding. However, it is hoped that this paper can provide information that can be useful in assessing the socio-economic worth of a cloud-seeding program and which can help to suggest what further studies would be worthwhile in identifying the potential of long range cloud-seeding programs as related to water resources management and planning.

Rainfall data utilized in this paper were obtained from first-order and cooperative weather observing stations of the National Weather Service (Figure 1). These data spanned the period 1935-75, and although the seeding program was in operation during the months of April and October each year, only the period May-September of each year was examined. There are a number of reasons for deleting the months of April and October in the analysis, the most significant being that the period May-September is more representative of the rainy season of this region of Texas. Also, during the period May-September, the meteorological conditions producing the rainfall are relatively more homogenious than other periods, so that the data can be treated in as nearly an unbiased fashion as possible.

To show the patterns of seasonal rainfall in the region of the High Plains considered in this study, the data have been presented both in map and tabular form for selected time periods. Isohyets were drawn on the maps to connect points having equal amounts of rainfall. An isohyetal analysis permits the use of interpolation for areas in which little or no data were available. The map analyses incorporate monthly rainfall data for 30 weather observing stations outside of the District's weather modification target area and six stations within it. The region surrounding the District's target area and encompassing the 30 stations will hereinafter be referred to as the "control area." When the study considers rainfall data for the period 1935-75, the number of stations within the control area having complete rainfall records for this time interval is limited to 11. Rainfall data for this same 41-year period are available for a total of eight stations within or bordering the target region.

3. RESULTS

When the mean rainfall totals for the months May through September over the period 1971-75 are plotted and analyzed, an area of maximum rainfall is observed in the area immediately east of the District's target area (Figure 2). In view of the fact that rainfall totals generally increase from west to east, a rainfall maximum would be expected to occur in the easternmost sector of the region under examination. However, in this instance, the area of rainfall maximum (greater than 19 inches) is limited to this sector and does not extend indefinitely eastward. Although the period May-September, 1971-75, was considerably wetter than normal, the most striking feature of this analysis is the bounded region of rainfall maximum just east of the target area.

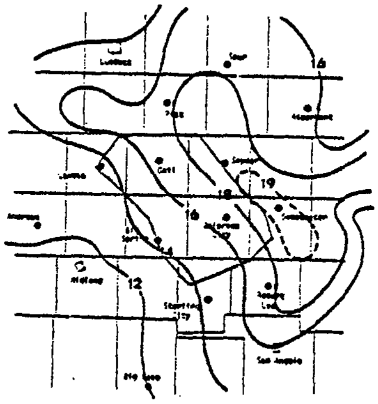

Fig. 2. Isohyetal pattern (in inches) for the period May-September, 1971-75.

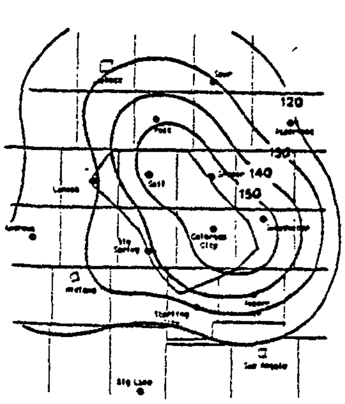

Fig. 3. Ratio (expressed as a per cent) of mean rainfall totals for the period May-September, 1971-75 to those for the period May-September, 1935-70.

When the rainfall totals for the five years of cloud seeding are compared with what is commonly regarded as "normal," i.e. in this instance, the arithmetic average of rainfall totals for the period May-September, 1935-70, the peculiarity of this particular rainfall distribution becomes even more prominent (Figure 3). The location of the greatest departures from normal are essentially synonimous with the District's target area.

Whenever individual cloud-seeding seasons during this 5-year period are considered, the area of maximum rainfall is observed to shift appreciably. During the warm season of 1975, greatest 5-month rainfall totals occurred almost entirely within the weather modification target area (Figure 4). Considering the whole region being examined, the 1975 seeding season was the wettest of the five, with points both east and west sustaining rainfall totals three to five inches above normal. Over most of the target area, however, 5-month totals were seven to ten inches above--or nearly double--the normal amount.

