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EFFECTS OF HAIL SUPPRESSION ON RAINFALL IN THE TEXAS HIGH PLAINS

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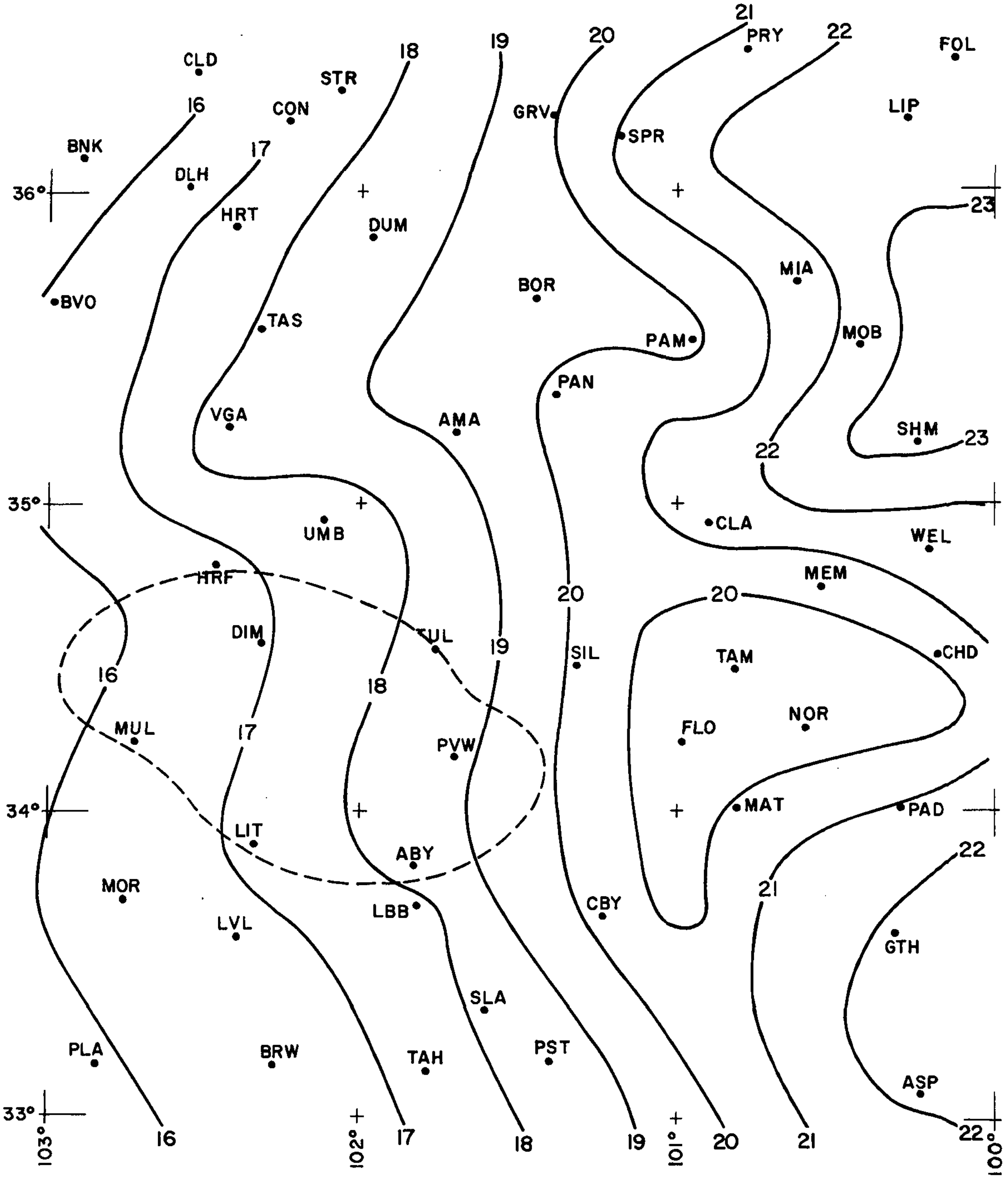
INTRODUCTION

Hail damage to agricultural crops and property in the Panhandle and South Plains of Texas has long been recognized as a major influence on the total economy of the State. Because of the high damage risk to crops, a number of farmers in Hale County organized in 1970 to sponsor a project designed to reduce the occurrence of hail by seeding clouds from aircraft. Three years later farmers in adjacent Lamb County launched a similar program. The two groups coordinated their operation to prevent duplication. Precise boundaries of the target area were modified each year in accordance with the amount of land under cultivation by the contributors (Henderson, 1976). Beginning in 1974 and continuing in 1975 and 1976 the target area included all of Hale County and portions of Castro, Swisher, Floyd, Lubbock, Parmer, Lamb, and Hockley counties. Approximate boundaries of the target area in 1976 are shown by dashed contours in Figure 1.

The operation consisted of locating potential hail producing clouds by means of a ground-based radar and guiding a seeding aircraft to the storm before it reached hail stage. The aircraft released silver iodide particles in various concentrations at cloud base. Theoretically, the silver iodide rises in the cloud to the freezing level where it serves to nucleate the formation of countless ice crystals, which consume the available water before it is able to form large hail stones.

Preliminary results from analysis of the hail data from this program (Henderson and Changnon, 1972) suggest that hailfall was considerably more severe adjacent to the operational area than within the operational area itself. In a more recent evaluation based upon the 1970 to 1973 period, Changnon (1975) reported that most of the data examined strongly suggest that hail suppression was successful. However, an analysis of hail and cotton-loss data by Scoggins (1975), based upon the same period of record, does not indicate a significant effect on hail damage due to the cloud seeding.

Early in the program, interest shifted from the effectiveness of the seeding in reducing hail to the question of whether or not the suppression activities may have inadvertently modified the amount and distribution of rainfall. It is this question regarding rainfall that the present research has considered. Scoggins (1975) has shown that the period from 1970 to 1973, on the whole, received less rainfall than the preceding 4-year period. However, this reduction occurred in both seeded and non-seeded regions. No significant difference in the observed rainfall between the two regions was detectable.



