

N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM
MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT
CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED
IN THE INTEREST OF MAKING AVAILABLE AS MUCH
INFORMATION AS POSSIBLE

NASA CR-166724

(NASA-CR-166724) AN EVALUATION OF THE
SPATIAL RESOLUTION OF SOIL MOISTURE
INFORMATION Final Report (Environmental
Research and Technology, Inc.) 83 p
HC A05/MF A01

N82-11513

Unclass
01617

CSSL 08M G3/43

AN EVALUATION OF THE SPATIAL RESOLUTION OF SOIL MOISTURE INFORMATION

ERT Document No. P-7505-F

Contract No. NAS5-25527

Final Report

March 1981

Prepared for

National Aeronautics & Space Administration
Goddard Space Flight Center
Greenbelt Road
Greenbelt, Maryland 20771

Prepared by

Kenneth R. Hardy, Stephen H. Cohen,
Linda Koshio Rogers, Hsiao-hua K. Burke,
Robert C. Leupold and Michael D. Smallwood

Environmental Research & Technology, Inc.
696 Virginia Road
Concord, Massachusetts 01742



ABSTRACT

The objective of this study is to evaluate and quantify the relative merits of soil moisture observations at a 1-km resolution rather than at a 10-km resolution. Soil moisture information is of value for improved runoff prediction and crop yield forecasting, and if soil moisture is to be determined using microwave radiometers from satellites, the resolution requirements have considerable impact on the specification of the satellite systems. The evaluation of the resolution of soil moisture information is divided into three major areas; these are an assessment of the rainfall-amount patterns in the central regions of the U.S., an investigation of the spatial scales of surface features and their corresponding microwave responses in the mid western U.S., and an evaluation of the usefulness for U.S. government agencies of soil moisture information at scales of 10 km and 1 km.

From an investigation of 494 storms, it was found that the rainfall amount resulting from the passage of most types of storms produces patterns which can be resolved on a 10-km scale. The land features causing the greatest problem in the sensing of soil moisture over large agricultural areas with a radiometer are bodies of water. Over the mid-western portions of the U.S., water occupies less than 2% of the total area, and consequently, the water bodies will not have a significant impact on the mapping of soil moisture. Over most of the areas, measurements at a 10-km resolution would adequately define the distribution of soil moisture. The spatial variation and the microwave response of other surface features, for example, urban and forest areas, are also discussed. With respect to the value of soil moisture information, crop yield models and hydrological models would give improved results if soil moisture information at scales of 10 km was available.

TABLE OF CONTENTS

	Page
ABSTRACT	i
1. INTRODUCTION	1
2. RAINFALL PATTERN ANALYSIS	3
2.1 Previous Studies on Rainfall Patterns	3
2.2 The Sources of Rain Gage Data	5
2.3 The Analysis of the Data	8
2.4 The Results of the Statistical Analysis	17
2.5 Implications of the Rainfall Patterns for Soil Moisture Retrieval	23
3. MICROWAVE RESPONSE TO LAND FEATURES	25
3.1 General Factors Affecting the Microwave Brightness Temperature	25
3.2 Spatial Scales of Surface Features of the Study Region	27
3.2.1 General Features of the Study Region	27
3.2.2 Detailed Features of Selected Sites	33
4. SOIL MOISTURE RESOLUTIONS FOR USE IN CROP YIELD AND HYDROLOGICAL MODELS	46
4.1 Current Soil Moisture Related Information	46
4.2 Future Applications and Improvements of Soil Moisture Information	49
5. CONCLUSIONS	52
6. REFERENCES	54
ACKNOWLEDGMENTS	56
APPENDIX A - FORMAT FOR THE INFORMATION EXTRACTED FOR EACH STORM CELL AND LISTING OF THE CELL DATA	A-1
APPENDIX B - NORMALIZED RAINFALL AMOUNT PATTERNS	B-1

1. INTRODUCTION

The objective of the study is to evaluate the improved usefulness of soil moisture observations from space with microwave radiometers having resolutions of 10 km and 1 km. The evaluation of the resolution of soil moisture information is divided into three major areas; these are: (1) an assessment of the rainfall patterns in the central regions of the U.S., (2) an investigation of the spatial scales of surface features of the mid-western U.S., and (3) an evaluation of the usefulness of soil moisture information at scales of 10 km and 1 km for U.S. government agencies.

Since the major input for producing soil moisture variability is rain, it is essential to determine the fine-scale structure of rainfall amounts. Eagleson (1978), Brady (1975), Eddy (1976), Huff (1971, 1979), and Huff and Shipp (1969) have investigated and described techniques for the determination of patterns of rainfall amount. In some cases (Eddy, 1976), the primary effort was directed toward the rain gage network density and procedures which would be required to estimate the rainfall over a given area within a given accuracy. In other cases (Huff, 1971; and Eagleson, 1978), the main attempt was to describe the average structure of rain or the structure of various types of storms on a monthly or seasonal basis. Generally, spatial correlations between the rainfall amounts at each of the gages were obtained. The results of the correlation analysis showed differences between each of the major types of storms. The study described herein uses rainfall amount information from 494 storms to determine some of the characteristics of rainfall amount patterns which in turn contribute in a major way to soil moisture variability. The analysis consisted of (1) contouring the rainfall amounts for each storm, (2) measuring the rainfall amount at various locations from the storm center, (3) assigning a synoptic type for each storm day, and (4) deriving statistics of the storm patterns for each synoptic type. With the exception that the peak rainfall amount will usually be underestimated, it was found that the rainfall amount patterns will be well represented by systems having a resolution of 10 km.

The second major area of investigation is an evaluation of the surface features and land use patterns in the central region of the U.S. The evaluation is aimed at a determination of the spatial scales of surface features that could affect the microwave response. Although there is a

wide variety of scales of surface features within the regions chosen for study, water bodies were found to occupy less than 2% of the total area. Also, the features usually had characteristic scales of more than 50 km. Thus, for the monitoring of large regions, a sensor having a resolution of 10 km would be adequate over the central U.S. However, for the monitoring of either small areas of less than a few tens of kilometers in size or those areas with a preponderance of small scale features, a sensor with a 10-km resolution would often lead to erroneous estimates of soil moisture.

The third area of this study is to define sources of spatial resolution constraints for soil moisture information as currently used for crop yield conditions (forecasting) and streamflow forecasting. Having defined the spatial resolutions and their constraint sources, the research evaluation task is to evaluate qualitatively the improvement in soil moisture information that would result by changing from a 10-km to a 1-km resolution.

2. RAINFALL PATTERN ANALYSIS

2.1 Previous Studies on Rainfall Patterns

Rainfall is a prime contributor to the pattern of soil moisture. At a particular instant in time, it is known that intense rainfall cells having diameters of about 2.5 km can occur (Crane, 1979). The cell diameter, as defined by Crane (1979), was the distance across the cell as detected by radar where the radar reflectivity fell to one-half of the maximum. The one-minute rainfall rate maps presented by Changnon and Huff (1980, p.121) show cell diameters, again using the one-half the maximum rate as the definition, of between 2.7 and 4.1 km. However, these near instantaneous rainfall rate patterns and the radar patterns are not representative of the total rainfall-amount patterns produced during the course of an entire storm event. Crane and Hardy (1981) have demonstrated that storms characterized by rainfall rates of more than about 12 mm hr^{-1} are usually made up of several storm elements with each element containing several clusters, and in turn the clusters may be made up of from one to about six individual cells. Similarly, Changnon and Huff (1980, p.25) present hourly maps of rainfall amount over a 10-hour period for a storm on 21 August 1953, and these maps clearly demonstrate the passage of three distinct rainfall events being advected over the same region of the network. This feature of distinct cells passing over the same area was also demonstrated in storm data presented by Eddy (1978).

It is the summation or integration of the rainfall over the entire storm period over a day which is of concern for this particular study. These patterns have much larger scales than exhibited by the individual cells within a storm. For example, Huff and Shipp (1969) present correlation patterns of total rainfall amounts about the central rain gage for summer storms in central Illinois. Over a distance of 5 km from the central gage, the correlation is very high and ranges from a low of .9 for air mass storms to about .97 for storms associated with low centers or for steady rain. Consequently, it is evident that the rainfall amount patterns produced by an entire storm have larger scales than the scales seen instantaneously by a weather radar or the scales represented by one-minute rainfall rate maps.

One of the major concerns for this study is how representative is the rainfall pattern as determined from given raingage networks. With an average spacing of 4.8 km as occurs in the Chickasha, Oklahoma rain gage network, Mignogno et al. (1980), report that the correlation of precipitation amount between neighboring gages averages 0.9 for all precipitation types combined. This correlation is consistent with the values given by Huff (1979) for different types of storms in central Illinois. On the other hand, Fogel and Duckstein (1969) report much larger variability in Arizona storms in which the duration was less than two hours; these authors analyzed storm data for a 50 km² network with an average gage spacing of 1.6 km. It was found that the rain amounts at adjacent gages were better correlated as the amount at the center of the storm increased. For example, if the storm center rainfall was 25 mm, the amount at 5 km is, on the average, only .4 mm or about 1.5% of the maximum; if the storm center rainfall was 100 mm, then at 5 km the rainfall amount is about 57% of the maximum. Eddy and Hembree (1978) also demonstrate this feature by the consideration of both a small storm with maximum rain amount of less than 2.5 mm in a total area of about 62 km² and a large storm in which the average rainfall amount over an area of about 1700 km² was more than 5 mm. Eddy and Hembree (1978) used data from the Montana HIPLEX rain gage network which had an average separation distance of about 3.5 km. From an analysis of both radar and rain gage data for the small storm, Eddy and Hembree (1978) state "(the storm) wormed its way rather nicely between the gages".

It is evident that the spacing of the rain gages in a network is an important factor for the accurate depiction of rainfall patterns. Moreover, a network designed for giving the distribution of annual rainfall will probably be inadequate for depicting the patterns of individual storms. In this regard, the results of past studies as summarized above point to the inference that networks having gage spacings of about 5 km will be adequate for describing the patterns of entire storms or of daily rainfall amounts. In addition, for a given network, the patterns of rainfall amounts will be more representative of the true patterns as the total rain amount over the network increases.

The primary objective of the rainfall pattern analysis in this study is to determine the spatial characteristics of rainfall amount for entire

storm periods. These characteristics are considered to be adequate to provide the information needed as a first step in describing soil moisture patterns. The variability of the rainfall amounts between different storm types is also presented.

2.2 The Sources of Rain Gage Data

The rain gage data used in this study were obtained from two sources; these are from (1) Project HIPLEX (High Plains Cooperative Program) of the Water and Power Resources Service (formerly the Bureau of Reclamation) and (2) the U.S. Department of Agriculture's Washita River Watershed observation network centered near Chickasha, Oklahoma.

The HIPLEX rain-gage networks at Goodland, Kansas and Big Spring, Texas provided data for the summer periods of May-August 1977 and 1978; data for a few storms which occurred in April, September or October were also included. The Goodland site contained 38 gages with a network density of 1 gage per 16.8 km^2 (spacing of about 4.5 km). The Big Spring network contained 68 gages with an average density of 1 gage per 104 km^2 (spacing was variable from 4 to 12 km). Figures 2-1 and 2-2 show the rain gage placements for the Goodland, Kansas and Big Spring, Texas networks. The rain gage information for both sites was stored in 15-minute intervals.

For the purposes of this study, a storm in the HIPLEX networks was defined by a minimum precipitation duration of 30 minutes, and a particular gage must have reported a minimum precipitation amount of 0.01 inches before it was counted as contributing to the storm pattern. Separate storms were identified when they were separated by a period of three hours or more in which no rain was observed in the network; usually the storms had durations of less than 12 hours, but on a few occasions storms in the HIPLEX networks had durations exceeding 48 hours. The cases were selected for plotting when a minimum of 90% of the network gages reported precipitation. Consequently, some small weak convective storms, which only covered a fraction of the network, were eliminated; this limitation was imposed in order to exclude storms which would have a minimal effect on soil moisture.