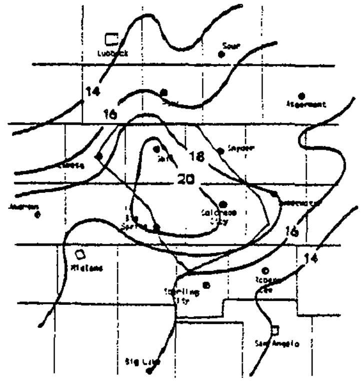

Fig. 4. Isohyetal pattern (in inches) for the period May-September, 1975.

The number of opportunities for seeding clouds, as judged by the project meteorologist, varied greatly during the 5-month operational period (Table 1). Earlier years of the 5-year period appeared to be the most active, while in 1974, atmospheric conditions much of the time were such that relatively few seeding missions were warranted. The warmest months, July and August, were also the most active in terms of number of seeding flights conducted.

Table 1. Number of cloud-seeding missions performed during 1971-75.

	1971	1972	1973	1974	1975	Total
May	14	7	7	3	5	36
June	9	10	9	2	3	33
July	2	9	14	3	13	41
August	7	12	10	6	6	41
September	3	4	5	0	1	13
Total	35	42	45	14	28	164

In 1973, the most active in terms of number of missions flown, the rainfall maximum for the region lies immediately southeast of the target area (Figure 5). The distribution of rainfall for the May-September period of this particular year resembles that of the 5-year seasonal mean (Figure 2), except that the axis of maximum rainfall extends from just east of the target area north and then westward over the central section of the target area. Intrusions of rainfall minima into the area of study can be seen to the southwest and northeast of the District's target area.

By contrast, in 1974, when the fewest number of flights for the period May-September was conducted, rainfall maxima lay to the south and southeast of the target area (Figure 6). In fact, the westernmost part of the target area was characterized by a rainfall minimum. The axis of rainfall minimum extended across the midsection of the District's target area. It is noteworthy that the month during which the most seeding missions were flown--July--was also the wettest month of the 1973 operational season at several points within the target area. This latter statistic, however, may be more an indicator of the presence of more "seedable" thunderstorms, rather than an increase in rainfall due to more frequent cloud seeding.

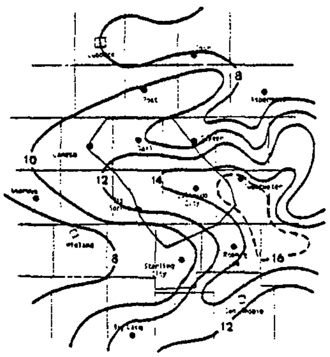

Fig. 5. Isohyetal pattern (in inches) for the period May-September, 1973.

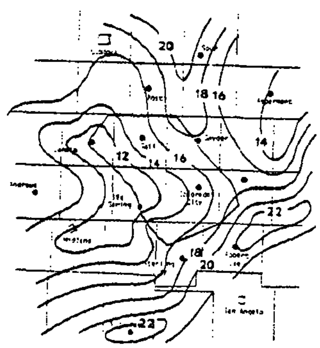

Fig. 6. Isohyetal pattern (in inches) for the period May-September, 1974.

The displacement of the area of maximum rainfall southeast of the District's target area introduces the subject of downwind effects of weather modification activities. The question arises that, if seeding with silver iodide enhances the capability of a convective cloud system to produce rain, could the effects more readily be observed downwind rather than in the intended target area? Although a rigorous treatment of this matter is beyond the scope of this paper, an observation or two on the relationship between rainfall occurrence and prevailing wind over the region will now be made.