MEAN ANNUAL PRECIPITATION

FIGURE 1

RAINFALL ANALYSIS

The region being investigated, shown in Figure 2, is part of the largest level plain of its kind in the United States. The climate is semi-arid with desert conditions to the west and humid subtropical conditions to the east and southeast. Several dominant macroscale systems account for most of the rainfall observed (Scoggins, 1975). The seasonal variation of rainfall may be due to: (1) the orientation of the general low-level wind flow with respect to the Gulf Coast; (2) the position of the upper atmospheric jet stream with respect to latitude; (3) the invasion of the polar air masses from the Arctic during much of the year; and (4) the presence of a variety of mesoscale systems, many of which are generated from convective heating in the warmer seasons of the year.

Figure 1 shows the distribution of mean annual precipitation for the 30-year period 1944 to 1973 (Haragan, 1978). It is apparent that rainfall decreases from east to west, although not at a uniform rate. Peak rainfall generally occurs in the late spring and early summer which is also the season of maximum hail occurrence. Approximately 43% of the average annual precipitation falls during the 3-month period, May through July, while 72% falls during the 6-month period, April through September (Haragan, 1976). The 5-month period, November through March, is a dry season as colder and drier polar air masses move southward cutting off the flow of warm moist air from the Gulf of Mexico.

Figure 3 shows the annual distribution of precipitation for three stations representative of the area (Haragan, 1978). The curves represent 7-day averages for the total period of record at each station. Two of the stations are outside the target boundaries, but Plainview was within the target area for the entire 7-year seeding period. Each station reflects the spring and summer maximum previously described.

The variability of annual precipitation is shown by Figure 4. The curve represents annual precipitation averaged over space and time. Time averaging involves 5-year running means beginning before the turn of the century. Space averaging is over nine stations: Amarillo, Crosbyton, Dalhart, Lamesa, Lubbock, Miami, Plainview, Post and Snyder. The natural variability of annual precipitation is large, because most precipitation is the result of scattered shower and thunderstorm activity which depend upon daytime heating, low-level moisture and an absence of subsidence aloft. Rainfall during a single month has varied from zero to twelve inches. This extreme variability in "natural precipitation" is relevant to the present investigation and is a source of uncertainty in all of the analyses.

RAINFALL PATTERNS DURING HAIL SUPPRESSION

The hail suppression program was operated from April through October, 1970-1976. The data employed in this investigation consist of the monthly rainfall totals from 52 cooperative reporting stations coordinated by the National Weather Service. The data have been analyzed for the seeding period, 1970 through 1976 and for the historical period, 1944 through 1969.

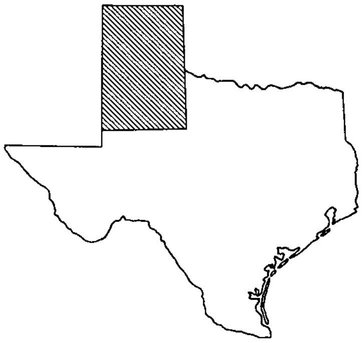


FIGURE 2.
Study Area (Hatched)

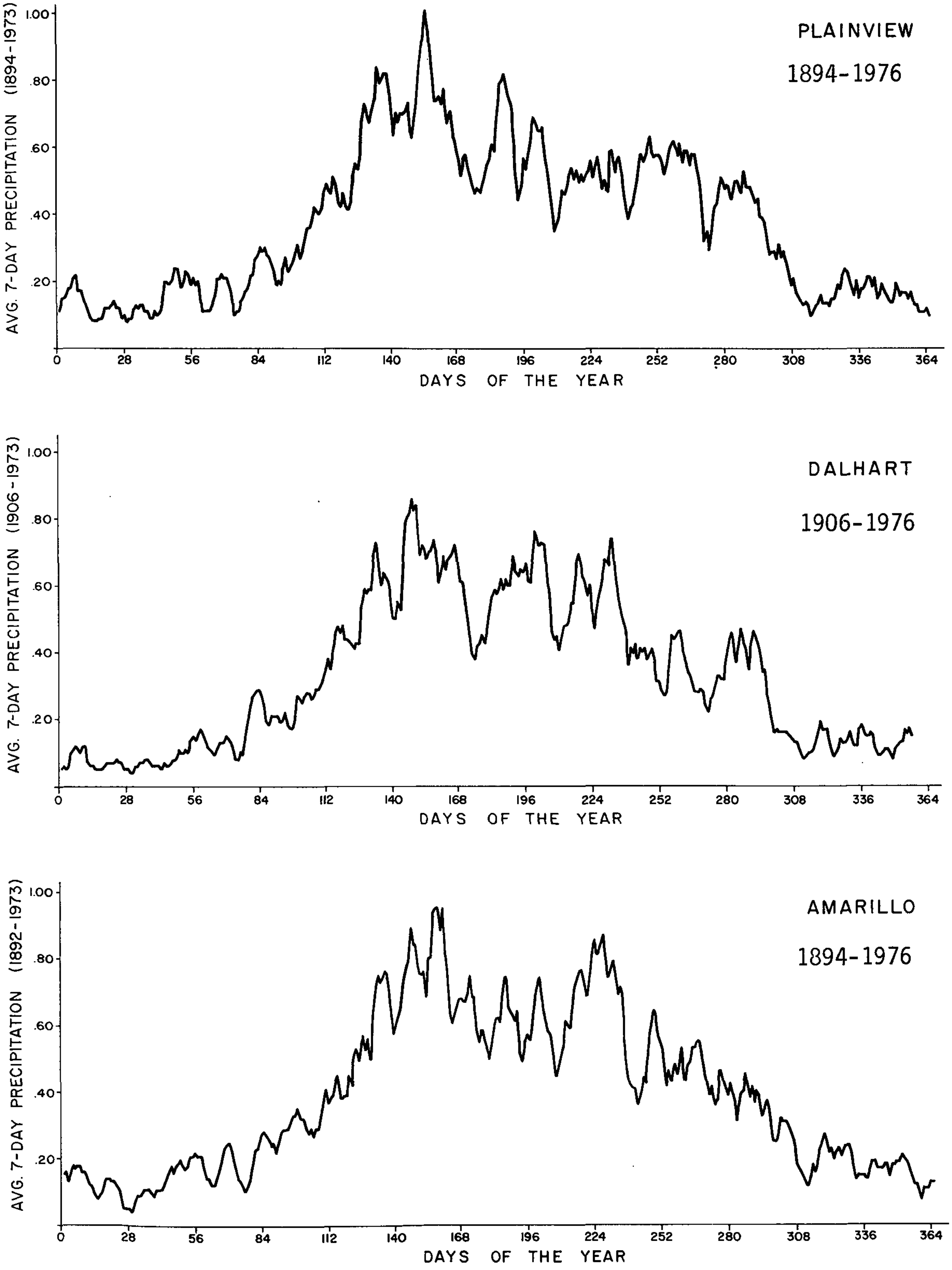
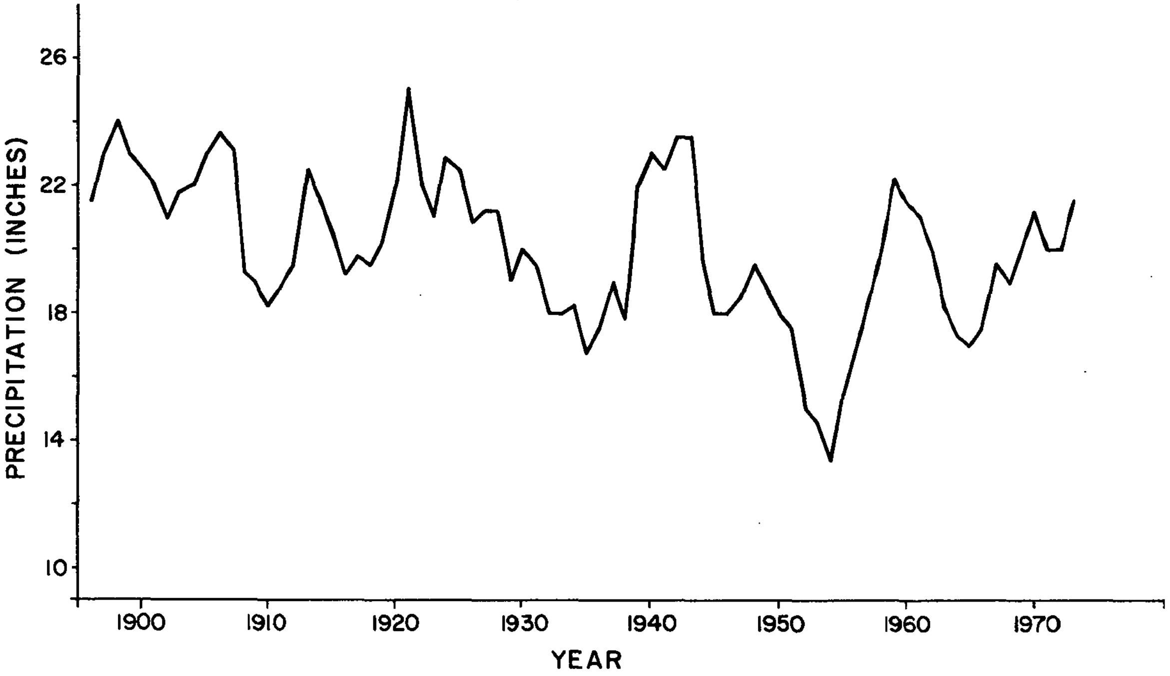