The rain-gage network at Chickasha, Oklahoma furnished information for the non-summer periods of September-May 1976 and 1977. The network

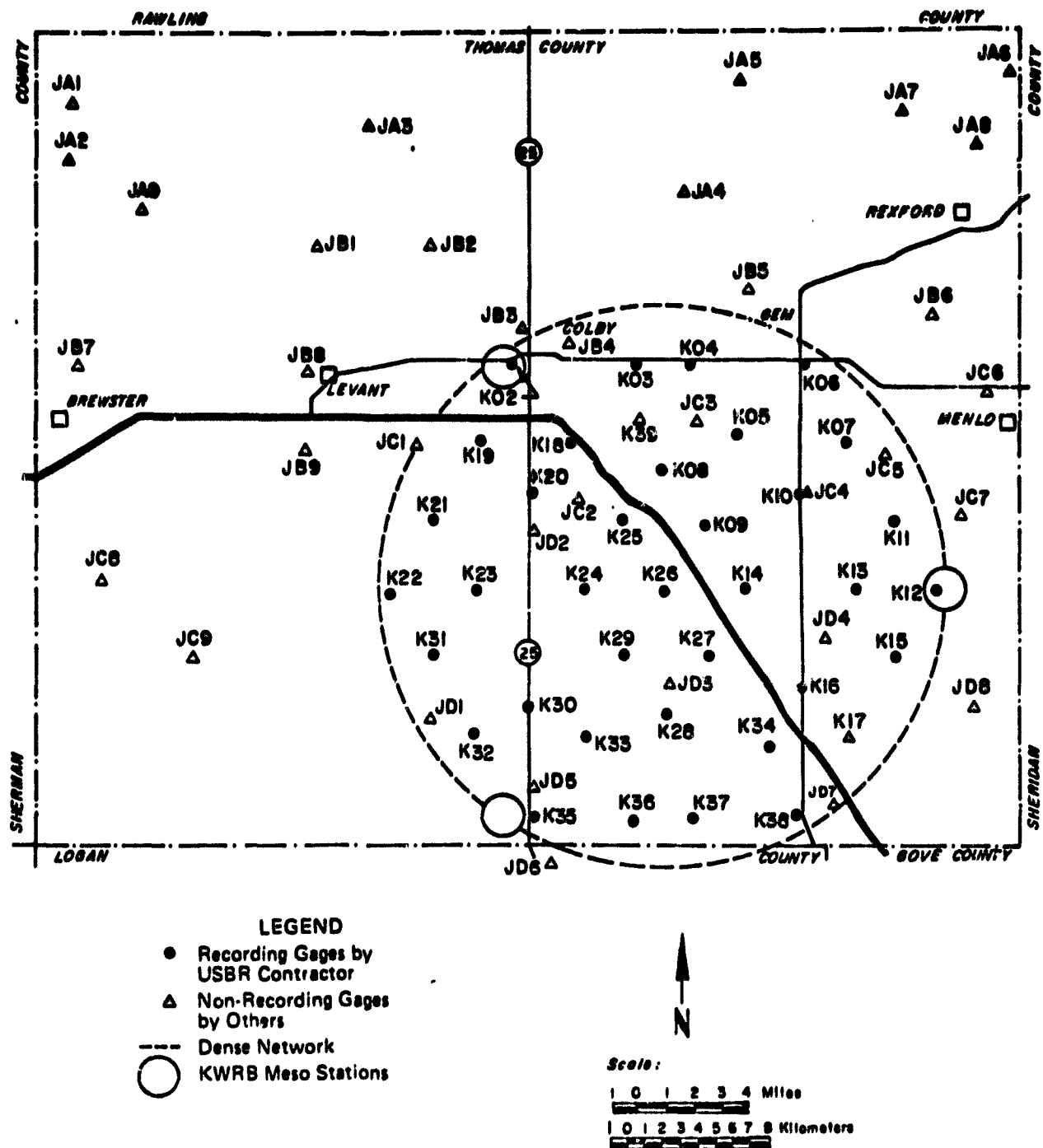


Figure 2-1 Location of the HIPLEX rain-gage network in the Goodland-Colby, Kansas area

contained 168 gages with a spacing between gages of about 4.8 km (Mignogno et al., 1980). Figure 2-3 shows the placement of rain gages for the Oklahoma network. The precipitation amounts were for 24-hour intervals. Therefore, the storm duration as defined for the Oklahoma data was for a fixed period of 24 hours.

The intent of this study is to obtain patterns of rainfall for all seasons. Only summer storms were observed during the HIPLEX programs. Therefore, data for non-summer storms were obtained from the Oklahoma network. Figure 2-4 shows the monthly distribution of the number of storm days used for this study. There were 20 days of storm data from Texas, 24 days from Kansas, and 129 days from Oklahoma. The number of storm days analyzed totaled 173.

2.3 The Analysis of the Data

The HIPLEX data from the Kansas and Texas networks were analyzed by means of a contour plotting routine (Water and Power Resources Service, a) which provided isohyets of the storms. The output was obtained from an interactive computer display and an example is illustrated in Figure 2-5. The Oklahoma data were not available on computer tape or cards and consequently it was most efficient to hand plot the data and carry out a manual analysis of the isohyets. The contour intervals for the HIPLEX data were between 0.1 and 0.2 inches whereas the intervals for the Oklahoma data were between 0.01 and 0.2 inches; the larger intervals were used when the maximum rainfall amount was large.

Once the contours of rainfall amount were obtained, the problem remained of how the patterns were to be catalogued. Since the primary objective was to determine the spatial features of individual storms, a spatial correlation analysis about the central gage of the network, as was carried out by Huff and Shipp (1969), was not considered to be an optimum technique. That is, an objective correlation analysis taken without regard to the position of the storm centers would not provide the required statistical information about the structure of the storms. A correlation analysis centered around a storm maxima was a possibility, but this was thought to be an unnecessarily detailed approach considering

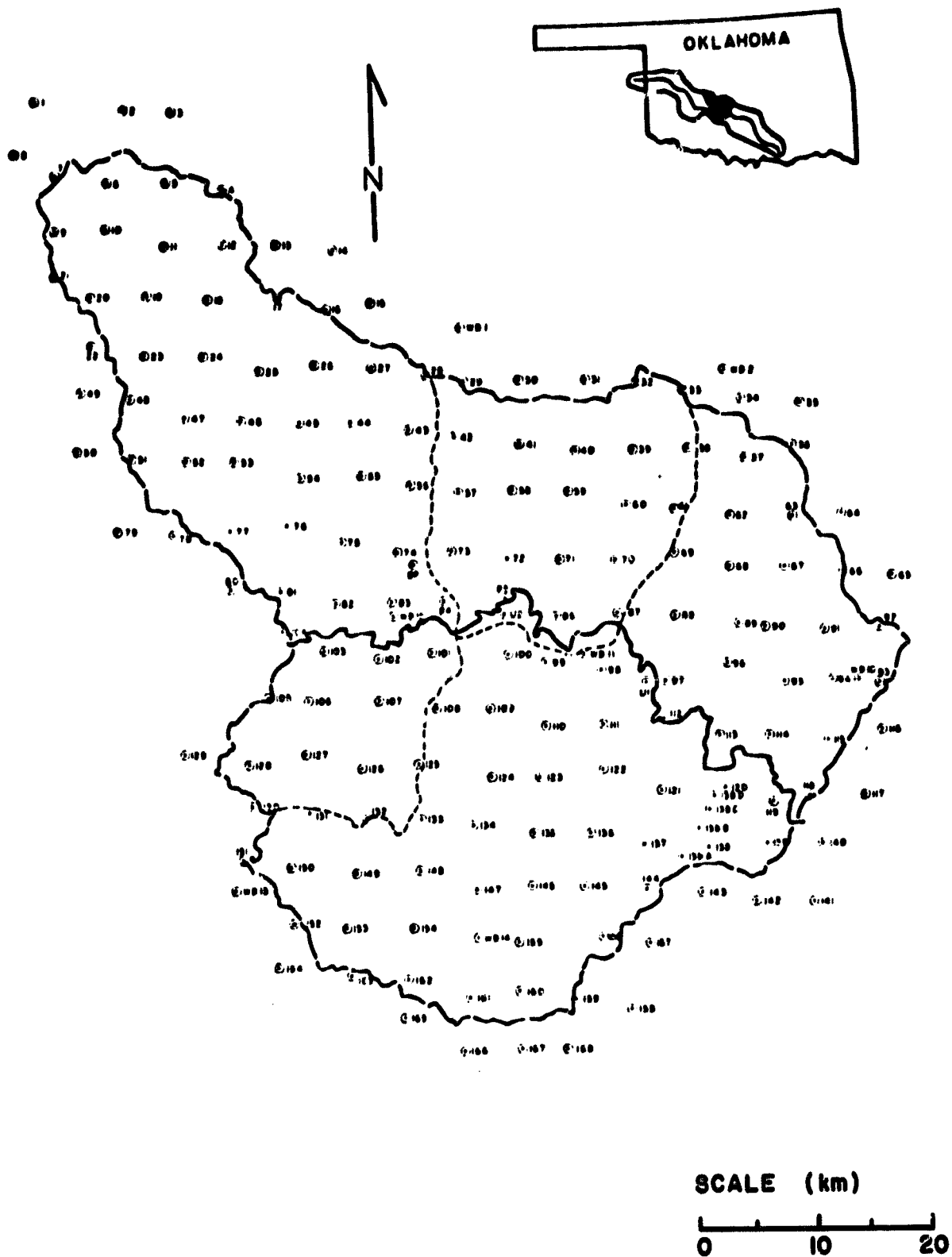


Figure 2-3 Location of the HIPLEX rain-gage network in the Washita River Watershed area

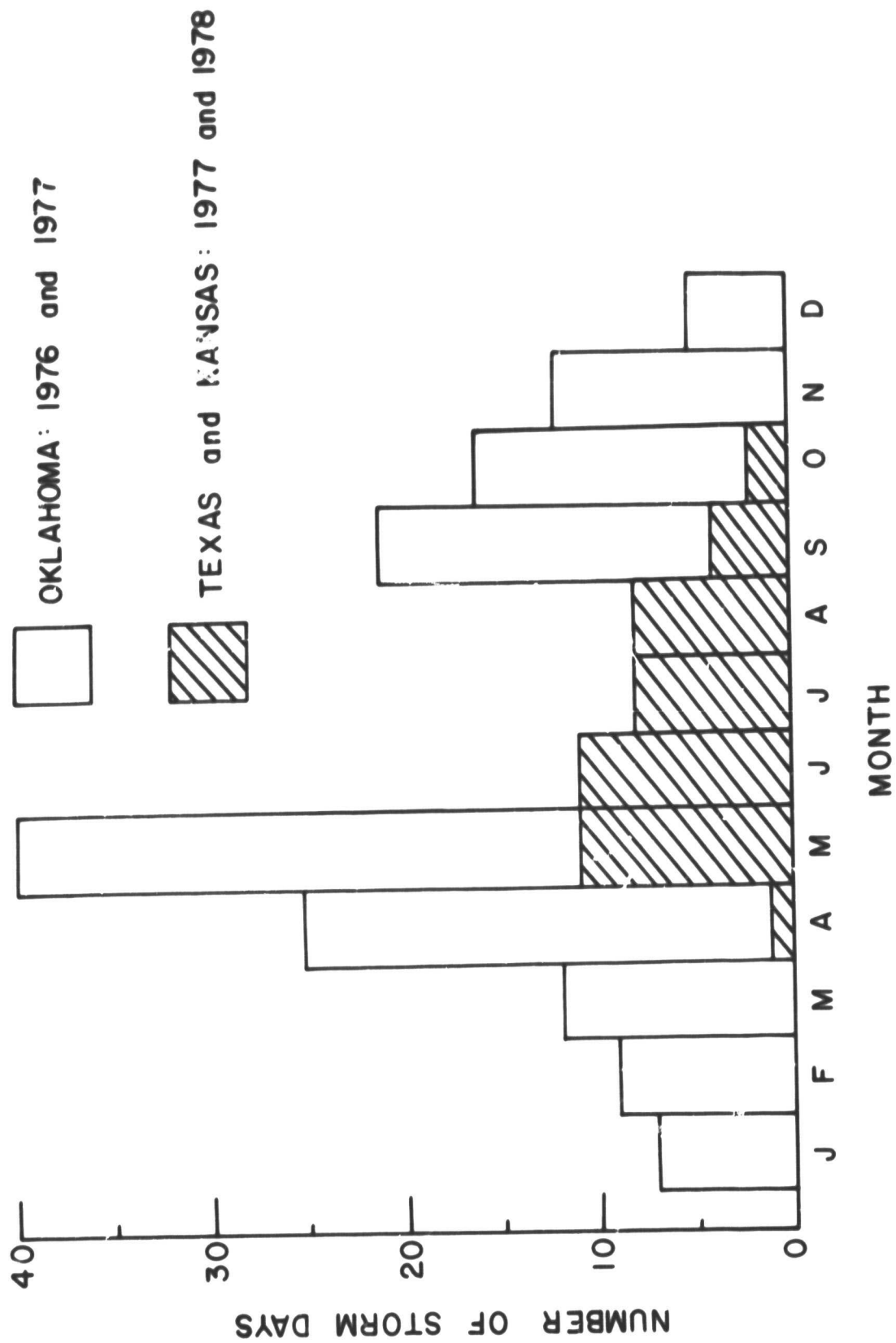


Figure 2-4 Monthly distribution of storm days for Oklahoma and for Texas and Kansas combined

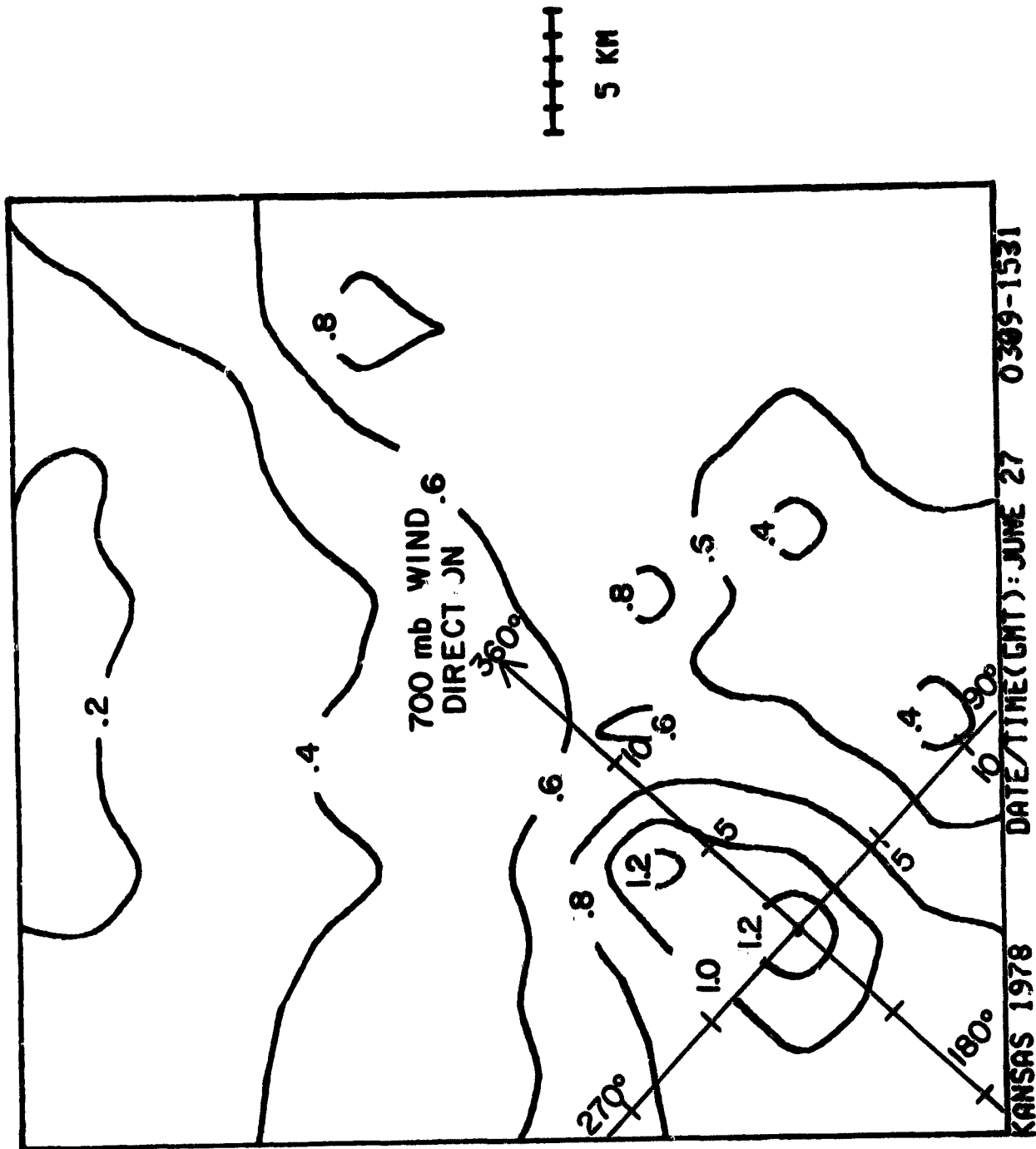


Figure 2-5 An example of the contours of rainfall amount which were obtained from the computer plotting routine. The data are from the Kansas HIPLEX program on 27 June 1978 when a maximum of 1.41 inches of rain was recorded at one of the gages.

