Stith, J.L., D.A. Griffith, R.L. Rose, J.A. Flueck, J.R. Miller, Jr., and P.L. Smith, 1986: Aircraft observations of transport and diffusion in cumulus clouds. J. Clim. Appl. Meteor., 25, 1959-1970.

Stone, R.H., and A.W. Huggins, 1996: The use of trace chemistry in conjunction with ice crystal measurements to assess wintertime cloud seeding experiments. Preprints of Thirteenth Conference on Planned and Inadvertent Weather Modification, Atlanta. American Meteorological Society, Boston, 136-141.

Super, A.B., 1974: Silver iodide plume characteristics over the Bridger mountain range, Montana. J. Appl. Meteor., 13, 62-70.

Super, A.B., 1990: Winter orographic cloud seeding status in the intermountain west. J. Wea. Mod., 22, 106-116.

Super, A.B., 1995: Case studies of microphysical responses to valley-releasedoperational AgI seeding of the Wasatch Plateau, Utah. J. Wea. Mod., 27,57-83.

Super, A.B., and B.A. Boe, 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part III: Observations over the Grand Mesa, Colorado. J. Appl. Meteor., 27,1166-1182.

Super, A.B., B.A. Boe, E.W. Holroyd, III, and J.A. Heimbach, Jr., 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part I: Experimental design and instrumentation. J. Appl. Meteor., 27, 1145-1151.

Super, A.B., and J.A. Heimbach, Jr., 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part II: Observations over the Bridger Range, Montana. J. Appl. Meteor., 27,1152-1165.

Super, A.B., J.T. McPartland, and J.A. Heimbach, Jr., 1975: Field observations of the persistence of AgI-NH4I-acetone ice nuclei in daylight. J. Appl. Meteor., 14, 1572-1577.

Warburton, J.A., 1971: Physical evidence of transport of cloud-seeding materials into areas outside primary targets. Proceedings of International Conference on Weather Modification, Canberra. Australian Academy of Science, 185-190.

Warburton, J.A., R.H. Stone, III, and B.L. Marler, 1995: How the transport and dispersion of AgI aerosols may affect detectability of seeding effects by statistical methods. J. Appl. Meteor., 34, 1929-1941.

Warburton, J.A., L.G. Young, and R.H. Stone, 1995: Assessment of seeding effects in snowpack augmentation programs: Ice nucleation and scavenging of seeding aerosols. J. Appl. Meteor., 34, 121-130.

"REVIEWED"

Results of Monthly and Seasonal Gauge vs. Radar Rainfall Comparisons in the Texas Panhandle

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado

Roni Drori and Daniel Rosenfeld
Hebrew University of Jerusalem
Jerusalem, Israel

Scott Orr
High Plains Underground Water Conservation District
Lubbock, Texas

George Bomar
Texas Natural Resource Conservation Commission
Austin, Texas

Abstract. Gauge and radar estimates of monthly and seasonal (April-September in 1999 and 2000) convective rainfall were compared for a large network in the Texas Panhandle. In 2000, the network, covering approximately 3.6 x 10^4 km^2 (1.4 x 10^4 mi^2), contained 505 fence-post rain gauges with individual, subterranean, collector reservoirs at a density of one gage per 72 km^2 (29 mi^2). These were read monthly to produce area-averaged rain totals, obtained by dividing the gauge sums by the number of gauges in the network. The gauges were not read in September 2000 because of negligible rainfall. Comparable radar-estimated rainfalls for the same time periods were generated using merged, base-scan, 15-min, NEXRAD radar reflectivity data supplied by the National Weather Service through WSI, Inc. and the Global Hydrology Resource Center.

The gauges vs. radar comparisons were made on the basis of rain patterning and area averages. The Z-R relationship used to relate radar reflectivity (Z) to rainfall rate (R) was $Z = 300R^{1.4}$, which is the equation used in standard NEXRAD practice. Because all of the rain gauges could not be read on a single day, the gauges do not provide an absolute basis of reference for comparison with the radar estimates, which were made in time periods that matched the average date of the gauge readings. The gauge and radar monthly rain patterns agreed in most instances, although the agreement in August 2000 was poor. The monthly correlations of gauge and radar rain amounts were 0.86 in 1999, 0.96 in 2000 and 0.93 for the two years combined. The radar tended to underestimate heavy rain months and overestimate those with light rain. The radar overestimate for months with light rain may be due to evaporative losses beneath the level of the radar scan as the drops fell through dry air to the ground.

The period of comparison affected the results. The area-average gauge vs. radar comparisons made on a monthly basis agreed to within 20% on 5 of the 11 months

compared. Upon comparison of the gauge and radar rainfalls on a two-month basis to diminish the impact of variations in the date of the gauge readings, it was found that all but one of the five comparisons was within 5%. The exception (April/May 1999) differed by 16%. The seasonal gauge and radar estimates in 1999 and 2000 agreed to within 4% and 8%, respectively, which is extraordinary considering the uncertainties involved. Thus, the longer the period of comparison the better the agreement appeared to be. It is concluded that the use of radar in Texas can provide an accurate representation of rain reaching the ground on a monthly and seasonal basis.

1. DEDICATION

This paper is dedicated to the memory of Mr. A. Wayne Wyatt (Figure 1), past Manager of the High Plains Underground Water Conservation District (HPUWCD), who died suddenly on December 5, 2000. Mr. Wyatt assumed his duties as general

Figure 1. Photograph of A. Wayne Wyatt, manager of the High Plains Underground Water Conservation District No.1 since 1978 until his death. During the latter portion of his tenure, Wayne promoted the investigation of cloud seeding for enhancing the water resources of the Texas Panhandle. He is also responsible for the implementation of the rain gauge network used in this study.

duties as general manager of the High Plains Water District on February 1, 1978 and remained in this position until his death. Besides overseeing the Water District's many programs and activities, including the installation of the gauge network used in this study, he was serving as chairman of the Llano Estacado Regional Water Planning Group at the time of his death. The regional water-planning group is charged with developing a 50-year water plan for a 21-county area in the southern high plains of Texas. Wayne was a prime mover for the investigation of the potential of cloud seeding for enhancing the water resources for the area, and oversaw the operational cloud seeding effort under the sponsorship of the HPUWCD since its inception in 1997. In addition, he also kept a close watch on state and federal legislative issues that could affect ground water use within the region. During his 43-year career in ground water management, many peer groups and professional organizations honored him.

2. INTRODUCTION

The measurement of precipitation is of concern to many interests and disciplines. Although simple conceptually, accurate measurement of precipitation is a difficult undertaking, especially if the precipitation takes the form of convective showers having high rain intensities, strong gradients and small scale. Rain gauges are the accepted standard for point rainfall measurement, although individual gauge readings are subject to errors in high winds and in turbulent flow around nearby obstacles. Rain gauges do not, however, provide accurate measurements of convective rainfall over large areas unless they are distributed in sufficient density to resolve the salient convective features. In some circumstances this might require hundreds, if not thousands, of rain gauges (Woodley et al., 1975).

