Results of monthly and seasonal gauges vs. radar rainfall comparison in the Texas panhandle

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

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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.

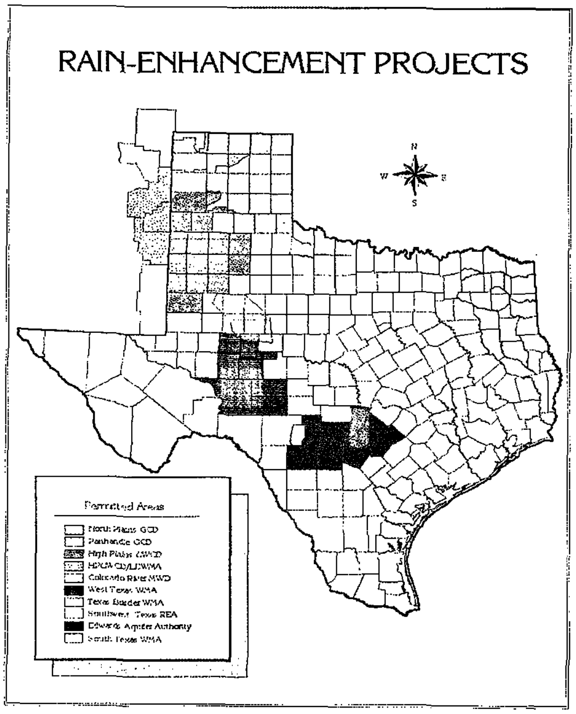


Figure 2. Map showing the nine operational cloud-seeding targets in existence in Texas as of the summer of 2000.

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

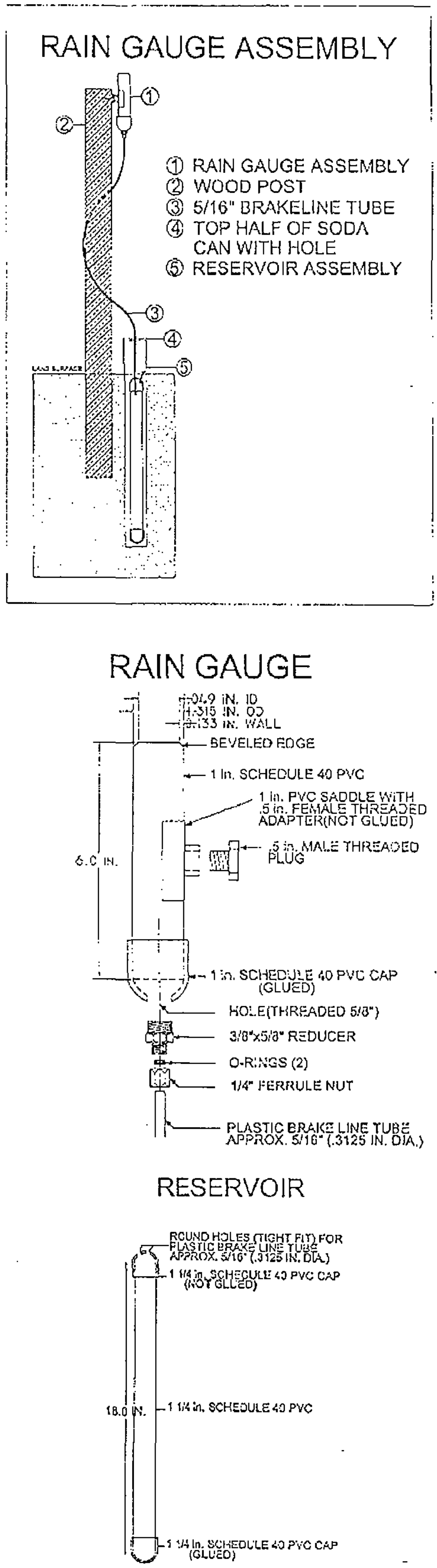


Figure 3. Design of the rain gauge system developed at the HPUWCD. a) the rain gauge assembly, b) the rain gauge, and c) the reservoir.