that the data were obtained from gages spaced at intervals of about 5 km. The technique selected was rather straightforward and was designed to obtain the desired feature of the storms in a quantitative manner. This technique involved determining the probable direction of the storm motion by using the direction at the 700 mb level. The direction was obtained from radiosonde data which were considered to be representative for conditions over the network at the time of the storm. A grid in this direction and perpendicular to the direction was then centered over the maximum rainfall amount for the storms in the network. By making measurements parallel and perpendicular to the general direction of storm movement, information on the storm shape will be obtained. The correlation patterns presented by Huff (1979) for Illinois show an orientation effect for both individual storm rainfall and annual rainfall; the orientation is generally southwest to northeast which is the most frequent direction of travel for storms moving across Illinois. Often, there would be more than one maximum within the analyzed field and in these cases each maximum was considered as a separate storm. Thus, although 173 storm days were considered, a total of 494 individual storm maxima were identified and measurements from all of these were obtained. Once the rainfall maximum had been identified and the grid aligned along the 700 mb direction, the precipitation amount at a distance of 5 km (and sometimes 10 km) from the storm maximum was determined in the four directions of the grid. An example of the grid as it would apply to the storm of 27 June 1978 is given in Figure 2-5. A direction of 360°, as used in this analysis, is the direction of the 700 mb wind which was applicable for each of the storms. These basic measurements provided an estimate of how rapidly the rainfall amount diminished from the storm maximum. A rapid drop would indicate a small storm cell, whereas a slow decrease in the amount would indicate a generally larger storm. The format for the information extracted for each storm cell and the listing of the data for the 494 storms are given in Appendix A.

In addition to the precipitation data, descriptive parameters for synoptic classification were also collected. Initially, each case was assigned a type code for both the 500 mb and the surface synoptic patterns. Although 10 types or patterns were originally assigned, it was found that only four types occurred with significant frequencies.

These were identified by the surface weather map and are as follows:

- cold front,
- stationary front,
- surface high, and
- surface low.

The surface high cases were those in which a high pressure dominated the regions east of the networks resulting in a generally easterly flow or upslope flow over the network under consideration. The surface high classification is the one that is used to indicate the situation often catalogued or identified as air-mass showers. The surface low cases were characterized by a low pressure to the west of the networks and generally southwest to northwest flow over the network. The frontal cases were chosen by the proximity to the network of the frontal type.

The classification of the storm days by synoptic scale features proved to be difficult because two or more choices for a given situation were sometimes possible. Figures 2-6 and 2-7 illustrate the difficulty. A day classified as a surface low is shown in Figure 2-6; a weak low is centered near the southwest corner of Kansas with a stationary front running from southwest to northeast across the state. The flow at the surface over the HIPLIX rain gage network in Kansas is easterly and the rainfall pattern shows an increase from east to west. A day classified as a surface high is shown in Figure 2-7; a high is to the north of Kansas, but there is a front in a similar position as for the case in Figure 2-6 and the flow over the network is also easterly. The rainfall pattern is more showery in nature than for the case shown in Figure 2-6.

Both of the cases in Figure 2-6 and 2-7 might have been classified as stationary front cases; it is also evident that the basic flow pattern differs only slightly for the cases chosen to illustrate a surface low and a surface high classification. With these types of difficulties in using a synoptic classification scheme, there is bound to be some overlap in the attempts to isolate the rainfall patterns associated with large scale weather patterns.

There is, however, a more basic problem with using synoptic-scale features to classify precipitation which generally occurs at much smaller

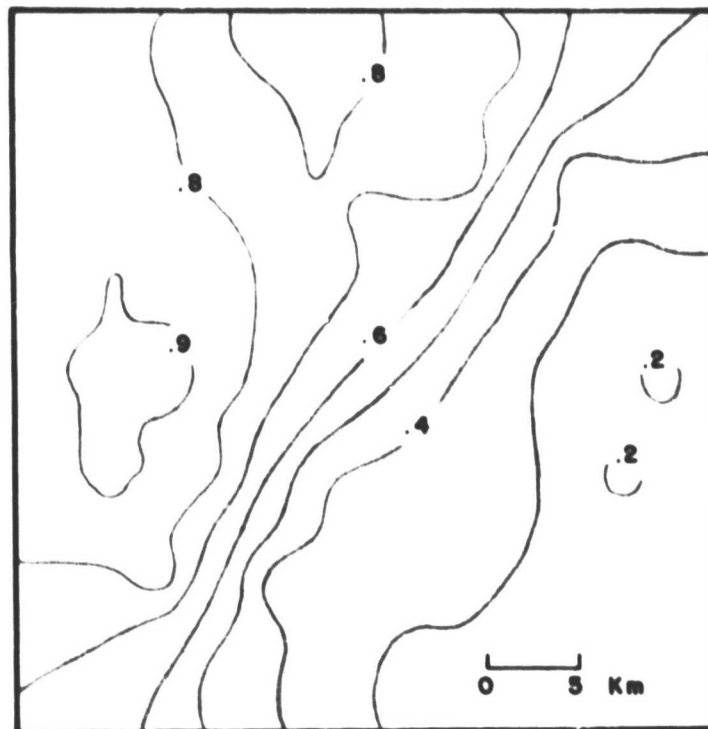
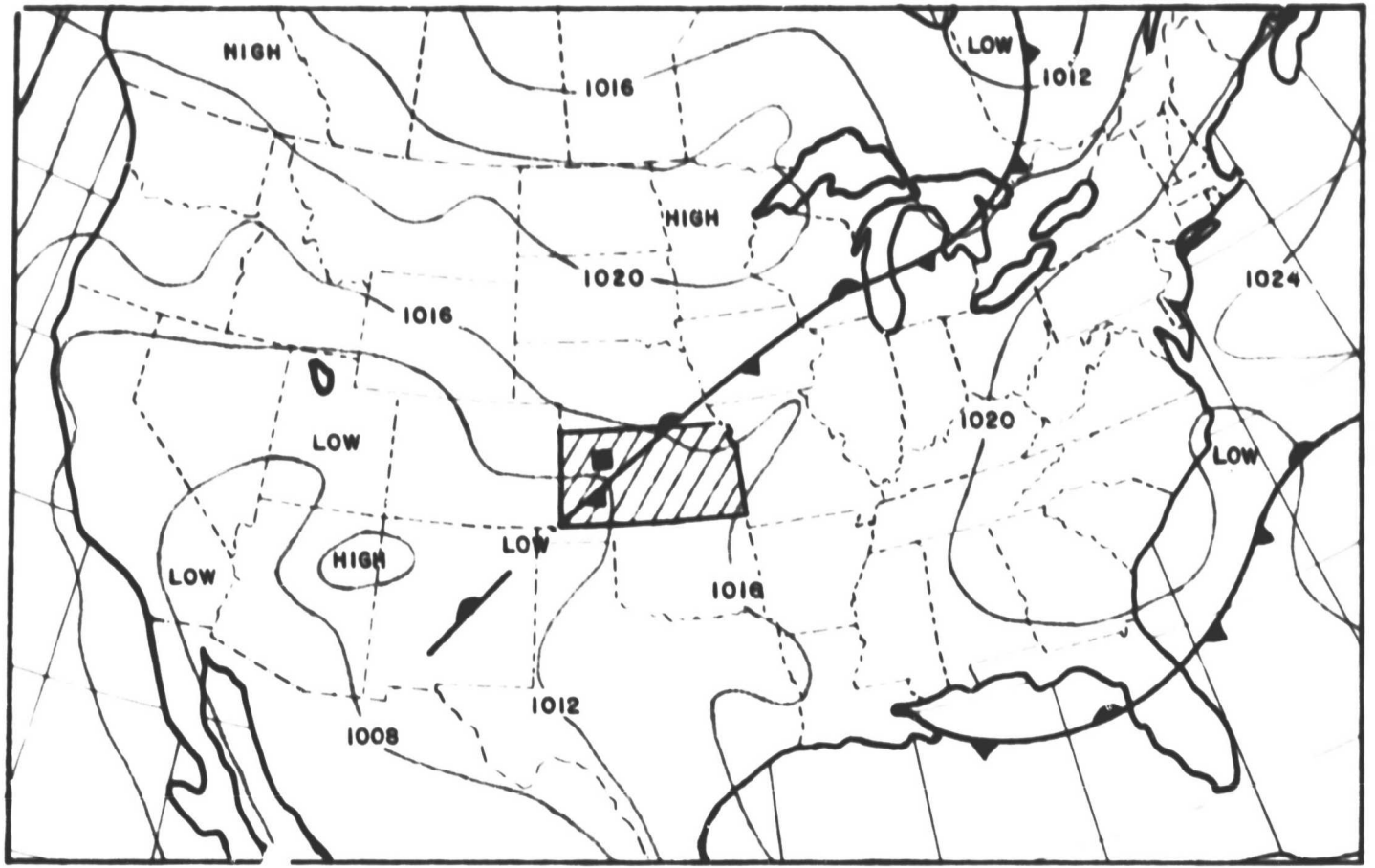


Figure 2-6 Synoptic pattern (above) and rainfall amounts in inches over the Kansas HIPILEX network (below) for 20 July 1978. The day was classified as "surface low". The location of the network in Kansas is shown by the solid square.