Radar is an attractive alternative for the estimation of convective rainfall, because it provides the equivalent of a very dense gauge network. Radar estimation of rainfall is, however, a complex undertaking involving determination of the radar parameters, calibration of the system, anomalous propagation of the radar beam, ground clutter and "false rainfall", concerns about beam filling and attenuation, and the development of equations relating radar reflectivity (Z) to rainfall rate (R), where radar reflectivity is proportional to the sixth power of the droplet diameters in the radar beam. A good source for discussion of these matters is **Radar in Meteorology** (Atlas, 1990)

Some scientists have spent virtually their entire careers perfecting radar rainfall estimates, but even then the results are not always to their liking. Variability due to calibration uncertainties and changes of rain regimes must be accounted for by comparisons with rain gauges, especially for rainfall measurements that are based on reflectivity-only radar data.

Woodley et al. (1975) provide an extensive discussion of the trade-offs in the gauge and radar estimation of conective rainfall and disuss the combined use of both to increase the accuracy of the rain measurements. Radar provides a first estimate of the rainfall and rain gauges, distributed in small but dense arrays, are used to adjust the radar-rainfall estimates.

Accurate representation of the rainfall is crucial to the evaluation of cloud seeding programs for the enhancement of convective rainfall. Some have used rain gauges over fixed targets; others have used radar for the estimation of rainfall from floating targets (e.g., Dennis et al., 1975; Rosenfeld and Woodley, 1993; Woodley et al., 1999), while still others have made use of radar and gauges in combination (e.g., Woodley et al., 1982, 1983). The operational cloud seeding programs of Texas (Bomar et al, 1999), which numbered nine as of the summer 2000 season (Figure 2), make extensive use of TITAN-equipped C-band radars to conduct project operations and for subsequent evaluation.. For those using radar there is the nagging uncertainty about the accuracy of their radar-rainfall estimates. This is addressed in this paper.

The initial intention was to use the C-band project radars to generate rain estimates for comparison with rain gauges that provide readings on a daily basis, but this proved to be unfeasible. None of the projects operate their radars round-the-clock, meaning that some rainfalls are not measured, thereby making it impossible to make daily comparisons. Further, the project radars may suffer from other problems, including attenuation of the beam in heavy rain and ground clutter, which is sometimes interspersed with rain events, especially during their later stages. Because this "false rainfall" cannot not be removed objectively without a removal algorithm, it is a potential source of error in estimating the rainfall to be compared with the rain gauges. In addition, non-standard calibration procedure between the different radars can result in systematic differences in the Z-R relations that needed to be applied for unbiased rainfall measurements.

At this point it was obvious that a change in plan had to be made. If rainfall were to be estimated around-the-clock in Texas and spot-checked by comparison with rain gauges, it would have to be done with a different radar system. An obvious possibility was the NEXRAD radar systems that are distributed about the state. These are S-band radars, which do not attenuate appreciably in heavy rain, and they are operated continuously in a volume-scan mode unless they are down for maintenance. In addition, the NEXRAD radars have a clutter-removal algorithm that eliminates most of the false rainfall produced during periods of anomalous propagation.

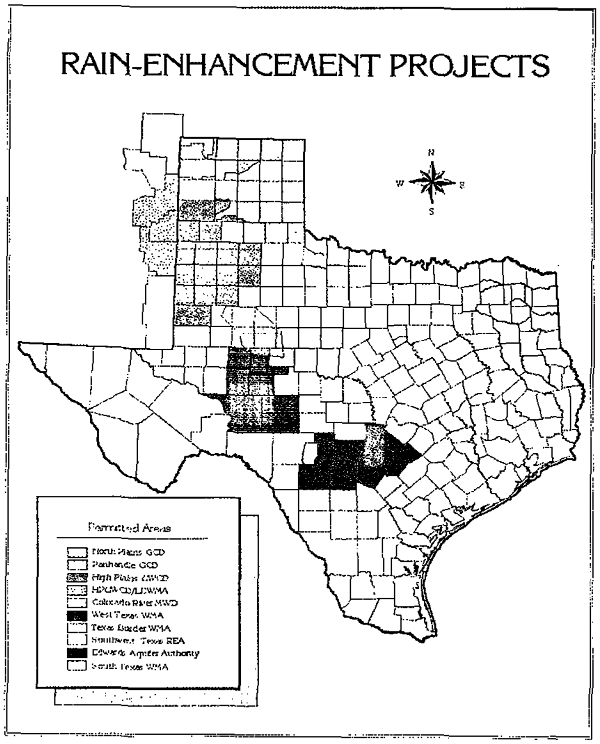


Figure 2. Map showing the nine operational cloud-seeding targets in existence in Texas as of the summer of 2000.

The availability of gauge data for this effort also posed a serious challenge. Upon looking for rain-gauge data from dense arrays big enough to resolve large convective systems on a daily basis, nothing suitable was found. It was obvious immediately, however, that it would be possible to make gauge vs. radar rainfall comparisons on a monthly and seasonal basis, using a unique network installed in the High Plains target (brown area in the Texas Panhandle shown in Figure 2). It would at least be possible, therefore, to assess the accuracy of long-term radar-rainfall estimates. These results could then be used for the benefit of the seeding projects and for others interested in the accuracy of the NEXRAD rainfall estimates.

3. GAUGE NETWORK AND DATA

Over the course of several years the High Plains Underground Water Conservation District (HPUWCD) has been instrumenting its District with fence-post rain gauges having tubing to individual, sealed, subterranean, collector reservoirs as shown in Figure 3. Evaporation is negligible under such circumstances. The network had 458 gauges in 1999 and 505 gauges in 2000 as shown in Figure 4. The gauge density in 2000 was one gauge every 72 km^2 (i.e., 1 per 29 mi^2), which would have been sufficient to resolve most individual convective systems if the gauges had had recording capability.

District personnel read and emptied the gauge reservoirs once per month, but they could not be read on one day. Typically, it took two to three days to read all of the gauges. This injected some uncertainty and noise into the gauge measurments of monthly rainfall, since the rain falling into gauges after they had been read would be ascribed to the following month whereas the same rain falling into gauges that had not yet been read would be ascribed to the current month. Thus, the gauge measurements cannot be considered an absolute basis of reference for comparison with the radar rainfall inferences.