FIGURE 3.

SEVEN DAY MOVING AVERAGES OF PRECIPITATION



TIME SERIES OF ANNUAL PRECIPITATION

FIGURE 4.

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Stations chosen to represent the target area were Dimmitt (DIM), Littlefield (LIT), Abernathy (ABY), Tulia (TUL), and Plainview (PVW). As indicated previously, precise boundaries of the target area varied from year to year, but on the average these five stations are representative. The remaining 47 stations were used as "control stations". Littlefield, Abernathy and Tulia are on the target boundaries during most of the project, while Dimmitt was on the boundary prior to 1974. No other stations with sufficiently long periods of record could be found within the target area.

In certain months and areas the average rainfall was less during the seeded period than during the historical period. In other months and areas, average rainfall during the seeded period was greater. Table 1 shows the percent of average rainfall (1944-1969) which fell during the seeding years (1970-1976). The percentage is shown for each target station and month under consideration. In addition, the average percentage is shown for both the target area and the surrounding control area (all stations outside the target area). As an example, Plainview received 68% of its expected precipitation in June during the seeding years. Overall, the target area and the control area each received 74% of expected precipitation during the period. The percentage of expected rainfall was also the same inside and outside the target area in May. During July, target area rainfall was 101% of expected while the control area received only 89%. August and September were wet during the seeding period. In both instances the control area received slightly more rainfall on a percentage-of-normal basis than the target area. Overall, the target area received 106% of its expected rainfall compared to 108% for the control area. If August and September are neglected, the average percentage rainfall for May, June and July is 82% of expected in the target area and 78% of expected outside the target area.

The period from 1944 through 1976 can be divided into 27 continuous 7-year intervals (i.e. 1944-50, 1945-51, etc.), the last of which (1970-76) corresponds to the cloud-seeding period. Table 2 shows the ranking of the 1970-76 period compared to the other periods for 23 stations both inside and outside the target area during the month of May. A "1" indicates that the seeding period was the driest 7-year period since 1944, a "2" the second driest and so on. The 7-year seeding period was the driest 7-year period since 1944 at Plainview and ranked as the second driest at Abernathy and Dimmitt. The seeding years ranked seventh and eleventh respectively at Tulia and Littlefield. At 7 of the 18 stations outside the target area the 7-year seeding period was the driest since 1944 and among the three driest periods at 11 stations ranging from Hartley to Tahoka. Thus, while May was a dry month within the target area during the seeding years, it was similarly dry throughout the Panhandle and South Plains region. It is difficult to attribute this large-scale drought to hail suppression designed to affect only a small portion of the total area. Rather, the reduction in rainfall during the seeding years appears to be another of the random fluctuations that characterize the long-term climatology of the area.