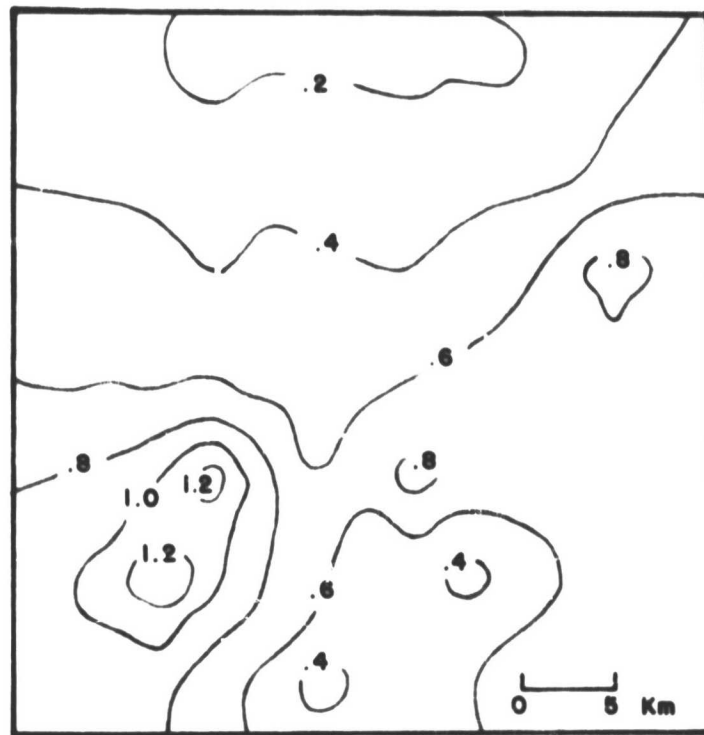
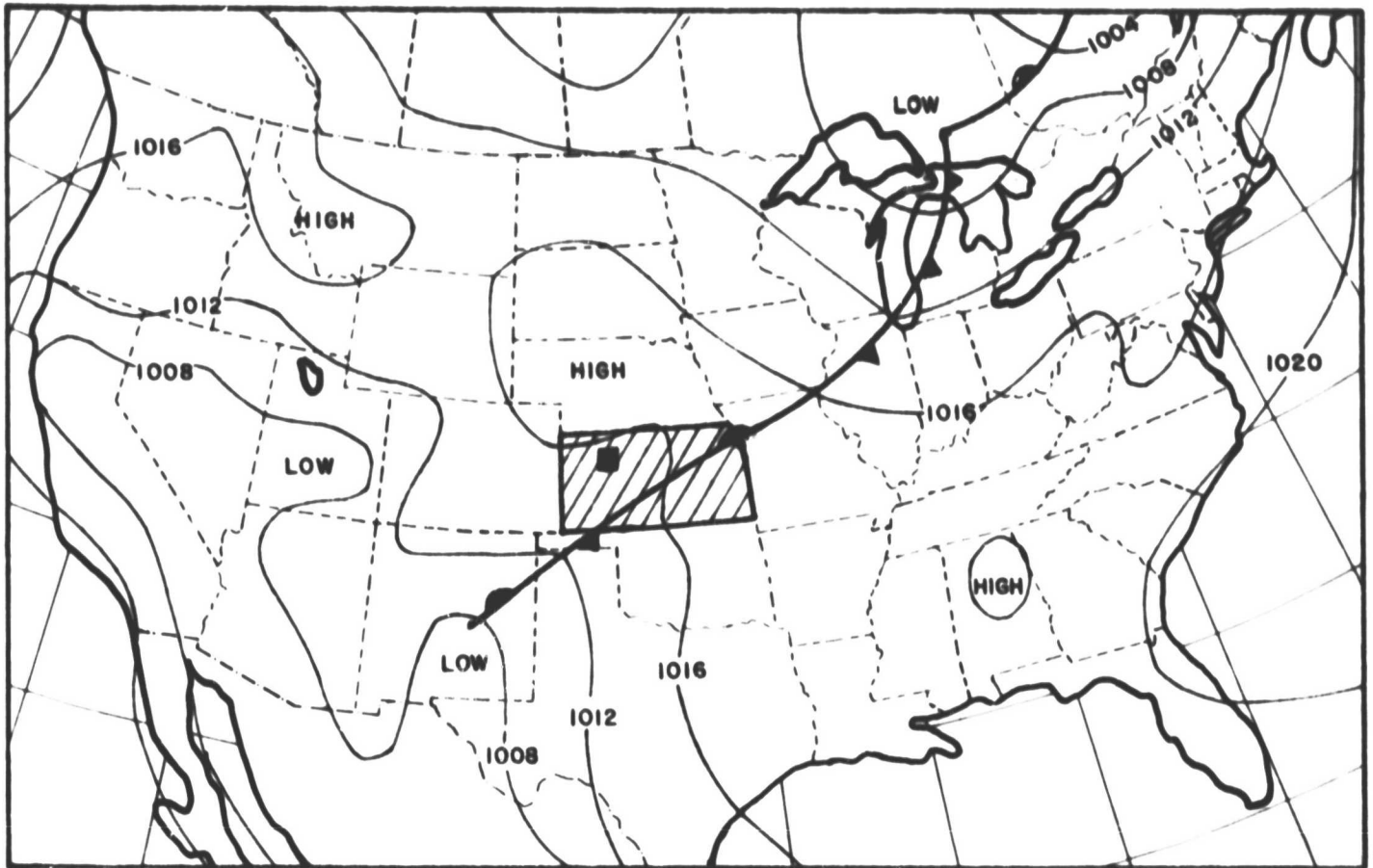


Figure 2-7 Synoptic pattern (above) and rainfall amounts in inches over the Kansas HIPLEX network (below) for 27 June 1978. The day was classified as "surface high". The location of the network in Kansas is shown by the solid square.

scales. The problem as quoted from Lilly (1975) is "that the actual development of convective cloud arrays occurs on a considerably smaller scale (than the synoptic scale) and often with a degree of organization which is clearly nonrandom but also largely unresolvable from conventional data processed in conventional operational ways". Ludlam (1976) also describes sub-synoptic scale features which may control the precise location of convective activity, although he emphasizes that favorable large scale flows must be present before any important convection is initiated. These interactions between synoptic-scale and smaller scales cannot be sorted out in the present study in which the days were classified only through synoptic-scale features.

Data from the four points of the grid at a 5 km (and sometimes also at a 10 km) distance from the storm center were extracted for all storm cells. The total of the maximum rainfalls for the 355 Oklahoma storms was about 210 inches, and for the 139 storms in the Kansas and Texas networks it was about 190 inches. The breakdown of the number of storms having a maximum rainfall within three categories for both the HIPLEX and the Oklahoma storms is presented in Table 2-1. For the purposes of statistical analysis, the rainfall amount patterns were normalized to the maximum precipitation for the storm.

TABLE 2-1
CATEGORIES OF RAINFALL AMOUNT USED IN THE ANALYSIS

Rainfall Amount	Code	Number of Storms	Percentage Occurrence
HIPLEX			
less than 1.0 inch	1	44	31.7%
1.0 to 1.75 inch	2	48	34.5%
greater than 1.75 inch	3	47	33.8%
	Total	139	
OKLAHOMA			
less than 0.25 inch	1	110	31.0%
0.25 to 0.75 inch	2	115	32.4%
greater than 0.75 inch	3	130	36.6%
	Total	355	

The rainfall amount categories in Table 2-1 refer to the maximum amount recorded at a gage for a particular storm. The amounts are separated into three categories of about equal frequency although the HIPLEX rainfall categories are considerably larger than those for Oklahoma.

Each of the rainfall amount categories shown in Table 2-1 were subdivided into the four weather types (cold front, stationary front, surface high, or surface low). Then, for each storm, the value of the rainfall amount, expressed as a ratio to that of the maximum for the storm, was obtained at distances of 5 km and often also at 10 km in each of the four directions of the grid as illustrated in Figure 2-5. For each weather type and for each of the rainfall amount categories of Table 2-1, the normalized value at each grid point was tabulated and average and standard deviation values were calculated. This led to a total of 22 normalized patterns of storm types. The maximum number of categories would be 24 because there were four weather types for three rainfall categories for both the HIPLEX and the Oklahoma networks. However, there were insufficient cases to warrant the computation of average and standard deviation values for the stationary front with rainfall less than .25 inches in Oklahoma and for a surface low with rainfall greater than 1.75 inches in the HIPLEX networks.

2.4 The Results of the Statistical Analysis

An example of one of the patterns of rainfall amount is shown in Figure 2-8. The pattern is for storms classified as occurring with a stationary front when the maximum rainfall amount of the storms fell between 1.0 and 1.75 inches in the Texas and Kansas HIPLEX networks. The upward direction of the figure is in the direction of the wind at 700 mb. The values along the axes are the mean values of the normalized rainfall amount at 5 and 10 km from the storm center. The numbers in brackets are the standard deviations computed for the approximately 17 cases which were used to determine the pattern. For each point in the grid the number of available cases usually varied because locations at 5 or 10 km from the storm center would sometimes fall outside the rain gage network.

The pattern in Figure 2-8 is almost symmetrical although it is somewhat elongated in the direction of storm motion. The storms which

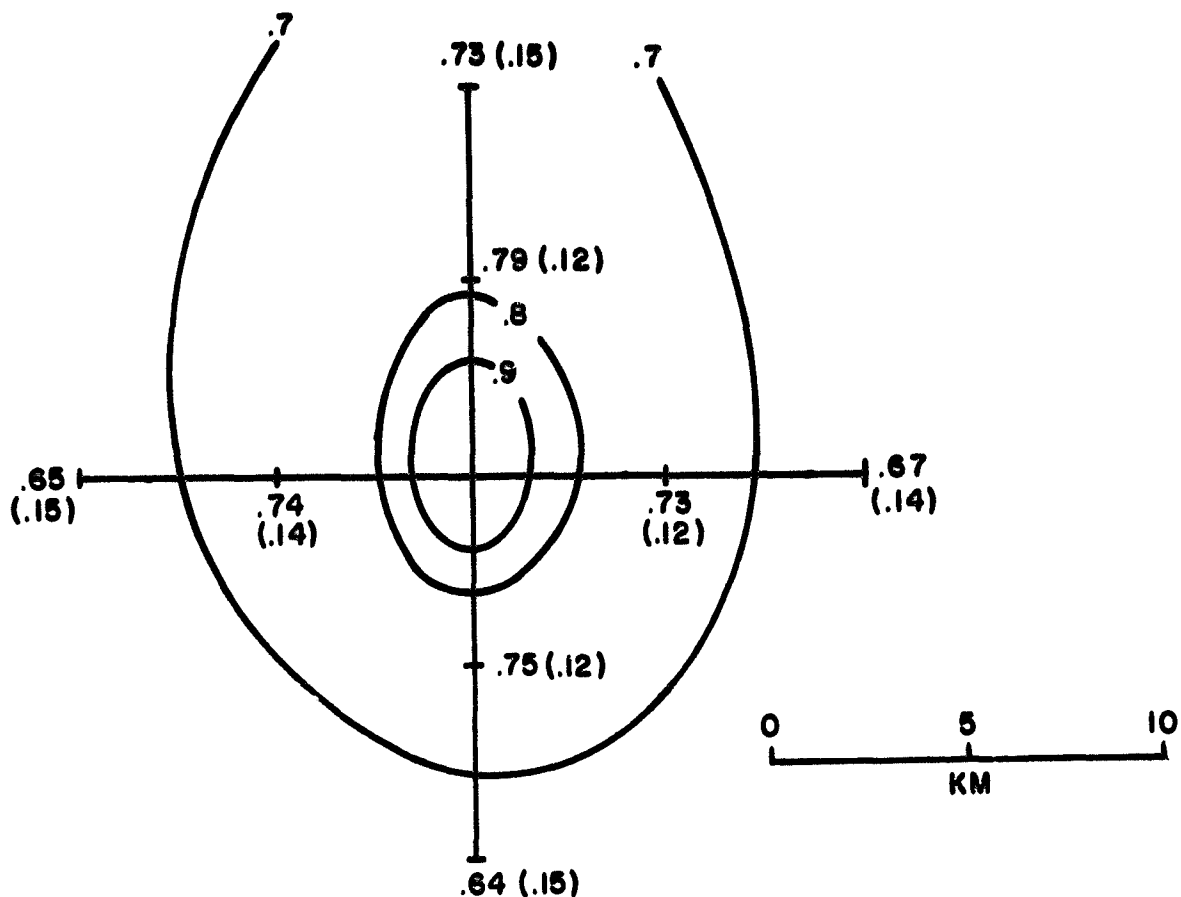


Figure 2-8 The average pattern of rainfall amount, normalized to the amount at the storm center, for summer storms in the Texas and Kansas HIPLEX rain gage networks. The pattern is for the 17 stationary front cases when the maximum rainfall of the storms observed in the network ranged from 1.0 to 1.75 inches. The number in brackets is the standard deviation for the rainfall amount at the point indicated.

make-up the pattern are relatively large since rainfall amounts at 10 km are still about two-thirds of the value at the storm center. The pattern shown in Figure 2-8 is fairly typical of those found for the other 21 categories; all 22 patterns are included in Appendix B.

One of the more variable patterns is shown in Figure 2-9. It is for non-summer storms occurring over the Oklahoma rain gage network and classified as being associated with a stationary front. The maximum rainfall amount of each storm ranged from 0.25 to 0.75 inches and approximately 7 cases were included. In contrast to the almost symmetrical pattern of Figure 2-8, the Oklahoma storms of Figure 2-9 exhibit considerable differences between the along-track and the cross-track values fall to 0.17 or lower, whereas the 10 km along-track values are 0.53 and 0.60. Thus, the storms are definitely elongated in the direction of the storm motion and the gradient in the cross-track direction is much larger than that for the data on the HIPLEX storms represented in Figure 2-8. The standard deviations of the values of Figure 2-9 are somewhat larger than these for most of the patterns. Generally, the standard deviations are about 15% of the mean value at the 5-km locations and about 25% of the mean value at the 10-km locations.

The mean values of the normalized rainfall amounts at 5 km, and also at 10 km when these were obtained, are shown in Table 2-2 for the HIPLEX storms and in Table 2-3 for the Oklahoma storms. The values are also plotted and the patterns drawn for all the 22 cases. Although there is considerable variability of the values between the categories given in Tables 2-2 and 2-3, generally the rainfall amounts along the axis of storm motion were about 10% higher than at the same distances perpendicular to the storm axis for the Oklahoma storms; the along-axis values were only 5% higher than the cross axis values for the HIPLEX storms. This difference between the HIPLEX and Oklahoma storms may be caused by the different temporal resolution of the data sources (Section 2.2). In this regard, the 24-hour data for Oklahoma during the winter generally show smaller storms than those depicted by the finer temporal data for the HIPLEX sites; that is, the rainfall amounts for the Oklahoma storms fall-off more rapidly from the storm center than for the HIPLEX storms.