The monthly gauge readings were made in the period April through September 1999

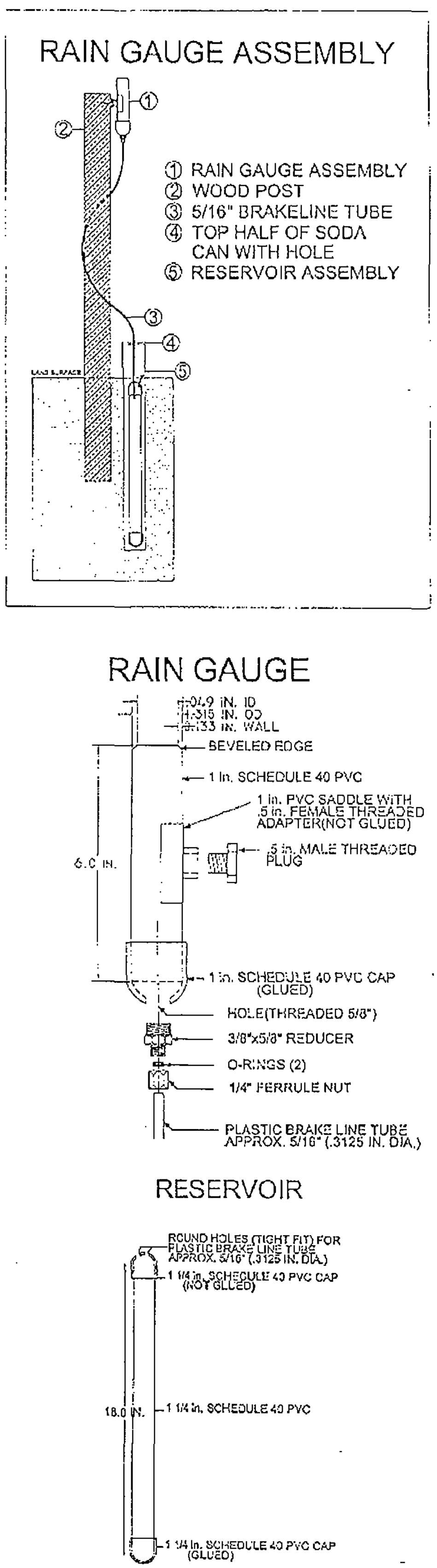


Figure 3. Design of the rain gauge system developed at the HPUWCD. a) the rain gauge assembly, b) the rain gauge, and c) the reservoir.

and April through August 2000. The gauges were not read in September 2000 because of miniscule rainfall --- 1.52 mm (0.06 in) area-average as measured by the radar --- and this month is not included in the gauge vs. radar comparisons. The gauge area means were computed by two methods. In the first method all gauge values were summed and divided by the total number of gauges in the network. The second method involved performing an isohyetal analysis, plannimetering the areas between the rain contours, the calculation of summed rain volumes, and the calculation of the area average by dividing the rain volume by the network area. Although the results for both methods are presented, the first method is preferred because of its objectivity. The gauge products and results are presented in Section 5.0, dealing with the gauge vs. radar comparisons.

4. THE NEXRAD RADAR, DATA AND PRODUCTS

Investigation of the availability of NEXRAD data revealed a source at WSI, Inc., which was made available through NASA's Global Hydrology Resource Center (GHRC). WSI Inc., receives instantaneous reflectivity data from the operational National Weather Service (NWS) radar sites located in the United States. These sites include S-band (10 cm) WSR-88D radars. The national and regional radar images are created from a mosaic of radar data from more than 130 radar sites around the United States, including new NEXRAD Doppler radar sites as they become available. A merged data set for the continental United States (CONUS) is produced by WSI, Inc., every 15 minutes, which is subsequently broadcast to the

"REVIEWED"

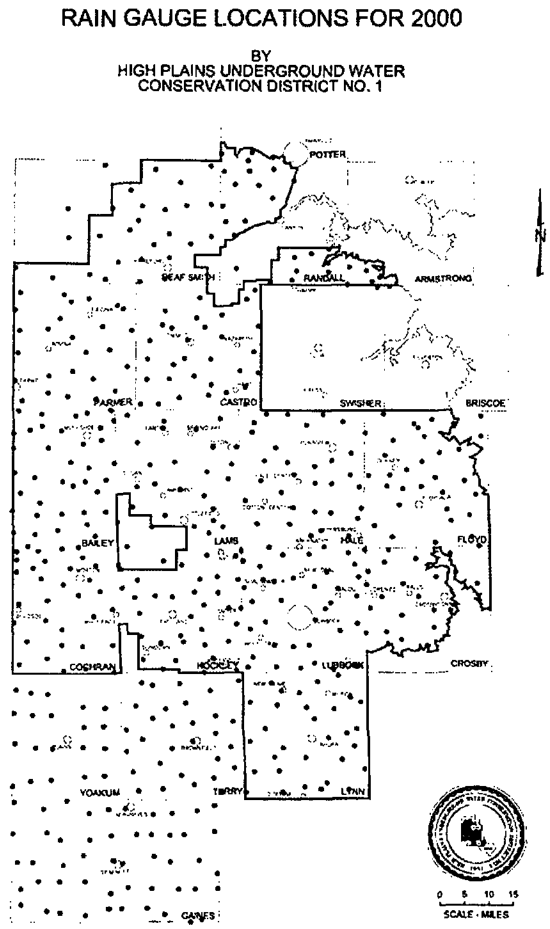


Figure 4. Map of the HPUWCD rain gauge network showing the location of its 505 gauges for the 2000 season

GHRC. The broadcast is ingested at the GHRC and stored therein at 16 reflectivity levels from 0 to 75 dBZ, every round 5 dBZ. This product has the designation of NOWrad (TM), a registered trademark of the WSI Corporation.

These base-scan 5-dBZ thresholds reflectivity data were secured for this study for the 1999 and 2000 April-September convective seasons and daily rainfall (0700 CDT on the day in question to 0659 CDT the next day) was obtained by converting the reflectivity data into rainfall rates using the Z-R relation ($Z = 300R^{1.4}$) proposed by Woodley et al. (1975) and now used as standard NEXRAD practice. Rain rates greater than 120 mm/hr were truncated to that value. The application of the Z-R relation to the threshold reflectivity values every 5 dBZ is not expected to compromise appreciably the accuracy over large space-time domains, given the fact that even a single threshold was shown to provide a remarkable agreement with the exact integration of the full dynamic range of intensities (Doneaud et al., 1984; Atlas et al., 1990; Rosenfeld et al., 1990). The rain totals were obtained for all of Texas and for various subareas, including the gauged High Plains network.

The GHRC also generates its own rainfall product for the United States For reasons unknown at this writing the GHRC rainfalls were found to be too high relative to the High Plains rain gauges by factors of 4 to 5, and with poor spatial matching, prompting us to do the integration of the 15-minute reflectivity maps, which is the basis for the analyses in this study.