Figures 5 through 9 illustrate the percentage of average rainfall (1944-69) which fell during the seeding period for each of the months of May through September. Figure 10 represents the average percentage rainfall over all five months. It is apparent that precipitation is much below normal

Table 1. Percentage of Average Precipitation During Seeding Years

Station	May	June	July	August	September	Average
Dimmitt	66	90	86	122	145	102
Littlefield	99	88	106	141	168	120
Abernathy	65	66	123	162	183	120
Tulia	73	56	91	101	137	92
Plainview	58	68	100	138	106	94
Target Area Average	72	74	101	133	148	106
Control Area Average	72	74	89	149	155	108

Table 2 Ranking of Seeding Years for 7-Year Average Precipitation (May)

Abernathy	2
Plainview	1
Tulia	7
Littlefield	11
Dimmitt	2 (tie with 1964-70)
Hartley	1
Dumas	3
Tascosa	7
Borger	1
Amarillo	5
Panhandle	6
Vega	1
Hereford	1
Umbarger	1
Morton	3
Levelland	1
Plains	12
Lubbock	2 (tie with 1959-65)
Tahoka	1
Brownfield	13
Crosbyton	6
Slaton	7
Post	2

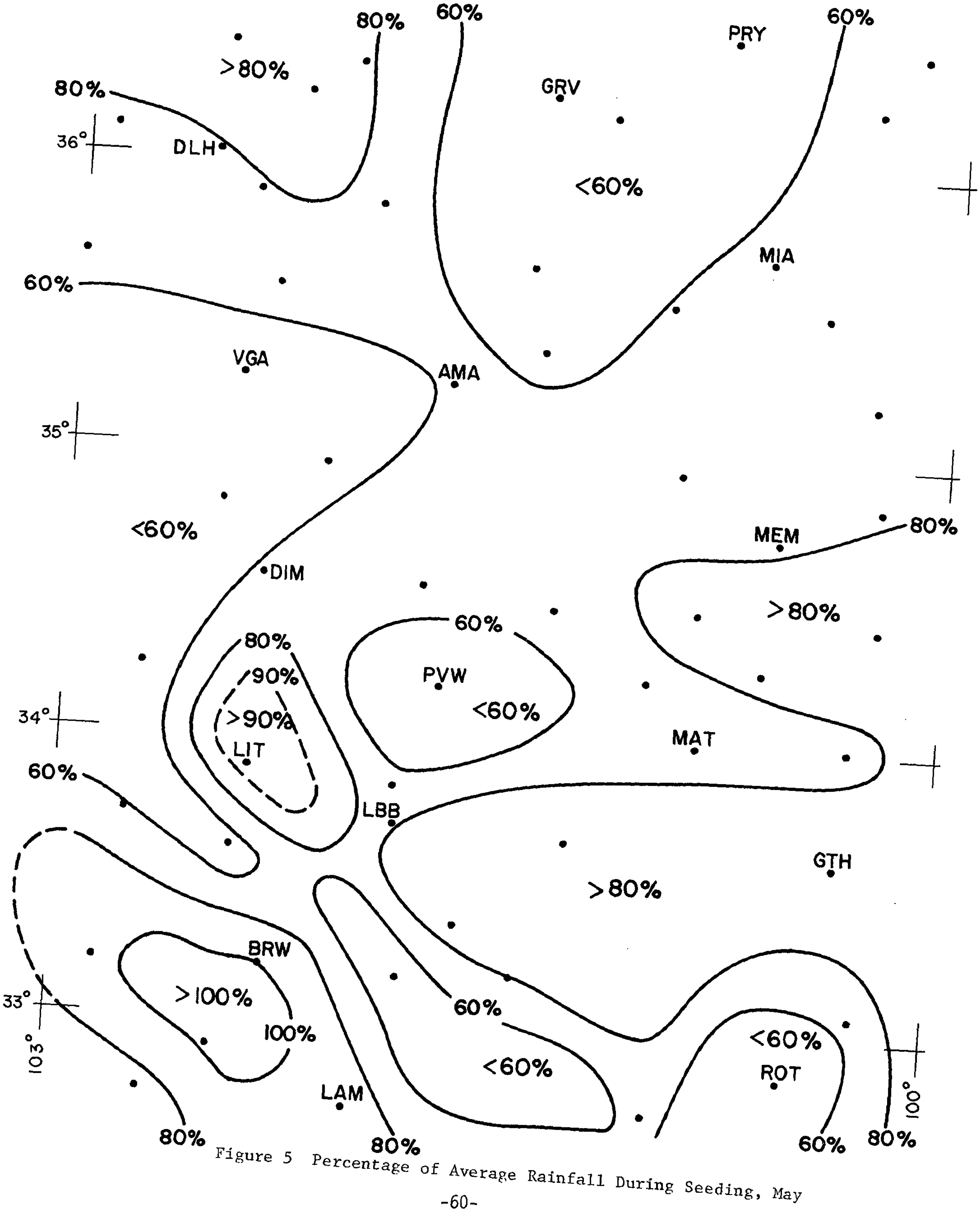

Figure 5 Percentage of Average Rainfall During Seeding, May

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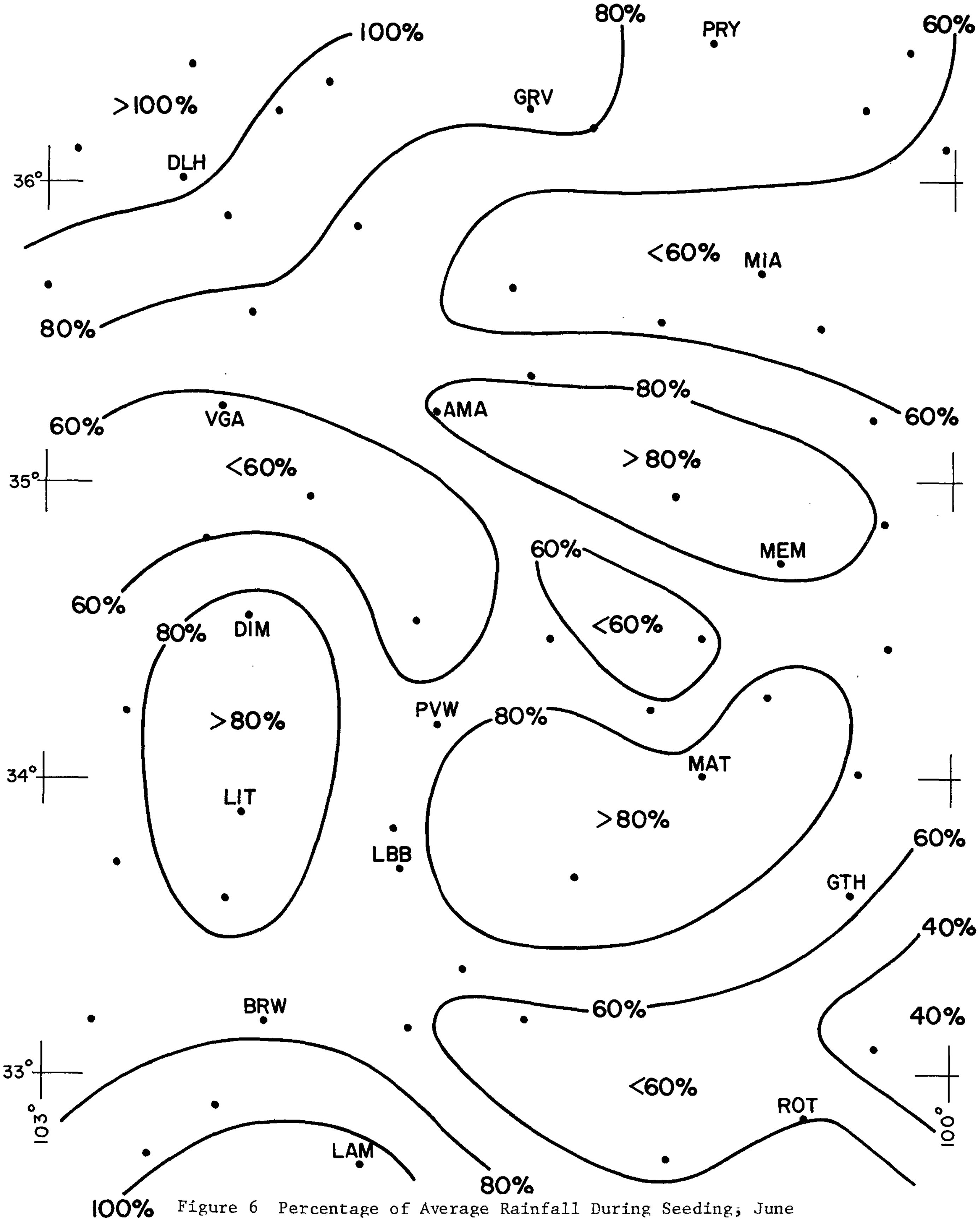