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

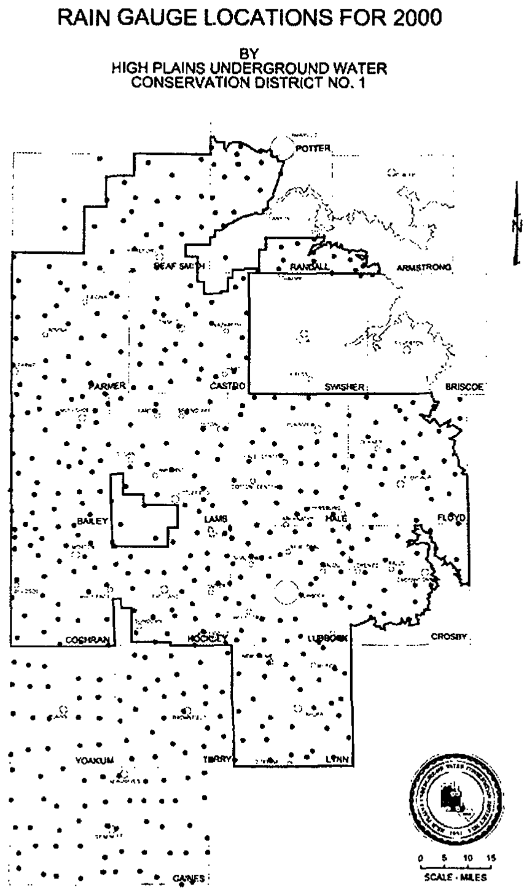


Figure 4. Map of the HPUWCD rain gauge network showing the location of its 505 gauges for the 2000 season

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.