There is no consistent trend of the normalized rainfall amount values

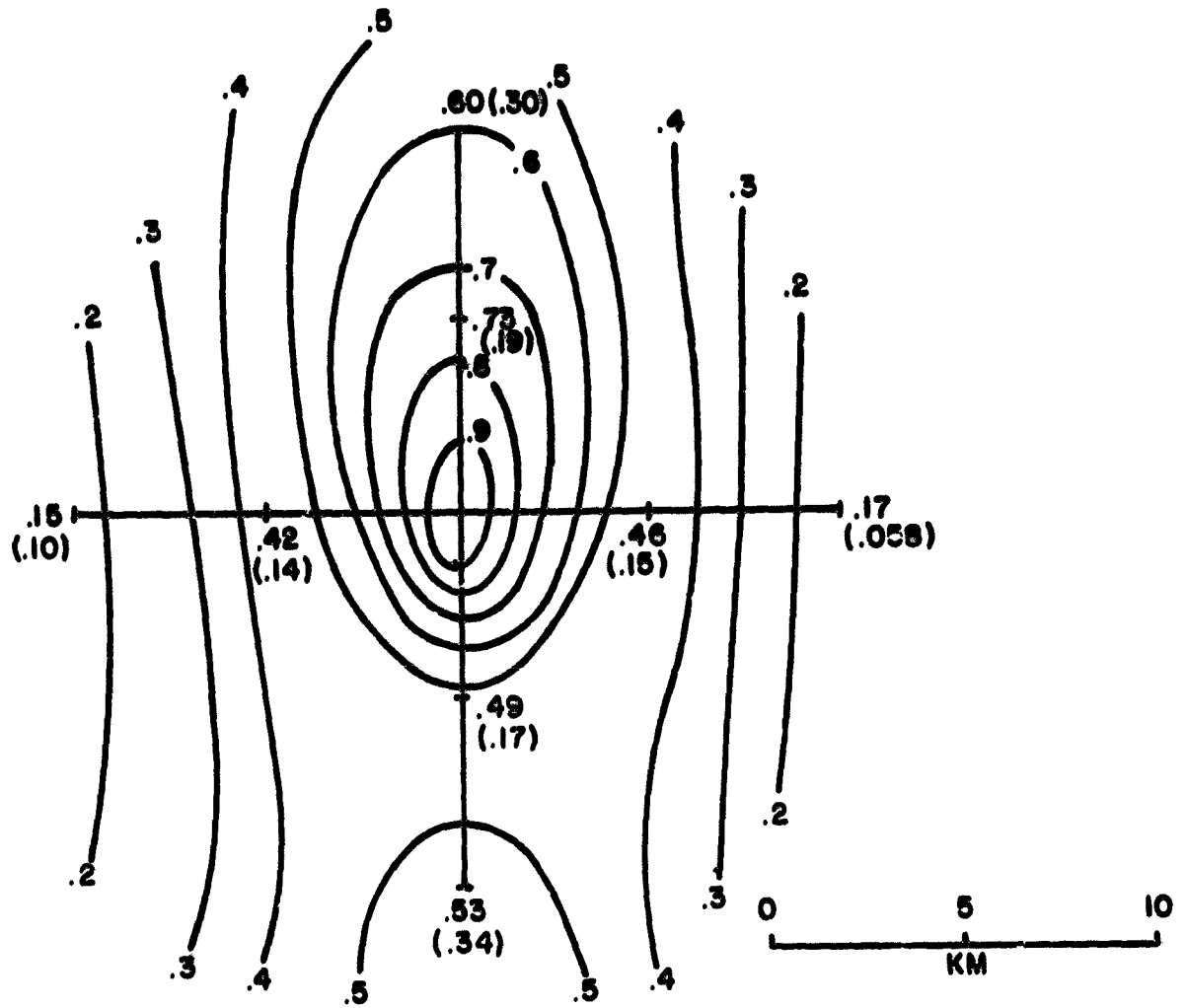


Figure 2-9 The average pattern of rainfall amount, normalized to the amount at the storm center, for non-summer storms in the Oklahoma rain gage network. The pattern is for the 7 stationary front cases when the maximum rainfall of the storms observed in the network ranged from 0.25 to 0.75 inches. The number in brackets is the standard deviation for the rainfall amount at the point indicated.

TABLE 2-2

THE VALUE OF THE RAINFALL AMOUNTS, EXPRESSED AS
A RATIO OF THE STORM MAXIMUM,
AT THE LOCATIONS INDICATED FOR THE HIPLEX DATA

Type of Pattern	Maximum Rainfall Amount (inches)	REDUCTION IN RAINFALL AMOUNT							
		Direction from Storm Motion (deg)/Distance (km)							
		360/5	360/10	90/5	90/10	180/5	180/10	270/5	270/10
Cold Front	<1.0	.76		.77		.69		.73	
	1 - 1.75	.77	.64	.73	.61	.77	.68	.75	.60
	>1.75	.77	.49	.73	.53	.79	.59	.70	.38
Stationary Front	<1.0	.80	.77	.74	.70	.77	.62	.75	.63
	1 - 1.75	.79	.73	.73	.67	.75	.64	.74	.65
	>1.75	.72		.64		.66		.62	
Surface Low	<1.0	.80		.78	.70	.78	.60	.78	.72
	1 - 1.75	.80	.76	.75		.85		.75	
Surface High	<1.0	.66		.68		.72		.64	
	1 - 1.75	.78		.65		.72		.73	
	>1.75	.82	.74	.79	.72	.81	.69	.77	.68

TABLE 2-3

THE VALUE OF THE RAINFALL AMOUNTS, EXPRESSED AS
A RATIO OF THE STORM MAXIMUM,
AT THE LOCATIONS INDICATED FOR THE OKLAHOMA DATA

Type of Pattern	Maximum Rainfall Amount (inches)	REDUCTION IN RAINFALL AMOUNT Direction from Storm Motion (deg)/Distance (km)							
		360/5	360/10	90/5	90/10	180/5	180/10	270/5	270/10
Cold Front	<.25	.82	.55	.65	-	.76	.75	.66	.75
	.25 - .75	.80	.72	.62	.53	.72	.62	.63	.55
	>.75	.69	.54	.56	.44	.70	.52	.62	.53
Stationary Front	.25 - .75	.73	.60	.46	.17	.49	.53	.42	.15
	>.75	.83		.68		.83		.76	
Surface Low	<.25	.65		.59		.60		.55	
	.25 - .75	.74		.67		.68		.52	
	>.75	.76		.62		.75		.55	
Surface High	<.25	.65	.57	.66	.48	.63	.69	.60	.53
	.25 - .75	.77		.70		.74		.68	
	>.75	.76		.70		.73		.66	

at 5 km as a function of the maximum amount for the storm (see Tables 2-2 and 2-3 and Appendix B). At a distance of 5 km from the storm maximum for the HIPLEX data, the normalized rainfall amounts for the cold front and surface-low situations are about the same regardless of the maximum rainfall amount. For the stationary front patterns, the storms are smaller, in a normalized sense, for higher rainfall amounts, but the reverse is the case for the storms associated with the surface high patterns. For the Oklahoma data (Table 2-3), the cold front storms have smaller normalized values at 5 km when the precipitation amount exceeds .75 inches, but the reverse is the case for all other storm types.

In general, for the HIPLEX storms, the rainfall amount at 5 km from the storm center is about 75% of the storm maximum; at 10 km from the storm center, the rainfall amount is about 65% of the maximum. For the Oklahoma storms which occurred in the September to May period, the rainfall amount at 5 km is about 65% of the maximum and at 10 km it is about 50% of the maximum.

2.5 Implications of the Rainfall Patterns for Soil Moisture Retrieval

Figures 2-8 and 2-9 illustrate the variation of the rainfall patterns derived from an analysis of 494 individual storms which were separated into various categories of synoptic type and of the maximum rainfall amount at the storm center. The storm centers were chosen to be at locations within the network where the rain gages reported a peak in the rainfall amount. With a spacing of about 5 km between gages, it is probable that the actual peak of the storm would fall in-between the gages and thus, the maximum values used in this study would be underestimated. Nevertheless, for the storm total rainfall amounts or the daily amounts used in this study, the patterns obtained from the networks are considered to be representative of the actual patterns.

As shown for the patterns of rainfall amount in Figures 2-8 and 2-9 and for most of the patterns in Appendix B, the largest gradients in the rainfall amount occur within the first 5 km from the storm center. Viewing the rainfall patterns obtained in this study with a remote sensor having a dimension of about 10 would usually result in an underestimate

of the peak rainfall amounts. Beyond 5 km from the storm center, the gradients are considerably reduced and the patterns would be reasonably well represented by a system which had a 10-km resolution. The worst case or the pattern having the largest gradients is shown in Figure 2-9. Near the storm center, a sensor with a 10-km resolution may underestimate the true value by about 20%. But beyond 5 km from the center, a 10-km resolution would lead to a good representation of the patterns for all the categories of storms.

The general conclusion is that over about 75% of the storm area, a 10-km sensor will adequately represent the patterns of rainfall amounts for individual storms or daily values. Because the gradients are large near the center of the storms, the peak radius of rainfall amount will nearly always be underestimated when viewed with a 10-km system unless some correction factor is applied to the observed data.

3. MICROWAVE RESPONSE TO LAND FEATURES

3.1 General Factors Affecting the Microwave Brightness Temperature

Thermal microwave radiation from soil depends on the dielectric coefficient and the physical temperature of the soil. Moisture produces a marked increase in both real and imaginary parts of the dielectric coefficient of soil, leading to a decrease in the soil's emissivity. Since emissivity decreases with increasing dielectric constant, the brightness temperature of soils at microwave frequencies decreases with increasing moisture content. Experimental observations and theoretical calculations indicate that the emissivity of soils at microwave frequencies, defined as the ratio of the microwave brightness temperature to the physical temperature, can range from >0.95 for dry soils to <0.6 for very moist soils.

It should be noted that radiometers at shorter wavelengths (1-4 cm) are only sensitive to the surface moisture content. At longer wavelengths (5-25 cm), radiation from deeper in the soil can be obtained due to the longer skin depths for the longer wavelengths. For a fixed antenna diameter, the spatial resolution for space borne radiometers is nearly proportional to the wavelength (longer wavelength, coarser resolution). Atmospheric effects, on the other hand, decrease for longer wavelength. The atmosphere is essentially transparent above 5 cm.

The effect of the soil type on the dielectric coefficient is coupled to soil moisture, and consequently the soil type influences the microwave brightness temperature. The coupling results because of the different strengths by which water molecules adhere to the soil particles. In order to compensate for the differences in different types of soils, the brightness temperature data can be plotted as a function of the percentage of field capacity which becomes essentially independent of the soil type (Schmugge, 1977). Thus, the percentage field capacity provides a better description of the water availability to plants and the degree of soil saturation.

The surface roughness is yet another factor that affects the microwave brightness temperatures. It increases surface emissivity due to scattering and therefore, the brightness temperature of rough surface is

also expected to be higher. This results in the observational fact that emissivities are never lower than 0.6 for real soil surfaces. Choudhury et al. (1979) developed a single modification parameter to characterize roughness effect. The results indicate that roughness effects are large for wet soils where the difference between smooth and rough surfaces can be as great as 50°K. Since a comprehensive model to treat all scales of surface roughness at various wavelengths is not developed, the simple type of modification parameter proposed by Choudhury et al. (1979) can be introduced, and it can be treated as an additional noise contribution to the observed brightness temperatures.

Surface slope affects the observed brightness temperature due to the relative change in the look angle from the antenna to the surface. Emissivity of the vertical polarization component increases from nadir to larger look angles until the Brewster angle ($>60^\circ$) and then decreases with angle; emissivity of the horizontal polarization component varies in the opposite manner. For satellite sensors the look angle is usually between 45° and 55° . In this range a change of slope of 10° can affect the brightness temperature by 10° to 20° K.

A vegetation canopy essentially obscures the soil surface such that the sensitivity of soil moisture content to the brightness temperature is greatly reduced. Over forest areas, the soil moisture information is lost at all microwave wavelengths. For agriculture fields, the moisture information is essentially lost at shorter wavelengths (1-4 cm) but it can be retrieved at longer wavelengths (5-25 cm), although with less sensitivity than if the ground were bare. Complete modeling of the vegetation effect in the microwave region is not available, but its general tendency (increasing the observed brightness temperature with increasing vegetation) is well understood and can be applied.

The above summarizes the overall microwave response to various features of land surfaces. It has been demonstrated that microwave remote sensing is a useful means of soil moisture monitoring from space. There are limitations; for example, surface roughness and a vegetation canopy degrade the sensitivity to a certain extent. Various soil types and surface slope can add more uncertainty to moisture retrieval. However, over extended farming areas, these factors are usually at a spatial scale of more than 10 km. Therefore, sensors with a spatial resolution

of 10 km or less will be relatively unaffected by the scale of the variability in soil type and surface slope.

On the other hand, the microwave signature can be greatly affected if there are small water bodies within the field of view. Emissivity of water (~ 0.3) is substantially lower than land surfaces in the microwave range. A mixture of dry soil and water bodies in the same field of view can easily be interpreted as wet soil. Figure 3-1 demonstrates the effect of brightness temperature of dry land with various percentages of water body (or bodies) within one field of view (solid line). The dashed horizontal lines are the corresponding brightness temperatures with soil backgrounds of various moisture content but without any water body. It is obvious that finer spatial resolutions can greatly reduce the ambiguities which result from the presence of small water bodies. This topic will be treated in more detail in the next section.

3.2 Spatial Scales of Surface Features of the Study Region

3.2.1 General Features of the Study Region

In addition to soil moisture content, there are other factors of natural terrain which directly affect the microwave response of land backgrounds. Using microwave measurements, large areas having specific characteristics can be delineated, for example, large water bodies, urban areas, and forest. All these features have distinct signatures in the microwave spectral region. Over water bodies the brightness temperatures are low and exhibit substantial polarization differences. The brightness temperatures over urban areas are also low but with little polarization difference. Over forest and dense vegetated areas, the brightness temperatures are approximately the same as bare lands but with less polarization difference. These can be distinguished from dual polarized microwave measurements or simply from existing geological information.