5. RESULTS

The gauges vs. radar comparisons were made on the basis of rain patterning and area averages. Because of a day or two variation when the gauges were read (discussed earlier), the gauges do not provide an absolute basis of reference for comparison with the radar estimates. The gauge and radar maps for the seasonal rainfalls in 1999 and 2000 are presented in Figures 5-8. Comparable products were produced for each month, but they are not shown here because of space and cost considerations. The gauge maps are isohyetal analyses of the plotted gauge data (not shown), which were provided by the HPUWCD. The units are in inches.

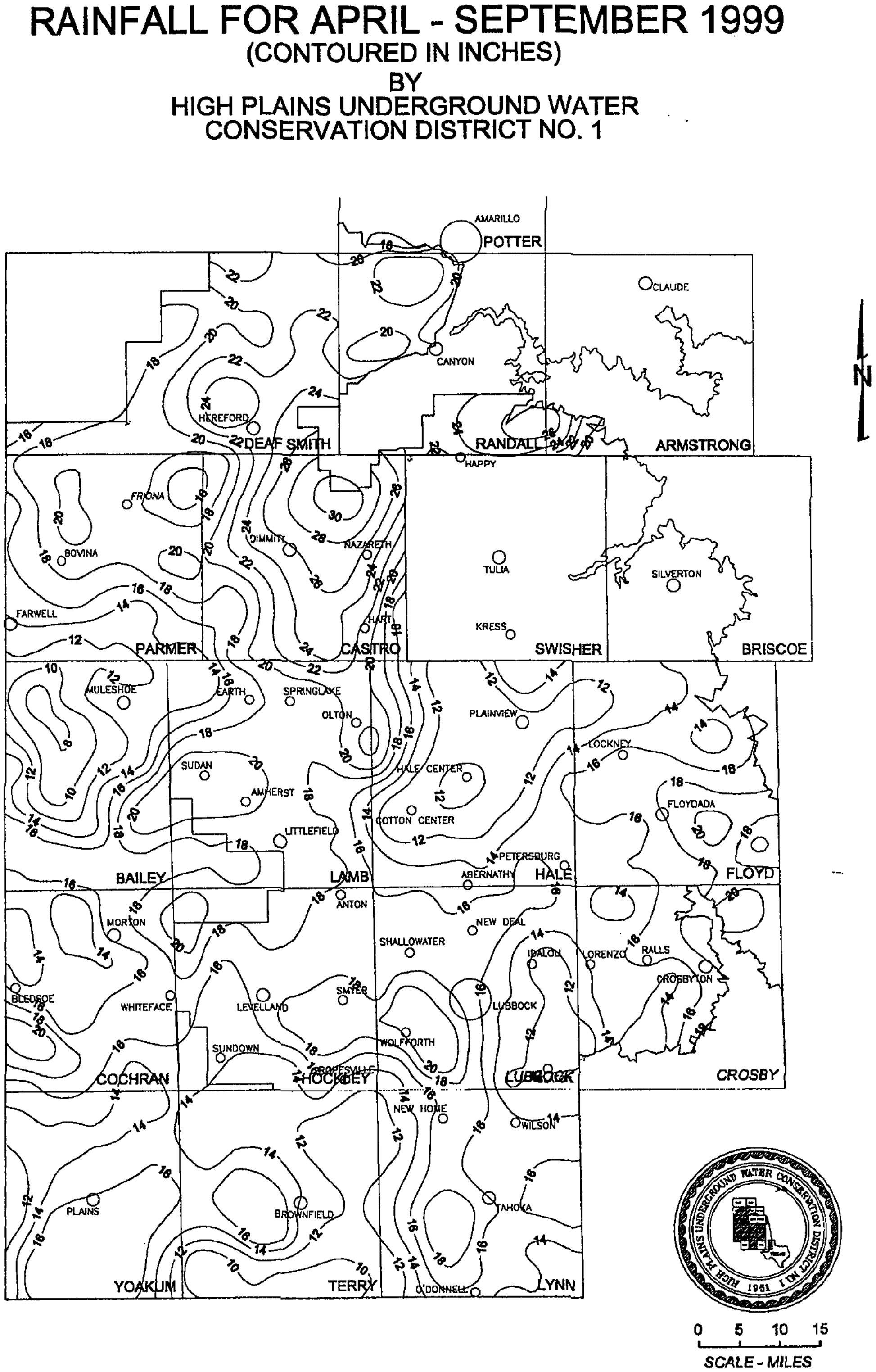


Figure 5. Isohyetal analysis (inches) in the seasonal (April through September) rainfall in 1999. The gauge maps were produced six months to a year prior to this study by personnel at the High Plains Underground Water Conservation District.