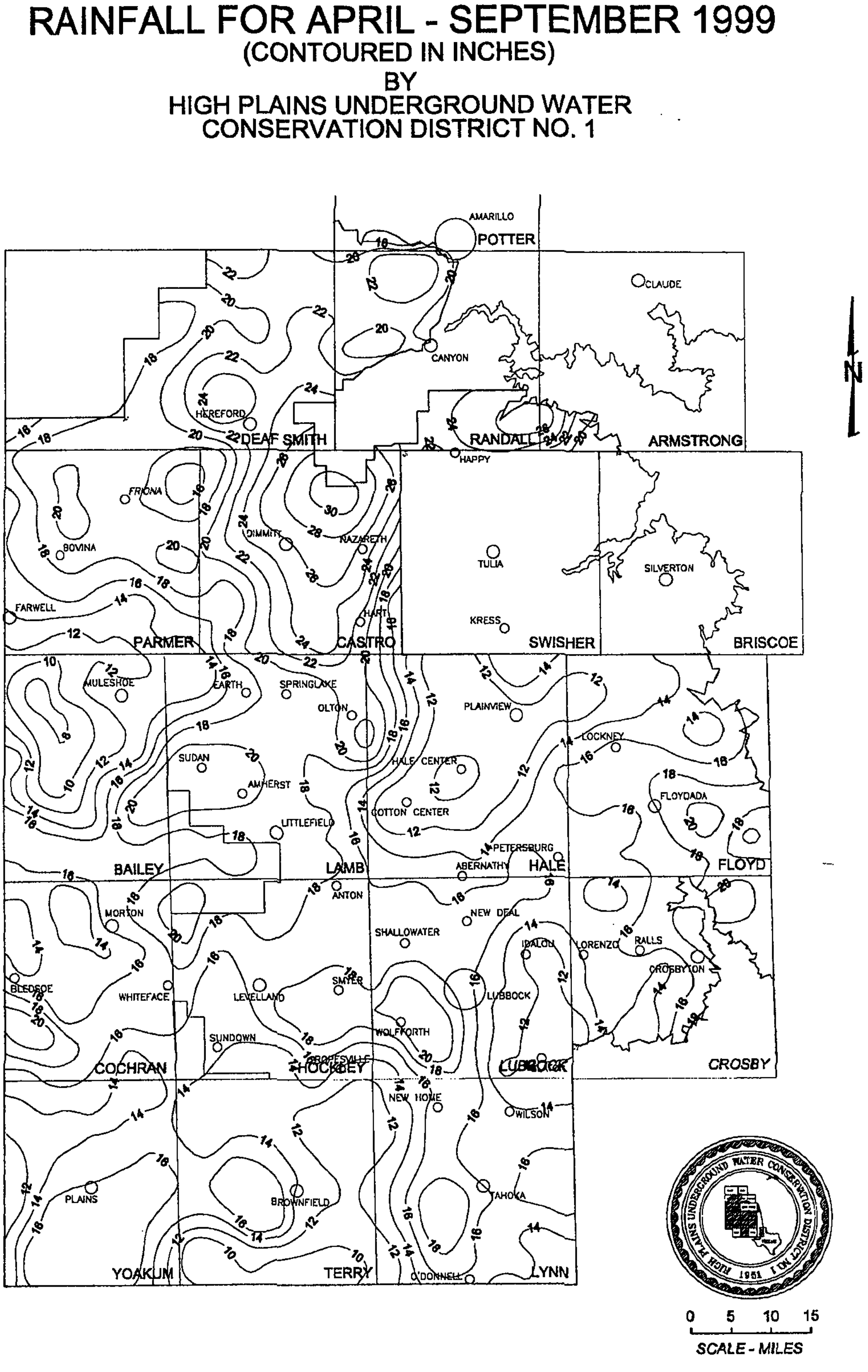


Figure 5. Isohyetal analysis (inches) in the seasonal (April through September) rainfall in 1999. The gauge maps were produced six months to a year prior to this study by personnel at the High Plains Underground Water Conservation District.