Laboratory experiments have suggested that silver iodide dispensed during the daytime into a convective-type cloud has a life-span of at least an hour (Hess, 1974). Indeed, sunlight seems to require from one to several hours to destroy the nucleation effectiveness of silver iodide.

It has been the experience of the District's project meteorologist that the measurement at the 500-millibar level of the prevailing wind over the study region is the best indicator of the direction and speed which cloud systems assume as they migrate into and out of the target area. Using 500-mb wind data collected at the National Weather Service observatory at Midland for 1200Z during the period May-September, 1972-74, as an indication of the prevailing wind over the target area at that level, the mean 500-mb wind is observed to emanate from the southwest, west, or northwest more than half of the time during the period May-September (Figure 7). Consequently, if the 500-mb wind is indeed a steering mechanism, cloud systems migrating over the target area would move into the general area of rainfall maximum shown in Figure 2. Obviously, the rate of movement of these cloud systems, as well as the strength of the individual cells within them, would dictate whether or not these cells, some of which may have been seeded, would reach the region of rainfall maximum.

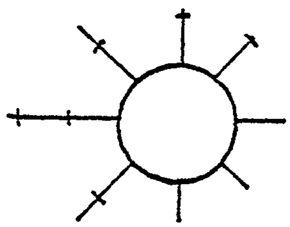

Fig. 7. Wind rose for Midland, Texas showing the frequency of observed 500-mb wind from eight compass directions for the period May-September, 1972-74 (each emanate is graduated in tens of percent).

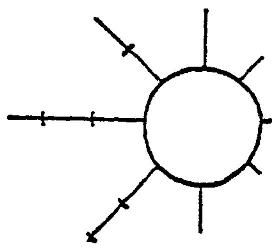

Fig. 8. Wind rose for Midland showing the frequency of observed 500-mb wind from eight compass directions for the period August-September, 1972-74 (each emanate is graduated in tens of percent).

A month-by-month breakdown of the prevailing wind over the District's target area at 500 mb reveals that, in May, August, and September, wind speeds at this level are greatest and the wind direction ranges from northwest to southwest (Figure 8). Therefore, clouds which produce much of the season's rainfall may well reach and even drift beyond the region of maximum rainfall shown in Figure 2. In the warmest months (July and August), wind direction is typically erratic and wind speed light such that many treatable cloud systems move erratically, and hence, unpredictably.

To better examine the downwind effects of weather modification activities, it should be added here that a test-case approach seems to be the most meaningful and convincing method of analysis; in this way, individually

Table 2. Comparison between precipitation totals observed at stations within and outside of the target area.

Station	Mean Total for Seeded Period May-September (1971-75)	Mean Total for Unseeded Period May-September (1935-70)	Departure from Normal (in percent)
Within target area			
Ackerly	13.91	9.41 1/	+48
Big Spring	14.78	11.05	+34
Colorado City	16.05	10.84	+48
Gail	16.83	10.72	+57
Knapp	19.12	10.77	+78
Lamesa	14.68	10.65	+38
Roscoe	19.12	12.11	+58
Snyder	18.41	11.84	+55
MEAN	16.61	10.92	+52
Outside target area			
Abilene	15.61	13.18	+18
Aspermont	15.88	12.86	+23
Ballinger	15.24	12.75	+20
Cope Ranch	13.32	9.46 1/	+41
Garden City	13.01	9.77	+33
Lawn	15.85	12.88 1/	+23
Lubbock	14.38	11.35	+27
Midland	10.48	8.48	+24
Post	17.72	12.01	+48
Seminole	13.09	10.80	+21
Sterling City	14.40	11.33	+27
MEAN	14.45	11.35	+27

1/ Data are for the period 1940-70.

treated clouds could be tracked and their behavior monitored to satisfactorily measure the temporal and spatial extent of their reaction to silver iodide.