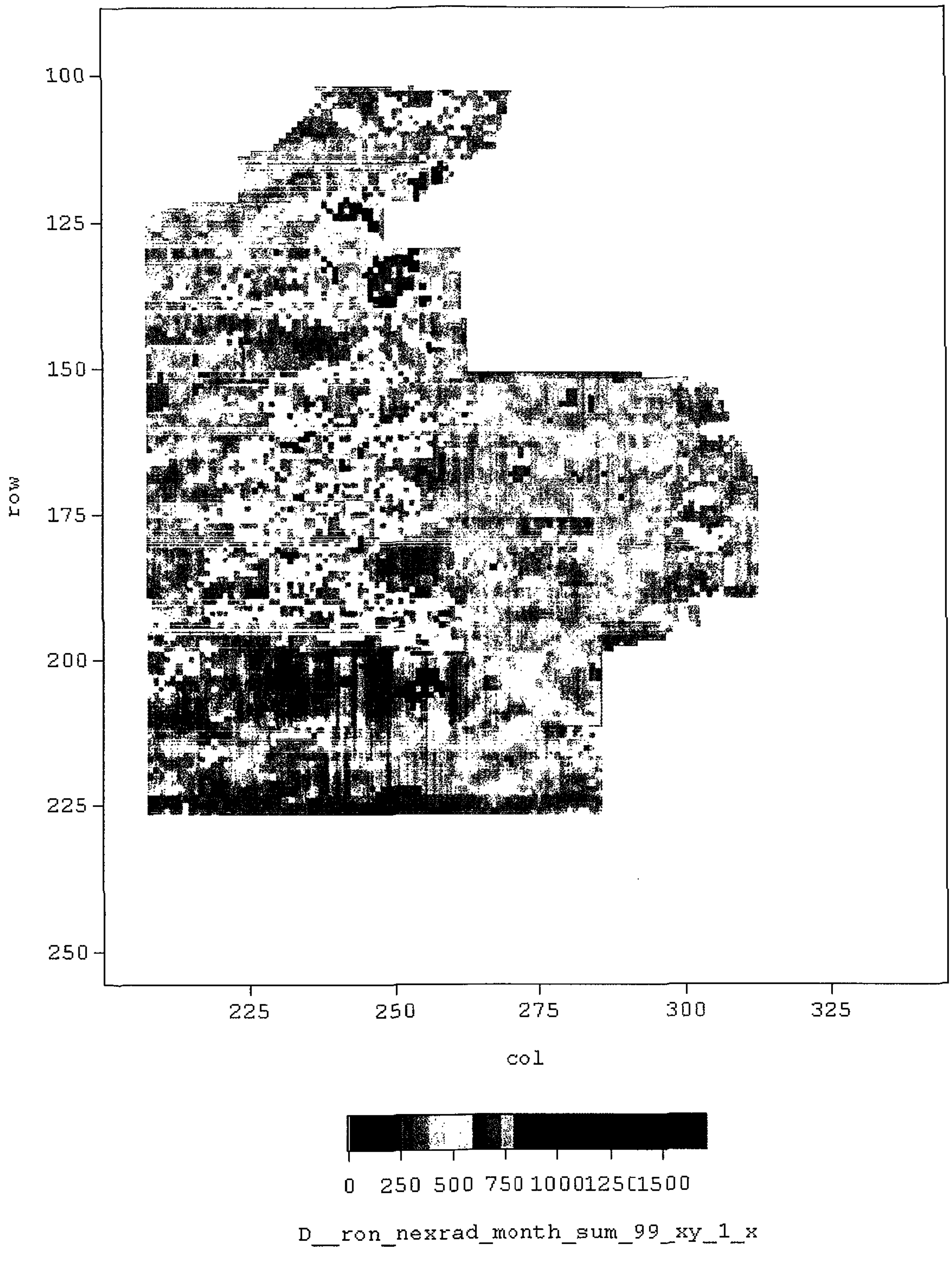
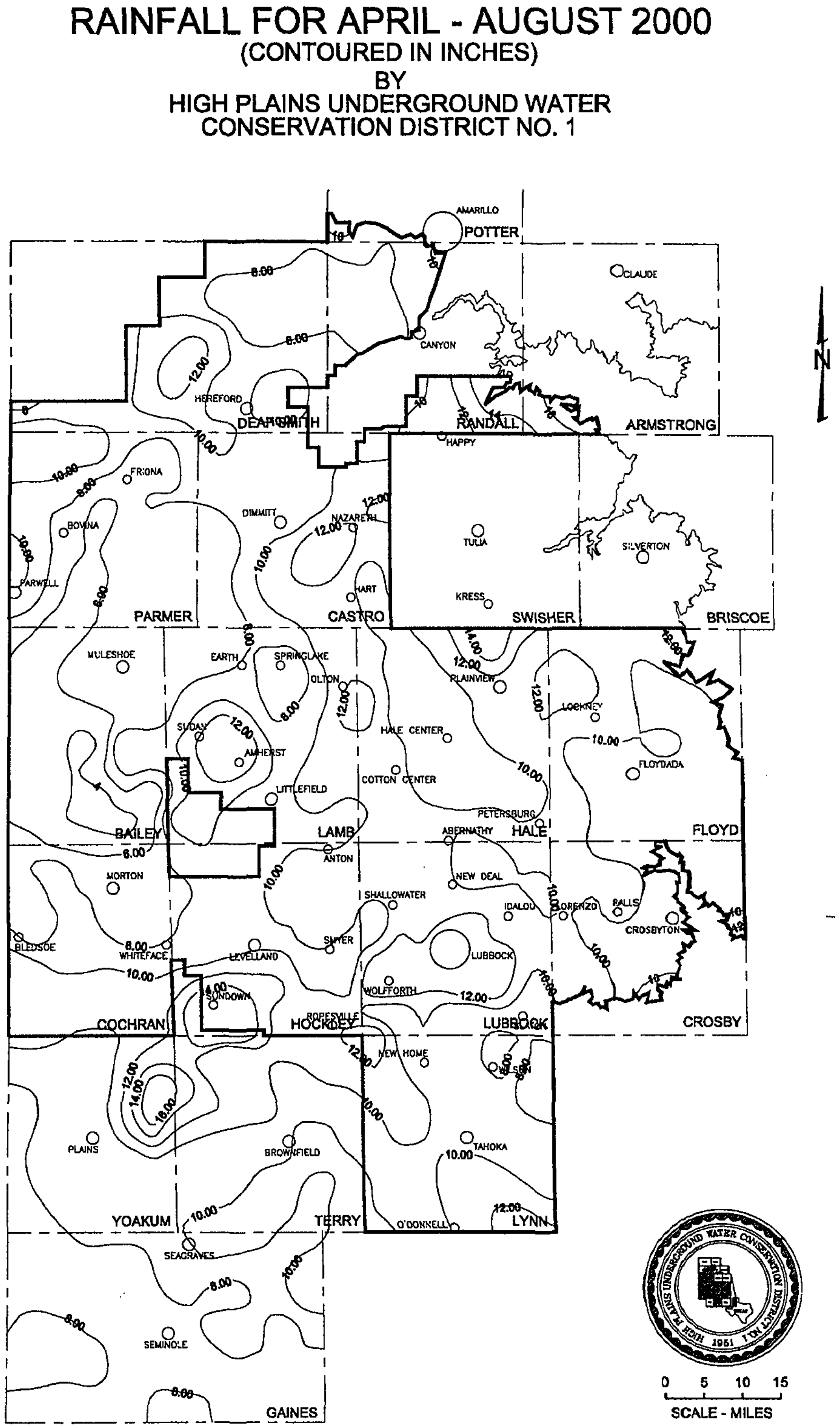


Figure 6. Map of the radar-estimated rainfalls (mm) for the 1999 season (April through September). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.



Figures 7. Isohyetal analysis (inches) in the seasonal (April through August) rainfall in 2000. Because of negligible rainfall, the rain gauges were not read in September 2000.