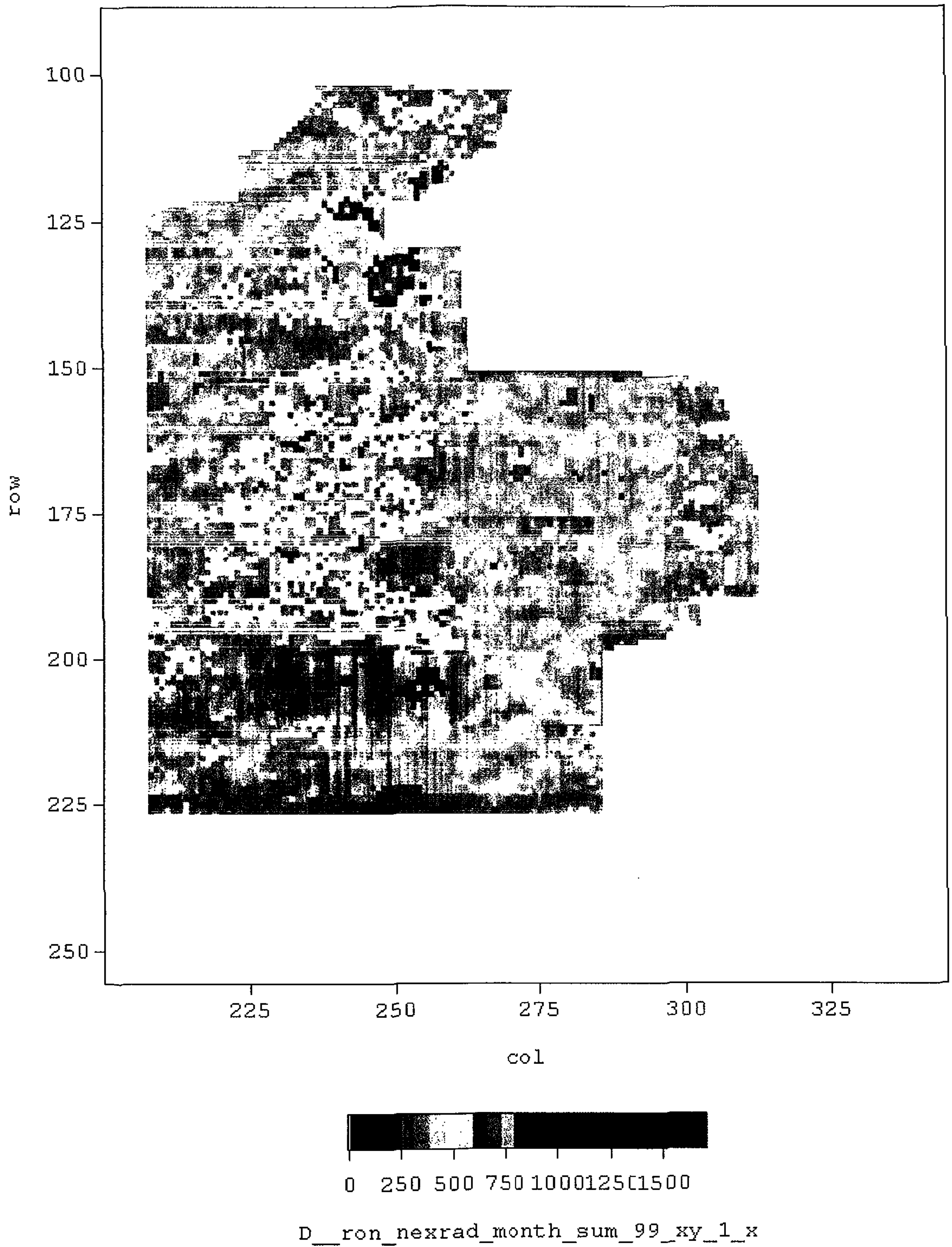
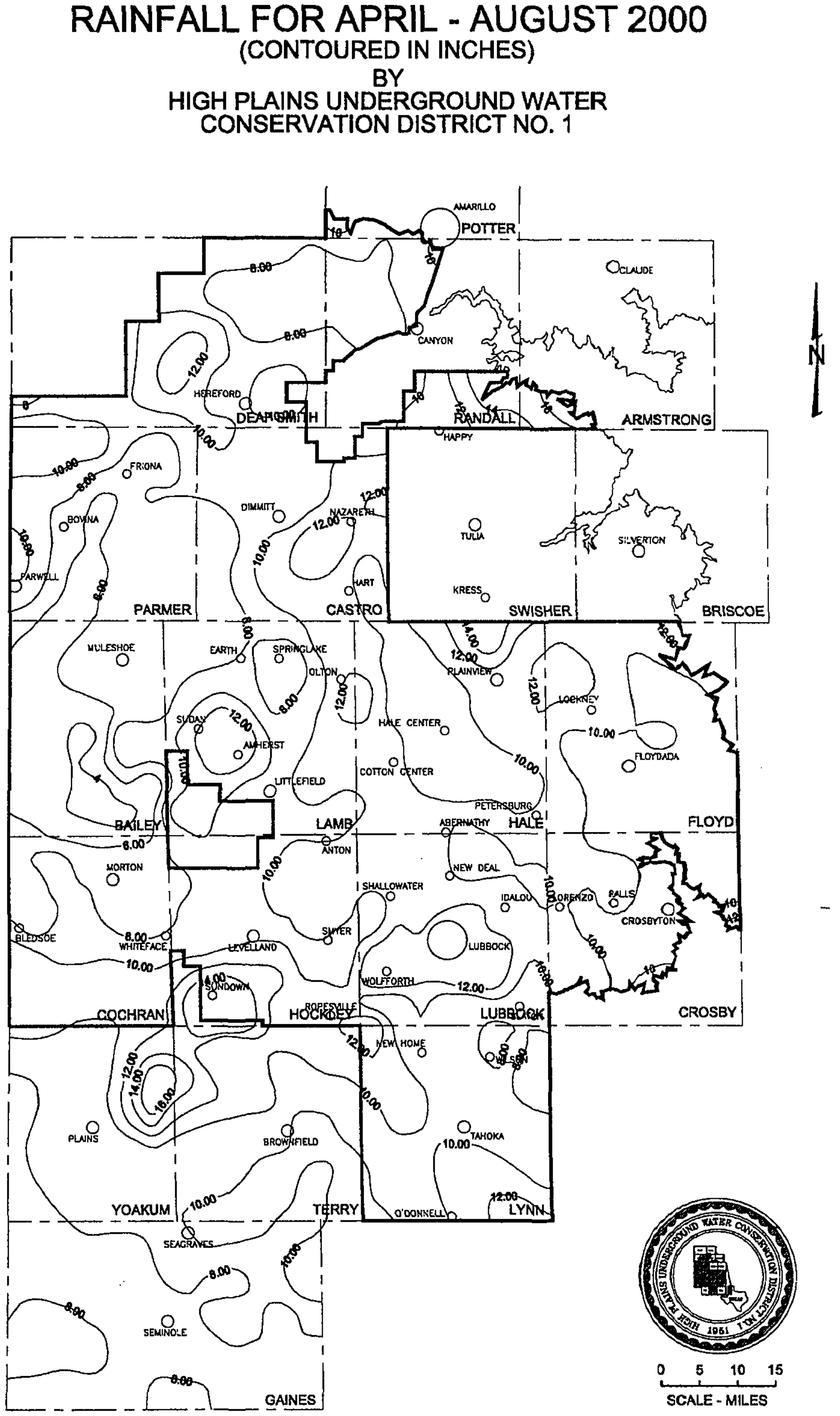


Figure 6. Map of the radar-estimated rainfalls (mm) for the 1999 season (April through September). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.