Figure 6 Percentage of Average Rainfall During Seeding, June

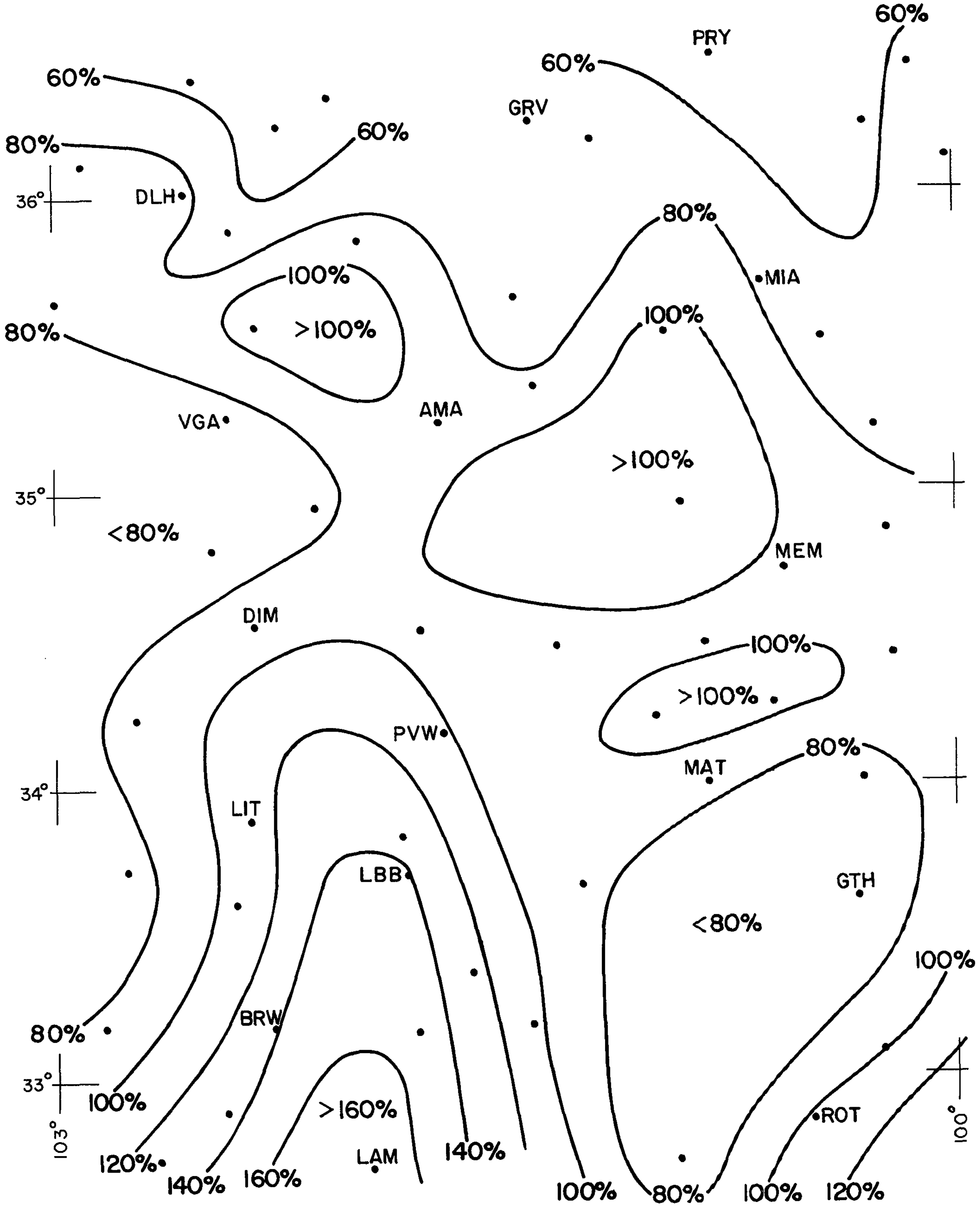

Figure 7 Percentage of Average Rainfall During Seeding, July

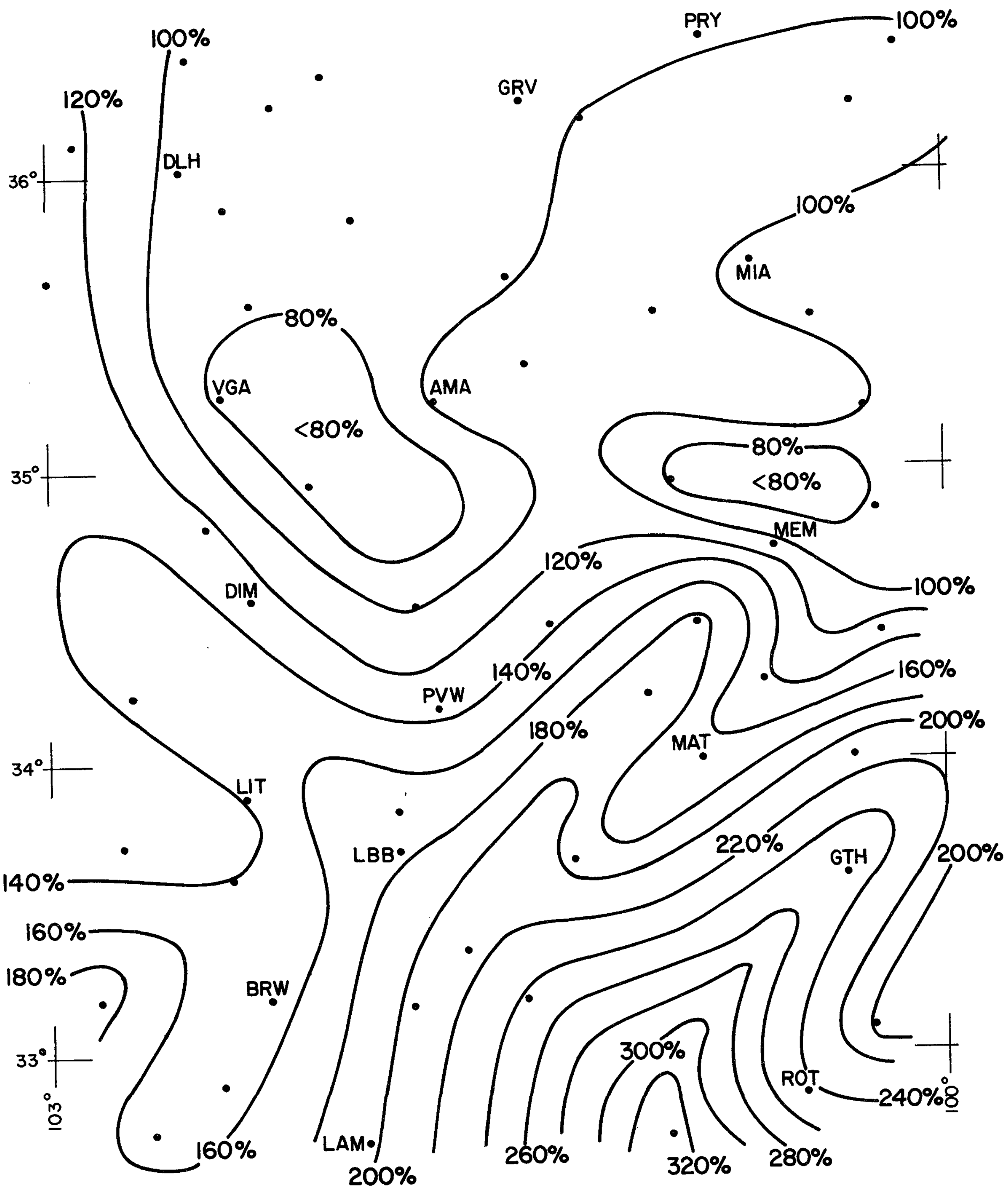

Figure 8 Percentage of Average Rainfall During Seeding, August

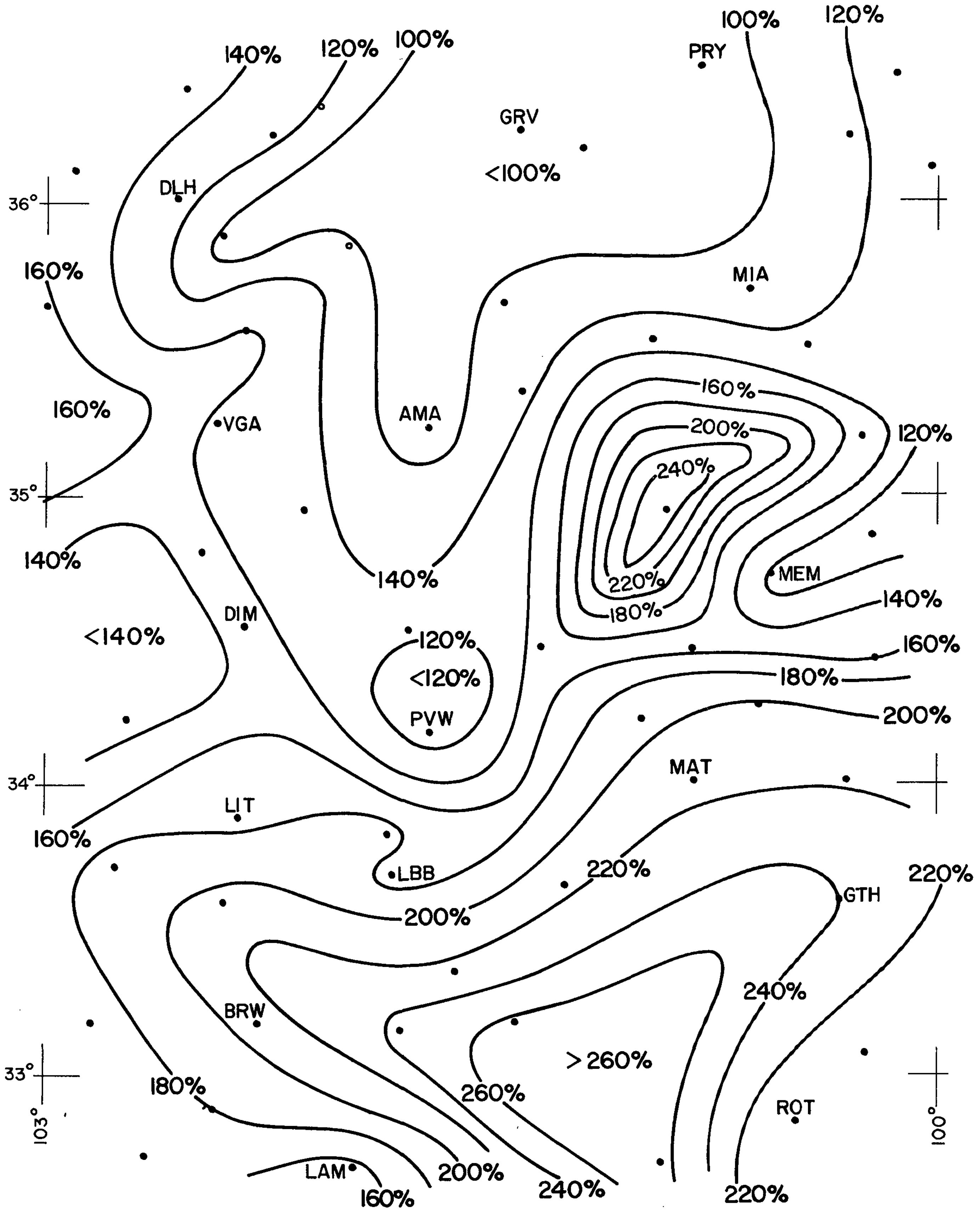

Figure 9 Percentage of Average Rainfall During Seeding, September

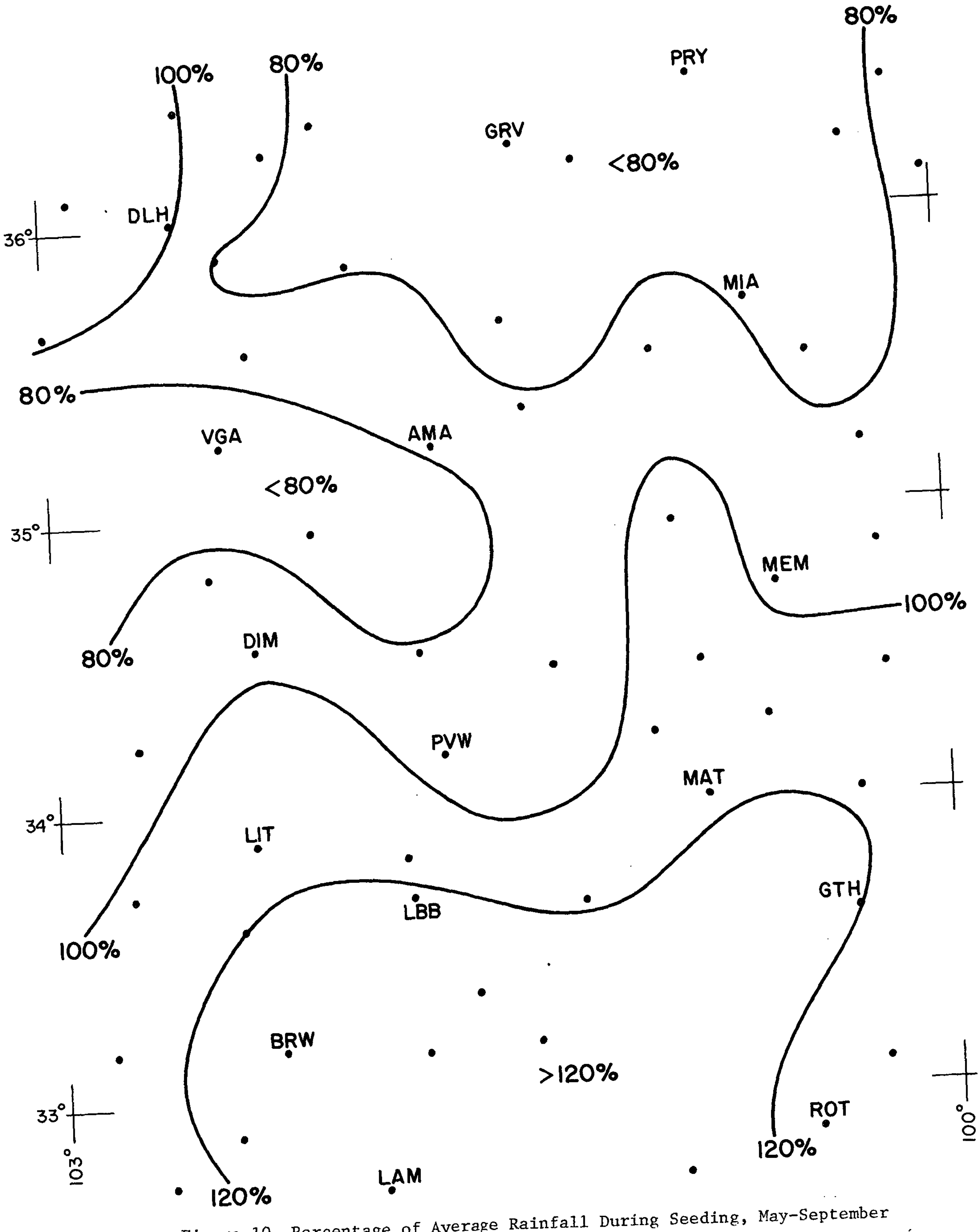

Figure 10 Percentage of Average Rainfall During Seeding, May-September

for the months of May and June. This is true for the entire Panhandle - South Plains region, however, and is not limited to the target area. As an example, Plainview, which is within the target area, received less than 60% of average rainfall during the seeding years in May. However, another area between Amarillo (AMA) and Perryton (PRY), well outside of the target area, also received less than 60% of expected rainfall. In June, several areas outside of the target area received a smaller percentage of their expected rainfall than stations within the target zone. This is true also of July, August and September, months during which the target area received rainfall equal to or above the expected amount based upon the historical record.

A rainfall gradient from west to east across the target area is evident in Figure 5 for May and to a lesser extent in Figure 6 for June. During May, Littlefield (LIT) received more than 90% of expected rainfall during the seeding period while Plainview (PVW) received less than 60%. While there is no evidence that this gradient is related to cloud-seeding, it is a possibility that should be investigated further, particularly since the dry area in the eastern portion of the target area is the region in which cloud seeding operations have been underway for the longest period of time.

MULTIPLE REGRESSION ANALYSIS

Information from the preceding analyses has been used to determine whether the seeded mean rainfall is greater or less than expectation. The next question to be addressed is: "Are the seeded means sufficiently greater or less than expectation to be significant?" To answer this question, the correlations between target and control-area stations were investigated (Haragan, 1976). The correlations were generally high during the historical period and it was decided to use prediction equations to estimate the amount of rainfall expected in the target area during the seeded period. In an earlier study using only four years of data, Schickedanz (1974) concluded that precipitation in the target area did not depart significantly from expectation.