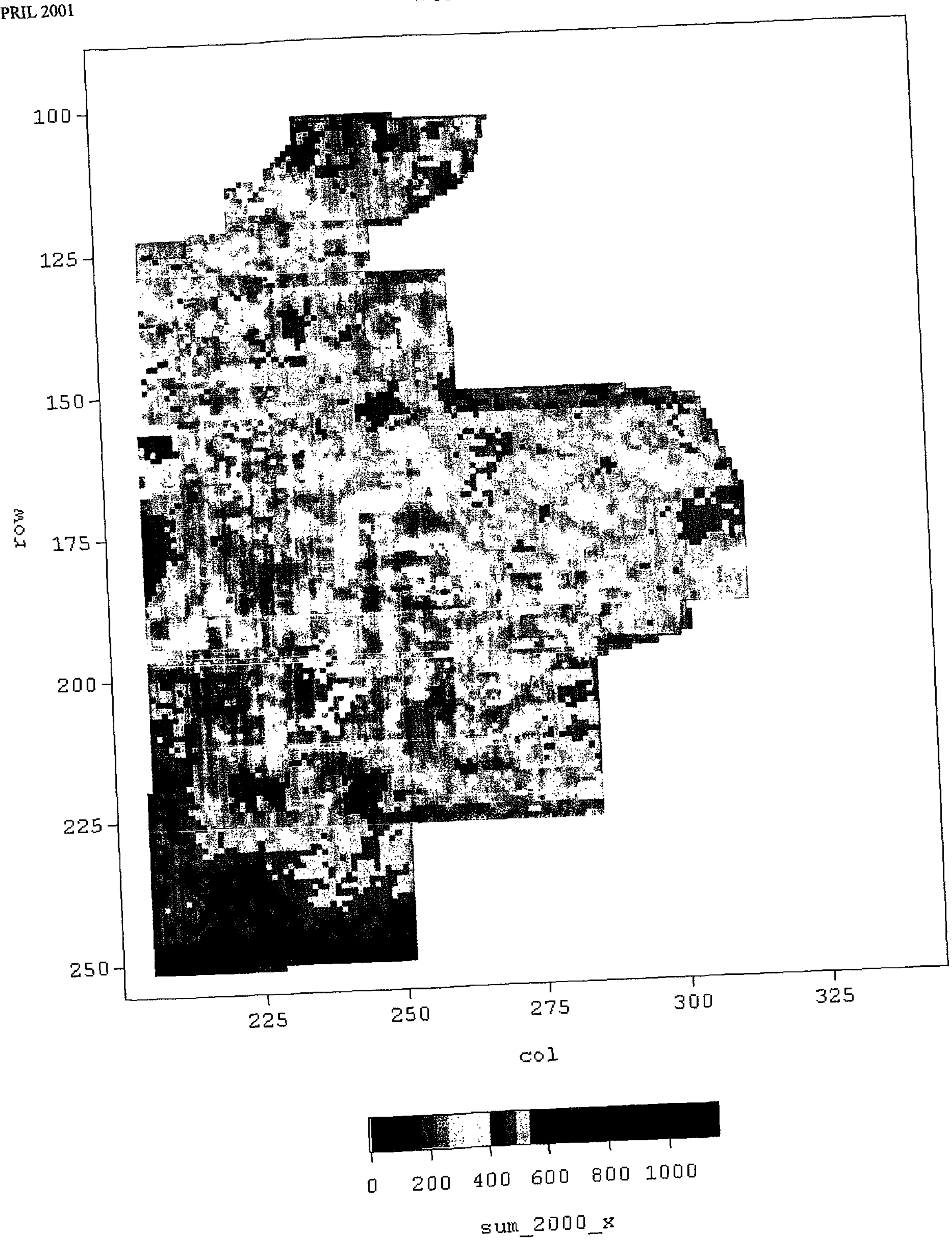


Figure 8. Map of the radar-estimated rainfalls (mm) for the 2000 season (April through August). The rainfall was negligible in September 2000). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.

The radar maps are colorized pixels, which can be related to rain depths in mm using the scale at the bottom of the figure. The first three authors generated these radar products. The independent production of the gauge and radar maps accounts for the differing rainfall units, where 1 inch is 25.4 mm.

The first step in the assessment was comparison of the rain patterning and maxima. This was a subjective process by which the agreement in each month was rated on a scale from 0 to10, where 0 means that there was no agreement and 10 indicates perfect agreement. The results are presented in Table 1. Although the results are good to excellent in most months, there were a few serious mismatches of maxima, especially in June 2000 (not shown) along the central portion of the Texas-New Mexico border. At first it was thought that this might be the result of heavy rain during the period the gauges were read, resulting in the errors discussed earlier. Only after all of the analyses had been completed was it determined that a gauge reading of 6 inches in the area of radar maximum had been thrown out as unreasonable prior to the isohyetal analysis, because it was much higher than the surrounding gauge readings. Upon adding this 6-inch maximum to the pattern, the gauge vs. radar disparity is reduced, but not eliminated entirely.

Quantification of the gauge vs. radar comparisons is presented in Table 2. Before making the comparisons the rainfall that appears in the eastern finger (covering 585 km^2) of the network on the gauge maps was subtracted from the overall gauge totals. This was necessary because the radar did not estimate rainfall for this small area.

The gauge sums divided by the number of network gauges served as the standard for the gauge vs. radar comparisons. The correlation of the monthly gauge and radar rain estimates was 0.86 in 1999, 0.96 in 2000 and 0.93 for the two years combined. The radar tended to underestimate heavy rain months and overestimate those with light rain with the crossover point at 50mm. The radar overestimate for months with light rain may be due to evaporative losses beneath the level of the radar scan as the drops fell through dry air to the ground.

The area-average gauge vs. radar comparisons agreed to within 20% on 5 of the 11 months compared (Table 2). The gauges were not read in September 2000 because of negligible rainfall. Agreement was appreciably better in months with heavy rain. The longer the period of comparison the better the agreement. The seasonal gauge and radar estimates in 1999 and 2000 agreed to within 4% (i.e., G/R = 1.04) and 8% (i.e., G/R = 0.92), respectively.

Note that the G/R values oscillate around 1.0 from one month to the next and that the "all months" G/R values are nearly 1.0. This suggests that a portion of the monthly differences can be explained by the gauges measuring some rains not observed by the radar and vice versa. As discussed earlier, this can occur when it rains heavily during the two to three days that it takes to read all of the rain gauges. If this is true, the oscillating errors should diminish when the comparisons are done for periods of two months or longer.

This hypothesis is tested in Table 3 and the results are dramatic. Using method 1 as the standard, note that four of the five two-month comparisons agree to within 5%, and that in the lone exception the gauges and radar differ by only 16%.

Table 1

Subjective Comparison of the Gauge and Radar Rainfall Patterning
(Scale of 0 to 10 where 0 = no agreement and 10 = perfect agreement)

Month(s)	Pattern	Maxs/Mins	Comments
April 1999	8	6	Good correspondence
May 1999	7	6	Good overall agreement, few maxima do not match
June 1999	8	8	Very good agreement everywhere in a heavy rain month
July 1999	9	9	Excellent overall agreement
August 1999	8	7	Very good overall agreement except for radar maximum not on gauge map
September 1999	9	9	Excellent overall agreement
April-Sept 1999	9	9	Excellent overall agreement
April 2000	8	8	Very good agreement except for a few mismatches
May 2000	9	6	Excellent pattern match but radar maxima greater than gauge maxima
June 2000	6	5	General agreement but poor match of rain maximum, especially along New Mexico border
July 2000	6	5	General pattern match, but some serious mismatches
August 2000	5	4	Poor match of pattern and maxima
April-Sept 2000	8	8	Very good overall agreement except for poor match of maximum along central Texas-New Mexico border