Another way to view the rainfall observed over the target area in comparison with that of the control is given in Table 2. Like the map analyses, the control area, as well as the target area, sustained rainfall significantly greater than normal. A more interesting aspect of this tabulation, however, is that the percent departures from normal are significantly higher for the target area than for the control area. Furthermore, the values of percent departure from normal increase significantly in a west to east direction over the target area while the values of percent departures from normal in most of the control area are nearly constant. As stated previously, this west to east increase may be related both to cloud movement within the target area and to the time required after AgI is dispensed at cloud base before the seeding material becomes active.

For the five years during which the cloud-seeding program has been in operation, the eight stations within the target area show a mean increase in rainfall of 52 percent; the 11 control area stations show a mean rainfall increase of only 27 percent. In other words, if these 19 stations, spaced rather uniformly over the target and control areas, can be regarded as representative of these two regions, the seeded area received nearly six inches of rainfall above normal compared to the unseeded area's 3.10 inches.

To examine further the historical trend in rainfall in this region of Texas, past rainfall records of 19 stations were tabulated (Table 3). These were blocked into 5-year groups starting with the 1971-75 period and reverting back in sequence to the period 1936-40. The data were computed in the same manner as that used in preparing Table 2.

The data of Table 3 show that wetter periods have occurred at times previous to the seeded period at stations located in the control areas (e.g. Midland, 1941-45; Lubbock, 1941-45), as well as the target area (e.g. Gail, 1961-65, Snyder, 1941-45). However, all eight of the target area stations received more rainfall during the seeded years than for any other 5-year period on record after 1941. For example, the rainfall total of 157 percent of normal at Gail for 1971-75 is 18 percent more than that observed during any other 5-year period at that station. The same is not true for most stations in the control area.

Table 3. Departure from normal (in percent) of mean precipitation totals for the period May-September for the years 1936-1975.

	1971-75	66-70	61-65	56-60	51-55	46-50	41-45	36-40
Within target area								
Ackerly	+48	0	+1	-10	-16	+7	+21	M
Big Spring	+34	-4	-11	-13	-22	-11	+28	+39
Colorado City	+48	-10	+39	+6	-9	-13	M	M
Gail	+57	-2	+28	-39	-39	M	-12	+5
Knapp	+79	-7	+22	-27	-20	+2	+19	-9
Lamesa	+39	+9	-17	-16	-27	-13	+24	-1
Roscoe	+58	+15	+22	-3	-23	-13	+28	-13
Snyder	+55	-11	+5	-8	-41	+9	+29	M
Outside target area								
Abilene	+18	+9	+27	-2	-21	-8	+15	+14
Aspermont	+24	-9	+36	-13	-25	+9	-5	-9
Ballinger	+18	+7	-9	-11	-20	-10	+3	-12
Cape Ranch	+41	+3	+12	-16	-38	-1	+26	M
Garden City	+33	+2	+15	-25	-49	+1	+25	+15
Lawn	+23	+6	+25	-6	-9	-17	-1	M
Lubbock	+27	+21	+6	-3	-18	+1	+33	+10
Midland	+24	-3	+4	+20	-38	-8	+28	+13
Post	+48	+3	+9	-5	-30	+7	+7	+2
Seminole	+24	+8	+6	-24	-20	+11	+15	+4
Sterling City	+27	0	+18	-25	-32	0	+18	+16

4. CONCLUDING REMARKS.

An analysis of available data discloses that for the 5-year period 1971-75, the target area of the District's weather modification program received more rainfall than any other similar 5-year period since 1935. Indeed, rainfall over the target area during the seeded years was at least double that observed during any other similar 5-year period during the years 1935-70. Furthermore, rainfall increases in the target area during the seeded years were 17 percent greater than those of the control area for the same time period.

Although the findings of this examination show that rainfall over the target area has been increased to a greater degree than that of adjacent areas, it cannot be said with certainty that these increases are directly related to the seeding of cumulus clouds. A more substantive analysis would require a greater data resource, as well as the utilization of more sophisticated statistical analytical procedures.

5. ACKNOWLEDGMENTS

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