The prediction equations were multiple regression equations of the form

$$\hat{P}_t = A + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5.$$

where $\hat{P}_t$ is the estimated precipitation in the target area during the seven seeding years for May. The month of May was selected because of the higher target-control area correlations during this month of the year (Haragan, 1976).

The five predictors were the average May precipitation during the seven seeded years at the following stations:

X_1, Borger (BOR), Amarillo (AMA), and Panhandle (PAN);

X_2, Plains (PLA), Brownfield (BRW), and Tahoka (TAH);

- X_3, Crosbyton (CBY) and Lubbock (LBB);
- X_4, Morton (MOR) and Levelland (LVL);
- X_5, Hereford (HRF), Umbarger (UMB) and Vega (VGA).

The partial regression coefficients B_1, B_2, B_3, B_4 and B_5 were derived from data during the historical period, 1944 through 1969 and refer to areas 1, 2, 3, 4 and 5 respectively. The observed target area rainfall was taken to be the average precipitation for Dimmitt(DIM), Tulia (TUL), Plainview (PVW), Abernathy (ABY) and Littlefield (LIT).

Several different regression models were used based upon different sub-sets of predictors. Results for the different models are shown in Table 3.

Table 3 Results of Regression Analysis

Model	Predictors	Predicted Rainfall ($\hat{P}_t$) (Inches)	90% Confidence Limits (Inches)	Observed Rainfall (Inches)
A	$X_1X_2X_3X_4X_5$	1.73	1.36 - 2.09	1.89
B	$X_1X_2X_3X_4$	1.74	1.39 - 2.10	1.89
C	$X_1X_2X_3$	1.78	1.43 - 2.13	1.89
D	$X_1X_2X_3X_5$	1.74	1.37 - 2.11	1.89

The confidence intervals define the acceptance region of the hypothesis that there was no effect of seeding in the target area. Since the observed value falls within the confidence region for each of the models, we cannot reject the hypothesis.

To investigate the possibility that seeding redistributed the rainfall, prediction equations were used to estimate rainfall in selected sub-regions of the target area. Four sub-regions were defined. The Western region included Dimmitt and Littlefield, the Eastern region was Tulia, Plainview and Abernathy, the Southern region was Littlefield and Abernathy and the Northwestern region was Dimmitt alone. Results of these predictions are given in Table 4.

The observed precipitation is outside the 90% confidence limits for the Western region. This means we reject the hypothesis that seeding did not affect rainfall and accept the possibility that the above-expected precipitation in the Western region was due to seeding. The observed rainfall in the Southern region is also beyond the 90% confidence limits for two of the models. Once again we reject the hypothesis that seeding did not affect the greater than expected rainfall. It should be noted, however, that the Western and Southern regions have the Littlefield station in common. The above-average rainfall for both regions was dominated by Littlefield. Precipitation for the Northwestern region (Dimmitt only) is within the 90% confidence interval. Thus, the abundant rainfall at Littlefield can explain the positive departures for the Western and Southern regions. The models do an excellent job of predicting rainfall in the Eastern and Northern regions. In no case is the observed rainfall less than the lower boundary of the

Table 4 Regression Analysis for Sub-Regions

Region	Model	Predicted Rainfall	90% Confidence Limits	Observed Rainfall
Western	A	1.56	1.23 - 1.88	1.96
	B	1.57	1.26 - 1.88	1.96
	C	1.60	1.29 - 1.91	1.96
	D	1.56	1.24 - 1.89	1.96
Eastern	A	1.84	1.39 - 2.28	1.84
	B	1.86	1.43 - 2.28	1.84
	C	1.90	1.47 - 2.33	1.84
	D	1.85	1.41 - 2.30	1.84
Southern	A	1.72	1.30 - 2.14	2.17
	B	1.84	1.39 - 2.29	2.17
	C	1.87	1.43 - 2.30	2.17
	D	1.72	1.31 - 2.13	2.17
Northwestern	A	1.38	1.20 - 1.57	1.37
	B	1.33	1.04 - 1.62	1.37
	C	1.36	1.06 - 1.66	1.37
	D	1.34	1.09 - 1.71	1.37

confidence interval.

There are three potential problems associated with the regression procedure used above. These are the requirements for the data to be normally distributed, the possibility that rainfall in the control areas is also affected by seeding, and the possibility that five target-stations selected are not representative of the target area. Schickedanz (1974) employed the Kolmogorov-Smirnov goodness of fit test to show that the distribution of precipitation data in the area was Gaussian. The possibility of seeding effects outside the target area must be investigated further, but it is unlikely that regions which are generally upwind of the target such as areas 2, 4 and 5 would be affected. The problem of a non-representative sample within the target area is potentially serious and should be carefully considered. An attempt is presently underway to acquire additional, unpublished rainfall data in the target area.

SUMMARY AND CONCLUSIONS

During the seeded period, 1970 to 1976, rainfall was below normal during May and June throughout the Texas Panhandle and South Plains. During July, rainfall was below normal in the Panhandle increasing to above normal in the southwestern portion of the South Plains. During August and September precipitation was above normal for most of the regions. There are no apparent differences between the average observed rainfall inside the target area and that in the surrounding control area. During May the 7-year seeding period was the driest 7-year period since 1944 at eight stations in the area, only one of which was within the target boundaries.

Considering the entire target area, observed precipitation during May is greater than expected based upon the regression models, but the difference is not statistically significant. In the western and southern sub-regions of the target area, the models indicate statistically significant positive departures in rainfall, while the eastern portion shows observed rainfall equal to that predicted by the model.

The rainfall gradient from west to east across the target area is reflected by the analyses showing percentage-departures from normal. This pattern of greater-than-expected rainfall in the west coupled with a rapid downwind decrease in precipitation should be investigated in more detail. Resolution in these analyses is not sufficient to pursue the idea of a rain-shadow effect due to seeding, but this possibility should not be overlooked. As indicated previously, observations in the target area are far from adequate. The possibility that the stations used in the research are not representative of the target area is very real. It is also possible that down-wind effects may extend to regions outside the control area being studied. Further investigation is warranted.

Subject to the above limitations, it is concluded that total precipitation in the target area was not affected by cloud seeding for hail suppression. While the possibility of a redistribution of rainfall remains, there is no indication of a decrease in total rainfall due to cloud seeding in any of the areas or sub-areas investigated.

ACKNOWLEDGEMENTS

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