Table 2
Comparison of Gauge and Radar-Estimated Rainfalls (in mm) for the High Plains Rain Gauge Network

Month	Gauge Mean (1)	Gauge Mean (2)	Radar Mean	(G/R)[1]	(G/R)[2]
		1999	Season		
April	97.14	97.06	68.26	1.42	1.42
May	69.58	70.41	75.60	0.92	0.93
June	114.63	117.78	101.92	1.12	1.16
July	44.79	34.02	59.81	0.75	0.57
August	34.44	35.82	46.95	0.73	0.76
September	60.17	56.38	50.42	1.19	1.12
April-Sept	420.75	411.47	402.96	1.04	1.02
		2000	Season		
April	25.85	24.14	14.59	1.77	1.65
May	9.62	7.16	21.92	0.44	0.33
June	103.52	95.30	92.57	1.12	1.03
July	56.13	49.37	64.31	0.87	0.77
August	2.01	1.42	18.57	0.11	0.08
September	NA	NA	1.53	---	---
April-Aug	197.13	177.39	213.49	0.92	0.83
1999 & 2000	617.88	588.86	616.45	1.002	0.96

Table 3
Two-Month Comparisons of Gauge and Radar-Estimated Rainfalls (in mm) for the High Plains Rain Gauge Network in 1999 and 2000

Months	Gauge Mean (1)	Gauge Mean (2)	Radar Mean	(G/R)[1]	(G/R)[2]
April/May 99	166.72	167.47	143.86	1.16	1.16
June/July 99	159.42	151.80	161.73	0.99	0.94
Aug/Sept 99	94.61	92.20	97.37	0.97	0.95
April/May 2000	35.47	31.30	36.51	0.97	0.86
June/July 2000	159.65	144.67	156.88	1.02	0.92

"REVIEWED"

6. CONCLUSIONS

The results of this study suggest that NEXRAD data can be used to provide accurate measurements of monthly and seasonal convective rainfall in Texas. Contrary to our expectations, no changes in the Z-R equation appear warranted. The accuracy of the radar-rainfall inferences is certain to decrease as the period of comparison is decreased to individual days or even shorter time frames. This can be readily documented using the NEXRAD data, provided suitable rain gauges in dense arrays can be found to serve as a basis for reference.

As mentioned before, the project radars are poorly equipped for area rainfall measurements. Their best use would appear to be in the conduct of seeding operations, particularly in the real-time assessment of the properties of the convective cells and in the tracking of the aircraft, and in the post-evaluation of the properties of individual storms. Such analyses are possible now thanks to the TITAN systems that are installed on the radars. These are not readily feasible using the NEXRAD radars in their present configuration.

The radar-based evaluation of seeded storms, regardless of the radar system, is still a problem in the minds of some, because it is presumed that seeding somehow alters the cloud-base (i.e., base-scan) drop-size distribution and, therefore the radar-measured reflectivity and inferred rainfall. This would indeed be a problem compromising the use of radar for the evaluation of seeding experiments, if it were true, but the available evidence suggests that it is not for glaciogenic seeding, such as done in Texas. Cunning (1976) made measurements of raindrops from the bases of AgI-seeded and non-seeded storms in Florida and found that the intra-day and inter-day natural drop-size variability was as large as that measured in rainfall from seeded storms.

It is recommended that these studies be continued in order to evaluate the accuracy of daily radar-rainfall estimates using the NEXRAD radar products. This is possible now, provided a suitable recording rain gauge standard can be found.

7. ACKNOWLEDGMENTS

The research of the first three authors was supported by the Texas Natural Resource Conservation Commission (TNRCC) under Agency Order No. 582-0-34048 and the first author had additional support from the Texas Water Development Board under Contract No. 2000-483-343. We thank the following individuals at the High Plains Underground Water Conservation District: Gerald Crenwelge the database engineer for his technical assistance, Dewayne Hovey for gauge plotting and mapping assistance and Keith Whitworth for drafting the isohyetal analyses. Finally, the High Plains Precipitation Enhancement Program acknowledges the participation and contributions from the following entities: South Plains Underground Water Conservation District, Sandy Land Underground Water Conservation District and the Llano Estacado Underground Water Conservation District.

8. REFERENCES

Atlas, D., D. Rosenfeld, and D. B. Wolff, 1990: Climatologically tuned reflectivity-rain rate relations and their links to area time integrals. *Journal of Applied Meteorology*, **29**, 1120-1139.

Atlas, D., Editor, 1990: **Radar in Meteorology**, Boston, Amer. Meteor. Soc., 806pp.

Bomar, G. A., W.L.Woodley and D. Bates (1999): The Texas weather modification program, objectives, approach and progress. J. Wea. Mod., **31**, 9-22.

Cunning, J.B., Jr., 1976: Comparison of the Z-R relationship for seeded and non-seeded Florida cumuli. J. Appl. Meteor., **15**, 1121-1125.

Dennis, A.S., A. Koscielski, D.E. Cain, J.H. Hirsch and P.L. Smith, Jr., 1975: Analysis of radar observations of a randomized cloud seeding experiment. J. Appl. Meteor., **14**, 897-908.

Doneaud, A.A., S.I. Niscov, D.L. Priegnitz and P.L. Smith, 1984: The area-time integral as an indicator for convective rain volumes. J. Climate Appl. Meteor., **23**, 555-561.

Rosenfeld, D., D. Atlas, and D. A. Short, 1990: The estimation of rainfall by area integrals. Part 2. The Height-Area Rain Threshold (HART) method. *Journal of Geophysical Research*, 95, 2161-2176.

Rosenfeld, D. and W.L. Woodley, 1993: Effects of cloud seeding in west Texas: Additional results and new insights. J. Appl. Meteor., **32**, 1848-1866.

Woodley, W.L., A.R. Olsen, A. Herndon, and V. Wiggert, 1975: Comparison and gage and radar methods of conective rain measurement. J. Appl. Meteor., **14**, 909-928.

Woodley, W.L, J. Jordan, J. Simpson, R. Biondini, J.A. Flueck, and A. Barnston, 1982: Rainfall results of the Florida Area Cumulus Experiment. 1970-1976. J. Appl. Meteor., 21, 139-164.

Woodley, W.L., A. Barnston, J.A. Flueck, and R. Biondini, 1983: The Florida Area Cumulus Experiment's second phase (FACE-2). Part II: Replicated and confirmatory analyses. J. Climate Appl. Meteor., **22**, 1529-1540.

Woodley, W.L., D. Rosenfeld, W. Sukarnjanaset, P. Sudhikoses, S. Ruangsuttinaruparp and W. Khantiganan, 1999b: The Thailand cold-cloud seeding experiment: 2. Results of the statistical evaluation. Proc. of 7th WMO Conf. on Wea. Mod., 16-22 Feb. 1999, Chiang Mai, Thailand.