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.

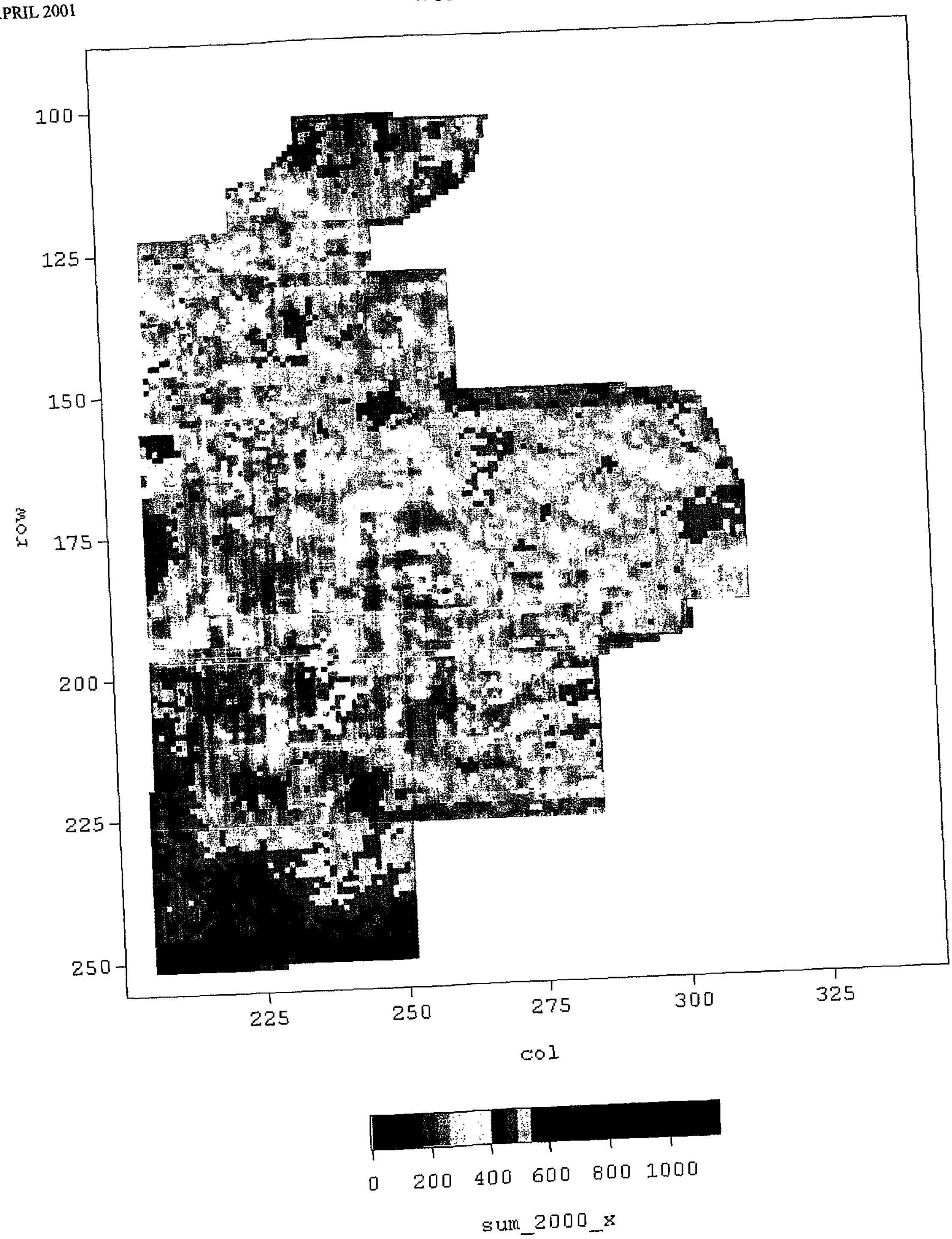


Figure 8. Map of the radar-estimated rainfalls (mm) for the 2000 season (April through August). The rainfall was negligible in September 2000). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.

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

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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.

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