The defined region for this study is shown in Figure 3-2. Major urban areas within the study region (between 32°N and 42°N , 104°W and 90°W) include Dallas/Fort Worth and Lubbock in Texas, Oklahoma City and Tulsa in Oklahoma, Wichita in Kansas, St. Louis and Kansas City in Missouri, Des Moines in Iowa and Omaha in Nebraska. These densely popu-

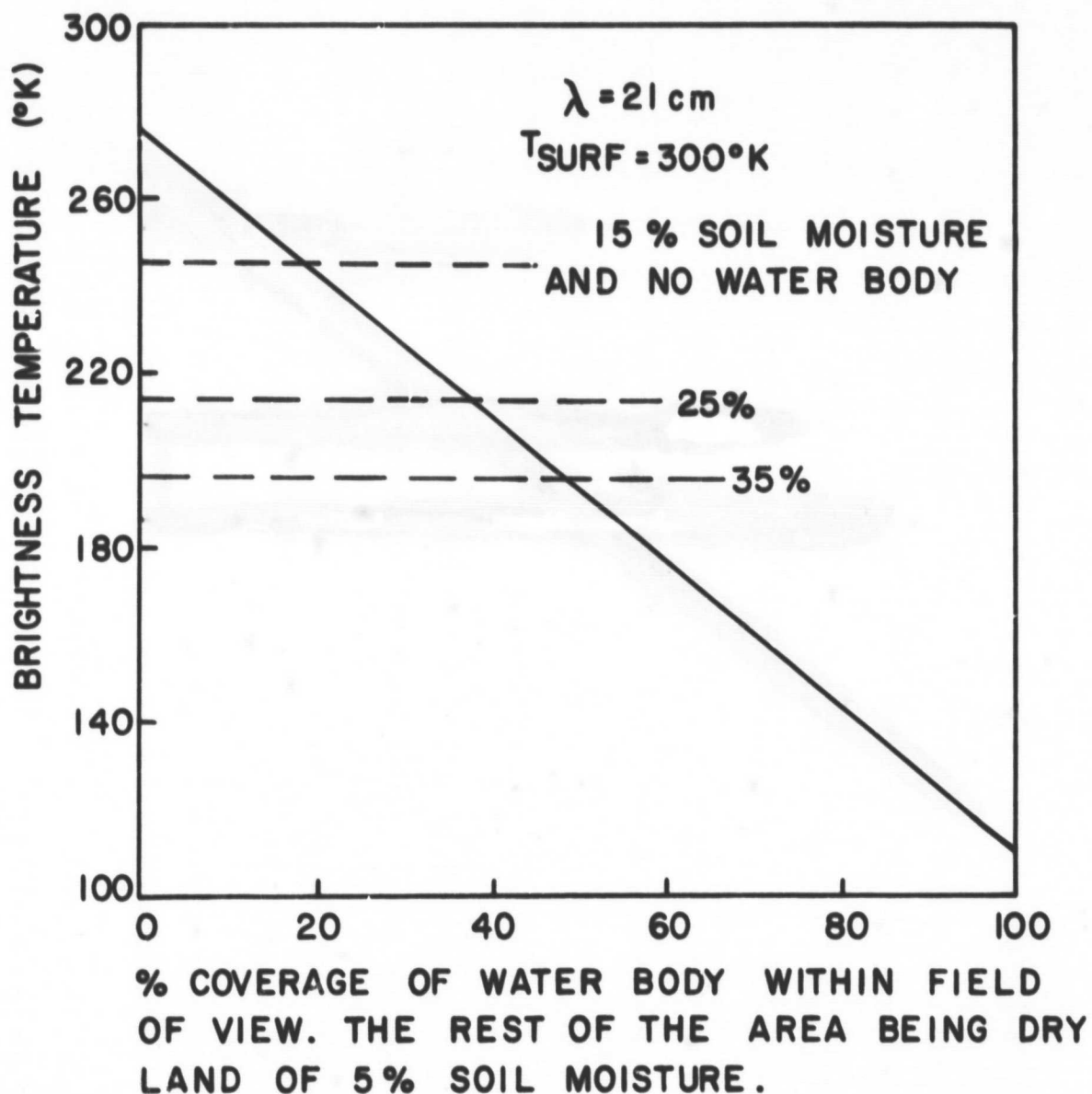


Figure 3-1 The response of microwave brightness temperature at 21 cm for backgrounds mixed with dry soil (5% soil moisture content) and various amounts of water bodies. The dashed horizontal lines are brightness temperatures with land background of various moisture content but no water body.

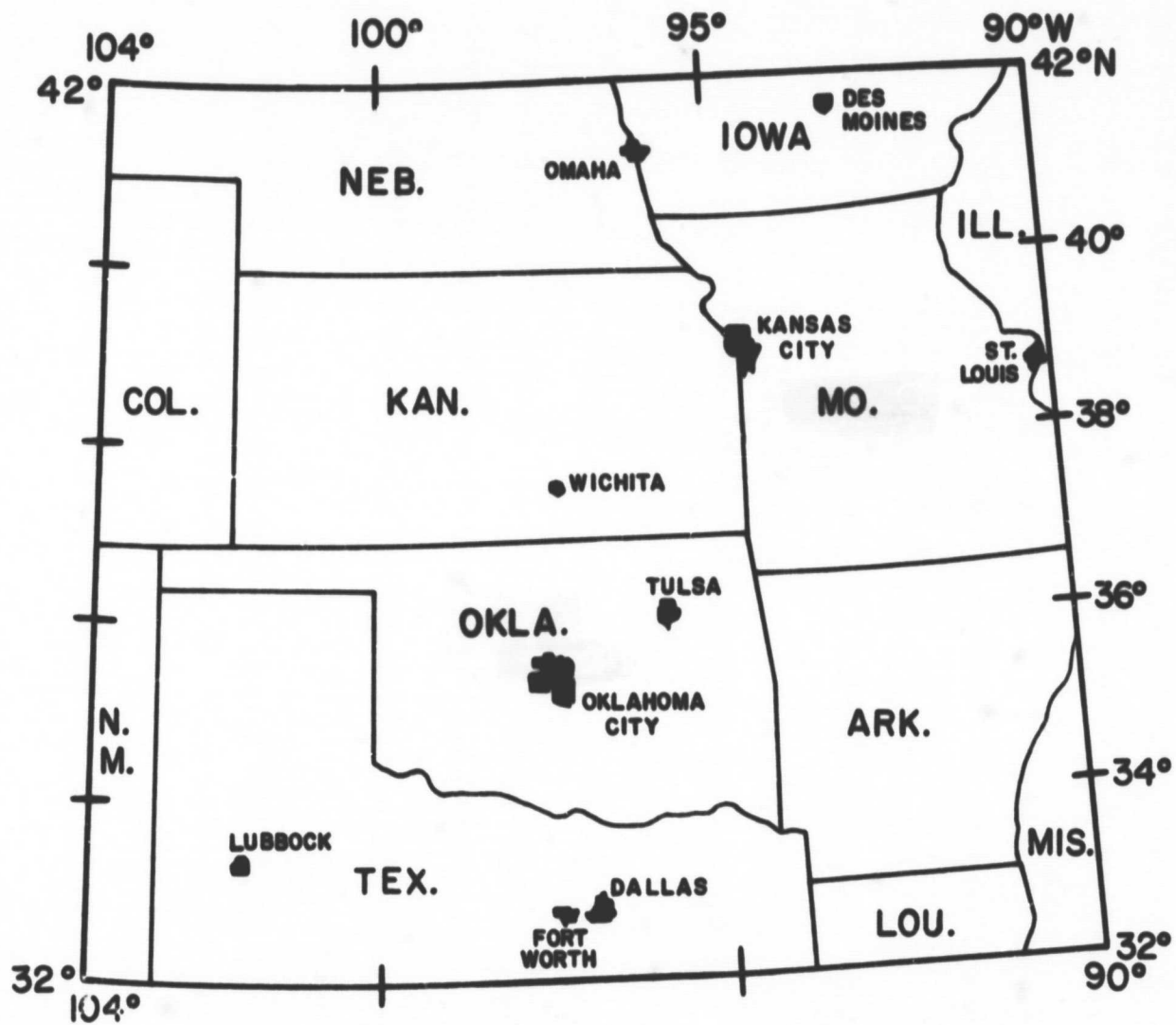


Figure 3-2 Densely populated areas within the study region.
Each area has population over 200,000.

lated and developed areas have dimensions which are usually of the order of 20-60 km, and they should be easily distinguishable in the microwave region.

The general features of the defined region for this study are carried out using information contained in the National Atlas of the U.S.A. (1970) and also from Landsat and other satellite imagery. In the National Atlas of the U.S.A., the potential natural vegetation of the U.S. is divided into 106 categories with spatial resolution of the order of 20-50 km. Analysis for the study region utilizing these categories are carried out and recombined into three general categories; grasslands in the western part, forests in the eastern part and mixed grasslands/forests in between the two parts; the distribution of these categories is shown in Figure 3-3a. The characteristic dimensions of the vegetation types shown in Figure 3-3a were determined along latitude (east-west) and longitude (north-south) lines at 1° intervals. The dimension of a specific vegetation type along a line was taken; when the vegetation type along the line changed, then another dimension appropriate for the new vegetation type would be obtained. A histogram of the dimensions for the vegetation map of Figure 3-3a is shown in Figure 3-3b. The grasslands have a fairly uniform distribution of sizes, but the other two vegetation types have a predominate dimension of less than 50 km. This general feature can be seen qualitatively in Figure 3-3a.

The features are also spot-checked with Landsat and other satellite imagery. In summary, this region includes pasture and forest land of the inland south, extensive cropland of the Great Plains, and irrigated cotton lands of the Texas High Plains. Much of the western portion of the study area is dominated by smooth plains, prairie grasses, and large areas of dry land wheat. An extensive area of irrigated cropland can be found in the Lubbock, Texas and other areas. The eastern portion of the study area is highly diversified in both land surface form and land use. The northeastern section consists of open hills, tablelands, high hills and low mountains; land use includes cropland, forest and woodland, and cropland with pasture. The southeastern section is largely smooth plains, irregular plains, plains with hills, and tablelands; predominant land use in this section could be described as woodland and forest interspersed with cropland and pasture.

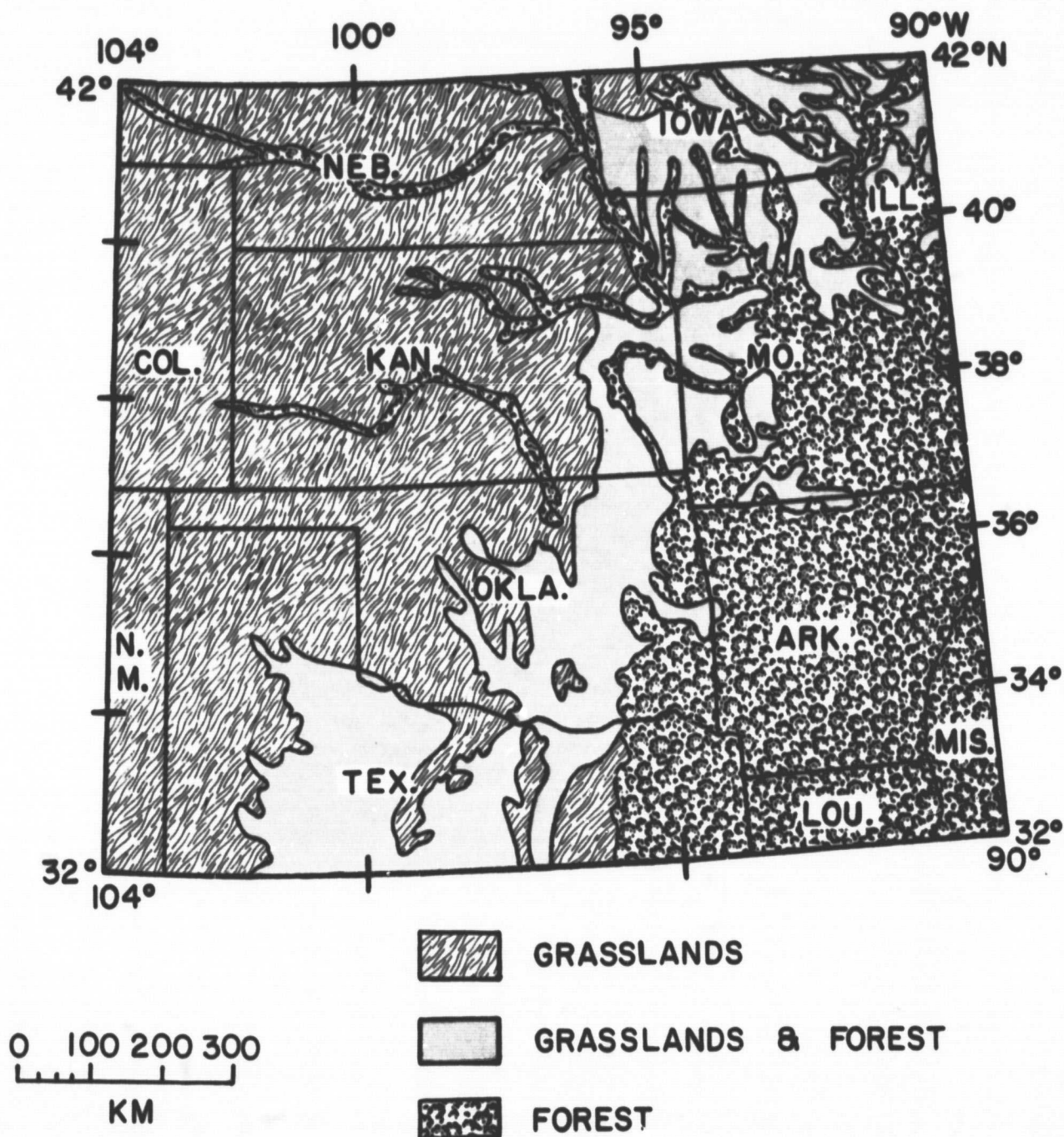


Figure 3-3a The study region categorized according to grasslands, forest and mixture of grasslands and forest.