CLOUD SEEDING - THE UTAH EXPERIENCE

Norman E. Stauffer, Jr.
Utah Division of Water Resources
Salt Lake City, Utah

Abstract. The first cloud seeding project in Utah began in the early 1950s in the central and southern portion of the state and lasted four years. The project was reactivated in 1973 by the original organizers and has continued to the present. The Utah Cloud Seeding Act was passed in 1973 by the Utah Legislature. This law provids for licensing cloud seeding operators and permitting cloud seeding projects by the Utah Division of Water Resources. The act states that for water right purposes all water derived from cloud seeding will be treated as though it fell naturally. The act also allows for the division to sponsor and/or cost-share in cloud seeding projects. Since 1976, the state through the division and Board of Water Resources has cost-shared with local entities for cloud seeding projects. In the 1970s, cloud seeding projects expanded to cover most of the state. The majority of projects were for wintertime snow pack augmentation, but a summertime hail suppression/rainfall augmentation project operated for six years in Northern Utah. The state participated in the NOAA Cooperative Weather Modification Research Project from 1981 to 1996. Wintertime snow pack augmentation projects continue to operate in Utah.

1. THE EARLY YEARS

Utah is the second driest state in the nation. It is not surprising, therefore, that a group of counties in Central and Southern Utah sponsored a cloud seeding project within a few years after the discovery of modern cloud seeding principles in the late 1940s, as did many other groups in the western and mid-western states.

A project began in April 1951 and operated until May 1955. The project used ground generators that burned coke impregnated with silver iodide and was operated by the Water Resources Development Corporation of Denver, Colorado. The sponsoring entity was the Southern Utah Water Resources Development Corporation.

The University of Utah Meteorology Department (Hales et al., 1955) and the American Institute of Aerological Research (1955) made evaluations of the effects of the cloud seeding. The two evaluations resulted in conflicting results, and the project ended.

The first legislation in Utah concerning weather modification was enacted in 1953. This law required the reporting of weather modification activities in Utah to the Department of Meteorology at the University of Utah.

2. THE BANNER YEARS

The years 1973 through 1981 were historic in shaping Utah's weather modification program. In 1973 some of the original organizers of the 1950s Central and Southern Utah Project reactivated the program. They lobbied the legislature, which resulted in passage of the 1973 Utah Cloud Seeding Act. They operated the Central and Southern Utah Project for wintertime snow pack augmentation in water years 1974 and 1975. They contracted, using their own funds (county taxes), with North American Weather Consultants to operate the project using ground generators that released silver iodide.

Through their lobbying and promotional efforts, state funding became available beginning in water year 1976. With the state funding and local participation, the winter program was expanded to cover more areas of the state. A summertime hail suppression and precipitation augmentation program was started in the northern portion of the state. State funding for the winter and summer programs was about 70 percent, and local funding was the remaining 30 percent.

With greatly increased interest in weather modification and the Cloud Seeding Act of 1973, the Division of Water Resources responded with a public involvement program. A Weather Modification Newsletter, published several times a year, began in 1975 and was distributed until 1980. Five annual one-day cloud seeding seminars were held, and the proceedings were published beginning in 1974. In 1975 the Division of Water Resources created a Technical Advisory Committee made up of university and government scientists, television weathermen, legislators, government agencies involved in water resources, and water users. The committee was realigned in 1977 into two separate committees. One was called the Program Advisory

Committee, comprised of water users and government agencies having stewardship over water resources. The other was the Technical Advisory Committee, composed of meteorologists, statisticians and scientists with expertise relating to program design, evaluation and research. Both committees functioned until 1983 and provided valuable input to the Division of Water Resources. Some cloud seeding research and evaluation began with state funding at Utah State University in the late 1970s. The NOAA/Utah Cooperative Research Program was in the planning stage in the late 1970s, and funding began in 1981.

The state experienced an economic downturn in the early 1980s. State funding for cloud seeding was greatly reduced and the summer project did not survive. The winter programs continued with eventually a much larger portion of the funding from the local sponsors. These nine years--1973 through 1981--were the heydays for cloud seeding in Utah.

3. 1973 CLOUD SEEDING ACT

The following is a summary of the 1973 Utah Cloud Seeding Act:

(1) Authority: The state of Utah through the Division of Water Resources shall be the only entity, private or public, that shall have authority to authorize, sponsor, and/or develop cloud seeding projects within the state of Utah.

(2) Ownership of Water: All water derived as a result of cloud seeding shall be considered as a part of Utah's basic water supply the same as all natural precipitation water supplies have been heretofore, and all statutory provisions that apply to water from natural precipitation shall also apply to water derived from cloud seeding.

(3) *Record-Keeping:* Repealed the 1953 law on record-keeping and required the Division of Water Resources to establish criteria for reporting data and record-keeping.

(4) Rules and Regulations: Any individual or organization that would like to become a cloud seeding contractor in the state of Utah shall register with the Division of Water Resources. As a part of the registration, the applicant shall meet qualifications established by the Division of Water Resources and submit proof of financial responsibility.

(5) Trespass: The mere dissemination of materials and substances into the atmosphere or causing precipitation pursuant to an authorized cloud seeding project shall not give rise to any presumption that such use of the atmosphere or lands constitutes trespass or involves and actionable or enjoyable public or private nuisance.

(6) Interstate Activities: Cloud seeding in Utah to target an area in an adjoining state is prohibited except upon full compliance of the laws of the target area state, as well as the provisions of this act.

(7) Exemptions: Cloud seeding for the suppression of fog at airports and frost prevention measures for the protection of orchards and crops are excluded from the act.

Based on the 1973 Cloud Seeding Act, the Division of Water Resources promulgated rules and regulations relating to cloud seeding in Utah. A license and permit are required for cloud seeding in Utah as well as proof of financial responsibility. Reporting of cloud seeding activities to NOAA as required by federal law is also required by the Division of Water Resources.

4. STATE FUNDING

The 1973 Cloud Seeding Act authorized the Division of Water Resources to sponsor and/or cost-share in cloud seeding projects. The legislature for water year 1976 provided funding for wintertime projects and a summertime project at about 70 percent cost sharing by the state. This level of funding continued through 1981.

Because of the state's economic downturn in the early 1980s, the legislature only provided funding for the winter projects in 1982 and 1983. Without state funding, the summer project ended in 1981.

An extremely wet period occurred statewide in the spring of 1983 and continued into 1984. No cloud seeding activities occurred in water year 1984. The wet conditions continued over most of the state except in extreme Southern Utah (Washington County). The only cloud seeding operation for 1985 through 1987 was in Washington County. There was no state funding for cloud seeding in 1987 because the state was constructing the West Desert Pumping Project to pump water from the Great Salt Lake to reduce flood damage.

The wet period ended in 1987 and the entire state entered into its most critical 10-year dry period. By