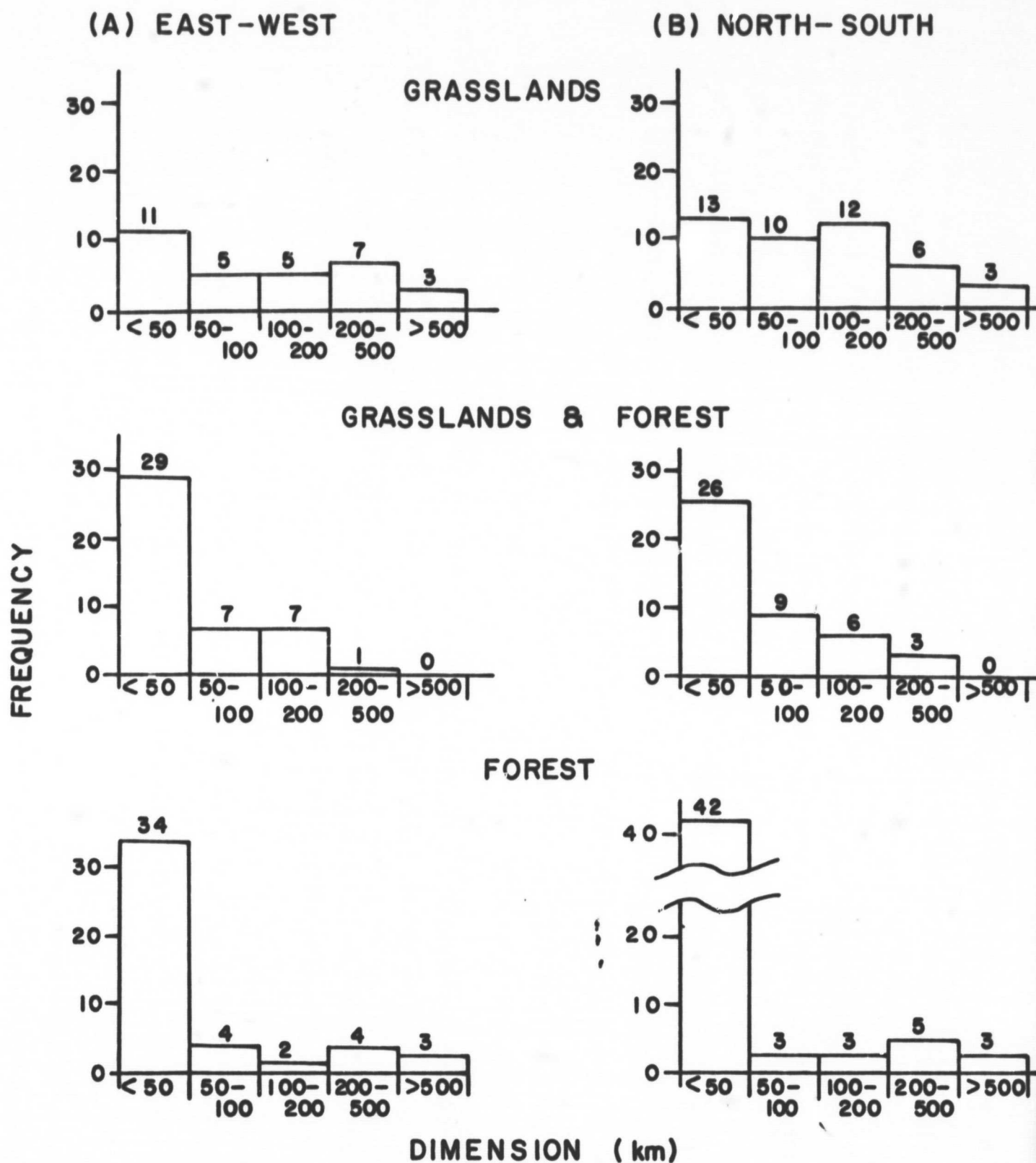


Figure 3-3b Histograms of the dimensions of grasslands, forest and mixture of grasslands and forest. They are obtained from Figure 3-3a along latitude (east-west) and longitude (north-south) lines at 1° intervals.

3.2.2 Detailed Features of Selected Sites

This section includes a description of the water bodies within the study region, and the details of land use for three test sites are mapped. The water areas are investigated in more detail due to the fact that they produce very different microwave signatures than land. For a mixed background of water bodies and dry land, the microwave signature resembles that of wet land. Therefore, if small water areas exist within agriculture land, they could cause ambiguities in the interpretation of microwave measurements. The three test sites are representative of the "scenes" expected over the whole study region. Each is a circular area of 50 km in diameter such that variations of 10-km and 1-km scales can be demonstrated.

Water Areas Within Mid-Western USA

Information of total water and residual water areas was obtained from an analysis of ERTS-1 data (Serebreny et al., 1975). By definition, residual water area is the difference between the total water area and the water area of those lakes equal to or greater than 10 km²; it may include both rivers and small lakes. Some of the areas analyzed by Serebreny et al. (1975) are contained in the study region of this project and are indicated in Figure 3-4. The common regions include:

- 1) eastern Colorado, southwestern Nebraska and north-western Kansas;
- 2) southeastern Nebraska and north-northeastern Kansas;
and
- 3) the panhandle of Texas, northeastern New Mexico, southeastern and southwestern corners of Kansas and Colorado respectively.

Each of the three regions of Figure 3-4 has an area of 195,200 km² (440 km to a side). Among the three regions shown in Figure 3-4, the total water areas are all less than 2% of the total area. Furthermore, of this 2% of water area, 70% or more of it is composed of smaller lakes and streams which make up the residual water area. These aspects were

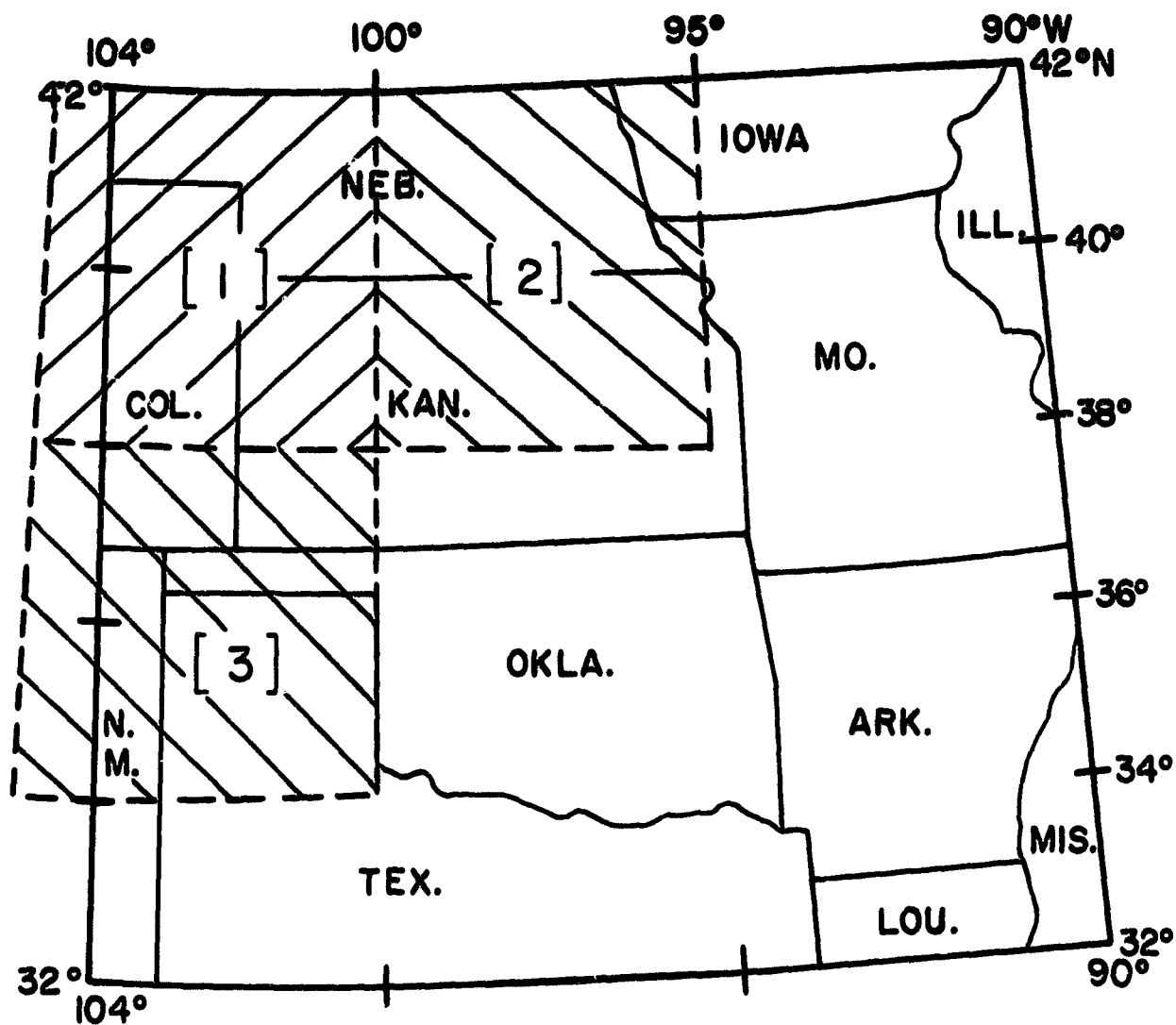


Figure 3-4 Areas with known total and residual water information from ERTS-1 data within the study region.

derived from data given by Serebreny et al. (1975) and shown in Table 3-1 which lists the size, total water area, total lake area and residual water area of each of the regions.

Based on the information of water area for the regions in Figure 3-4, the following conclusions can be summarized:

- 1) for large area monitoring of more than a few hundred kilometers in size in regions such as the mid-west region of the U.S. studied here, spatial resolution in the order of 10 km for the microwave radiometer would not seriously jeopardize accurate and efficient soil moisture monitoring due to the presence of water bodies. This conclusion is reached from the fact that water bodies occupy less than 2% of the total area of interest. A simple way to retrieve soil moisture information would be to first discard any extremely low brightness temperatures which could be due to the presence of water bodies. Then after averaging a number of pixels of data, the areal soil moisture content should be representative; and
- 2) for small area monitoring (less than a few tens of kilometers in size), water bodies can pose a problem since over 70% of all the water bodies are less than 10 km² in size. Any water body within the area can produce erroneous information of soil moisture. However, for the monitoring of specific small areas, regions with substantial water bodies should be known beforehand and these can therefore be treated separately by using the existing geological information.

In summary, soil moisture measurements using a microwave radiometer system with a spatial resolution of 10 km will be relatively unaffected by the presence of the water bodies which occur in the mid-western U.S. The use of a system with a 1-km spatial resolution would generally not provide significantly improved soil moisture information. Further details on the basis for this conclusion are provided through the analysis of the land use maps described in the next section.

TABLE 3-1
WATER AREA MEASUREMENTS

Region	Area (km ²)	Total Water Area and % of Total Area	Total Lake (>10 km ²) Area and % of Total Water Area	Residual Water Area and % of Total Water Area
1	195200 (440 x 440)	3598 km ² 1.84%	438 km ² 12.2%	3160 km ² 87.8%
2	195200	3135 km ² 1.61%	957 km ² 31.5%	2178 km ² 69.5%
3	195200	1336 km ² 0.68%	192 km ² 14.4%	1145 km ² 85.6%

Representative Sites for Demonstration

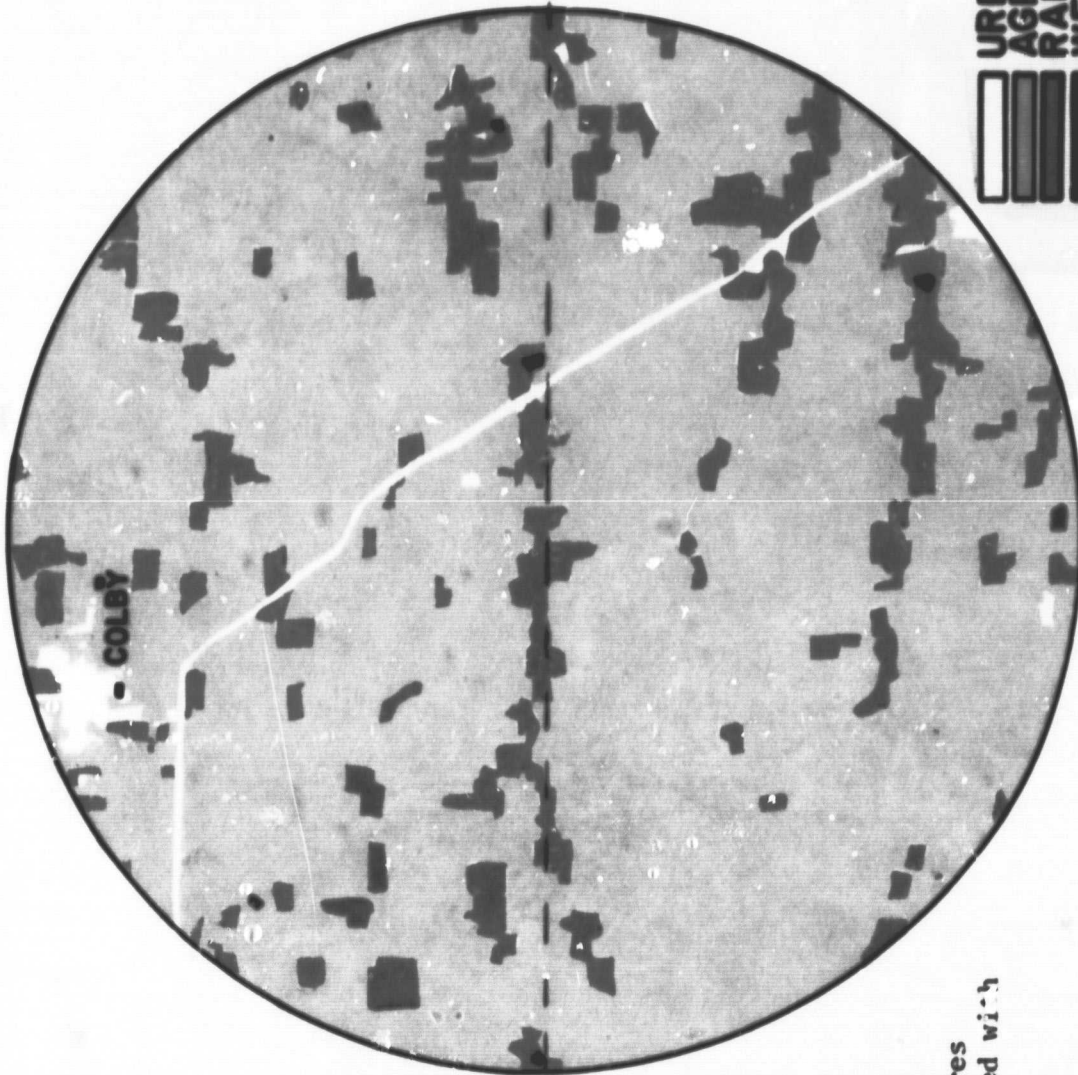
The three selected study areas are (1) Colby, Kansas, a typical mixed agriculture/grassland area; (2) St. Louis, Missouri, with mixed urban/agriculture background; and (3) Fort Smith, bordering Oklahoma and Arkansas, a typical watershed area surrounded by forests. The area maps used for these study sites were obtained from the USGS 1:250,000 scale land use maps.

The Colby, Kansas study site is largely an area of smooth to irregular plains underlaid by Upper Tertiary sedimentary rocks with 50 to 100% of the area gently sloping; 50 to 75% of this gentle slope is in the uplands. Local relief is 100 to 300 feet, and the region has a mean annual precipitation of 16 inches. Annual surface runoff is less than 0.5 inches with usable reservoir capacities generally exceeding average annual inflow. This is an area of mostly cropland (wheat and small grains) with grazing land.

Figure 3-5a demonstrates the general land use and background for the Colby area. The area was selected as it is representative of the major areas of agriculture and rangeland throughout the mid-western U.S. In this test area, populated and built-up areas are relatively sparse with the test area relatively smooth and uniform throughout the whole region. Regional soil moisture is of major concern for crop yield. For this type of area a spatial resolution of 10 km should be sufficient due to its uniformity. Figure 3-5b demonstrates variations of brightness temperatures at 21 cm along a scan line on 1-km and 10-km scales. Two background soil moisture conditions are assumed; dry (5%) and wet (35%). As can be seen, little additional usefulness can be obtained from soil moisture measurements with spatial resolution of the order of 1 km.

Both the St. Louis and the Fort Smith study sites are largely areas of irregular plains, underlaid by Upper Paleozoic sedimentary rocks, with 50 to 80% of the surface gently sloping; 50 to 75% of this gentle slope is in the lowlands. In both sites usable reservoir capacities exceed average annual inflow. Wheat and small grains dominate the cropland theme of the Oklahoma site; with mixed cropland, pasture and forestland occurring in the St. Louis site.

The St. Louis, Missouri area (Figure 3-6a) was also selected due to its uniqueness of mixed background of urban, water, agricultural and



URBAN OR BUILT-UP
 AGRICULTURE
 RANGELAND
 WETLAND
 BARE

LAND USE AND LAND COVER, 1974
 COLBY, KANSAS

5 0 5 KM
 5 0 5 MILES

ORIGINAL PAGE IS
 OF POOR QUALITY

Figure 3-5a
 Land use near Colby, Kansas
 area (USGS, 1:250,000 scale
 land use maps). Main features
 are agriculture lands spotted with
 rangelands.

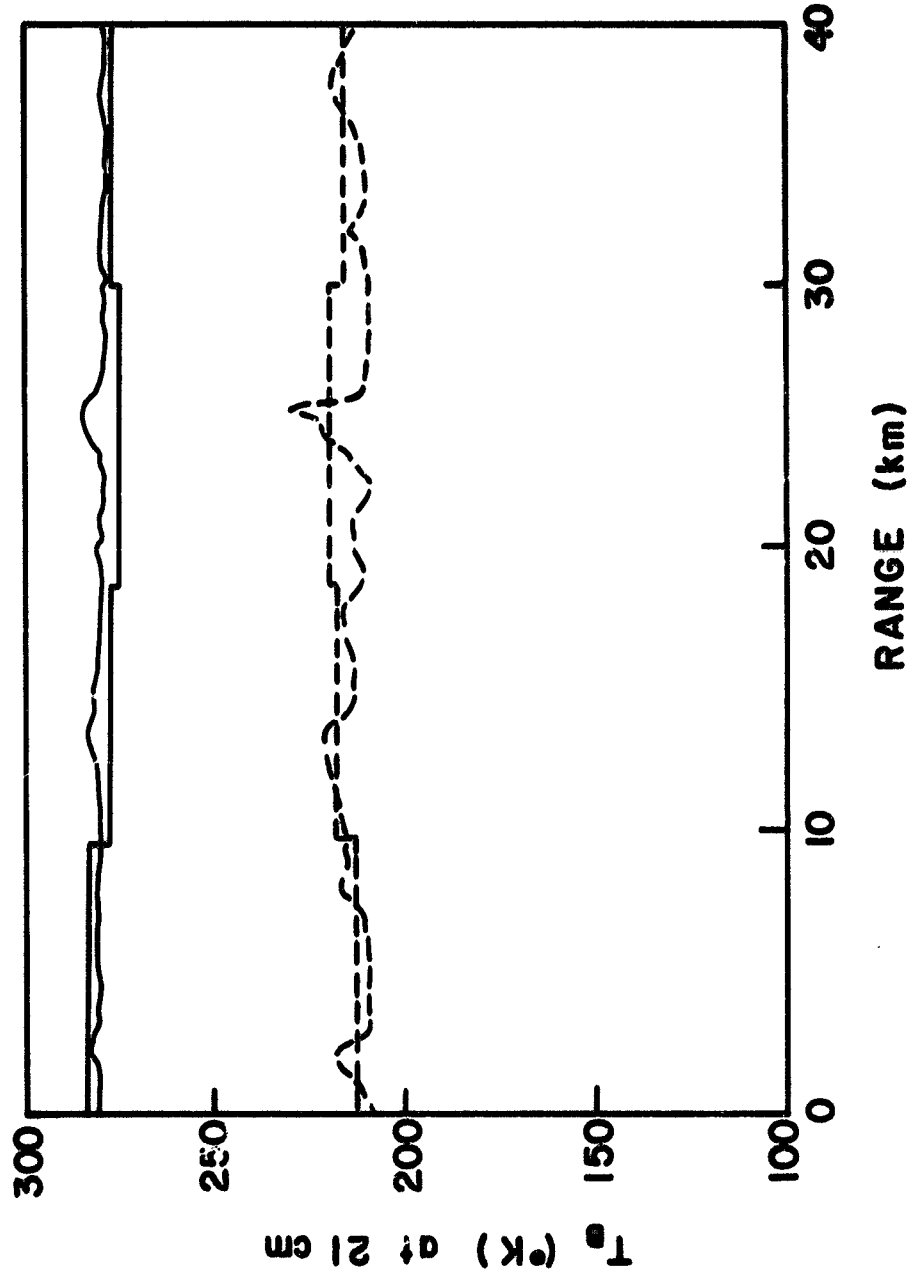


Figure 3-5b Simulated brightness temperatures at 21 cm along a scan line from Figure 3-5a (center, east-west) on 1 km x 1 km and 10 km x 10 km scales. Two background soil moisture conditions are assumed: solid lines for dry (5%) and dashed lines for wet (35%) conditions.

forest areas. The area is divided by the Mississippi River into two parts. The region that is west of the river consists of more than 95% urban or built-up areas. East of the river, the region becomes quite mixed; 30% is populated areas with scales of 5-10 km, 40% is agricultural land with scales ranging between 1-10 km, and the rest are spotty water, forest and bare land spread throughout with scales of the order of 1 km for each type. Precise monitoring from satellite should require spatial resolution of 1 km or better due to the variability of the background. However, due to its closeness to the major urban area, there is no large-scale farming business in the area. A sensor with spatial resolution of 10 km would flag most of this area as urban or densely populated and soil moisture information would be unavailable. The loss of information due to the use of a system with a 10-km resolution can be regarded as minimal since outside the urban area there will be large agricultural areas for which soil moisture information could be obtained with acceptable accuracy. The soil moisture information obtained from adjacent areas can then be applied to the areas of mixed background. Information obtained this way should be at least as good as direct measurement over the area with a 1-km resolution since the background would often be variable even with a 1-km "cell" resolution; thus the 1-km data would lead to difficulties in interpretation. The brightness temperature responses at 21 cm over 1-km and 10-km scales are also demonstrated in Figure 3-6h.

Figure 3-7a demonstrates the land use and background of the Fort Smith area. This area was chosen as a typical watershed area. The land use is predominantly agriculture. There is a large water body created by a dam, and the water covers a significant fraction of the western half of the area. Spotty wetlands and forest regions also occur throughout the entire region. Soil moisture information is obtainable with a microwave system over agriculture and bare areas which account for more than 50% of the total reference area. From Figure 3-7a, it is seen that the scales are in the order of 5-10 km for water bodies, 1-5 km for forest areas and 1 km for urban lands. Figure 3-7b demonstrates the brightness temperatures at 1 km and 10 km resolutions as carried out for the other two sites. Satellite monitoring of the soil moisture information for an area of this type would again require spatial resolution in the order of

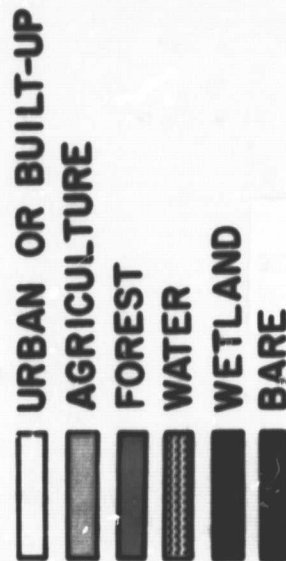
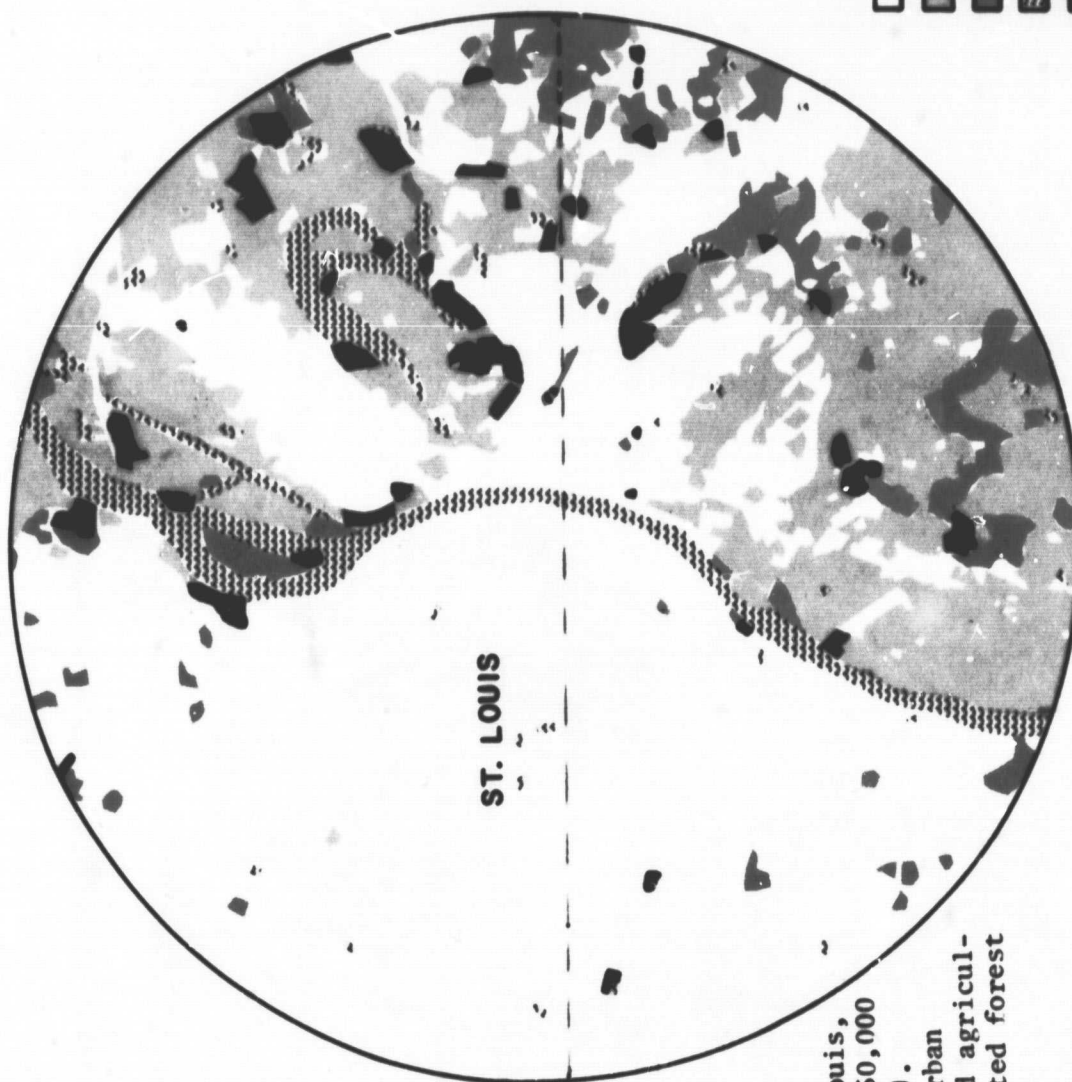
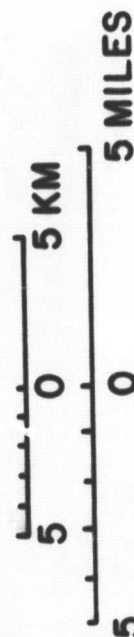


Figure 3-6a

Land use near St. Louis, Missouri (USGS, 1:250,000 scale land use maps). Main features are urban areas with scattered agriculture lands and spotted forest and water areas.



LAND USE AND LAND COVER, 1972 - 1976
ST. LOUIS MISSOURI; ILLINOIS

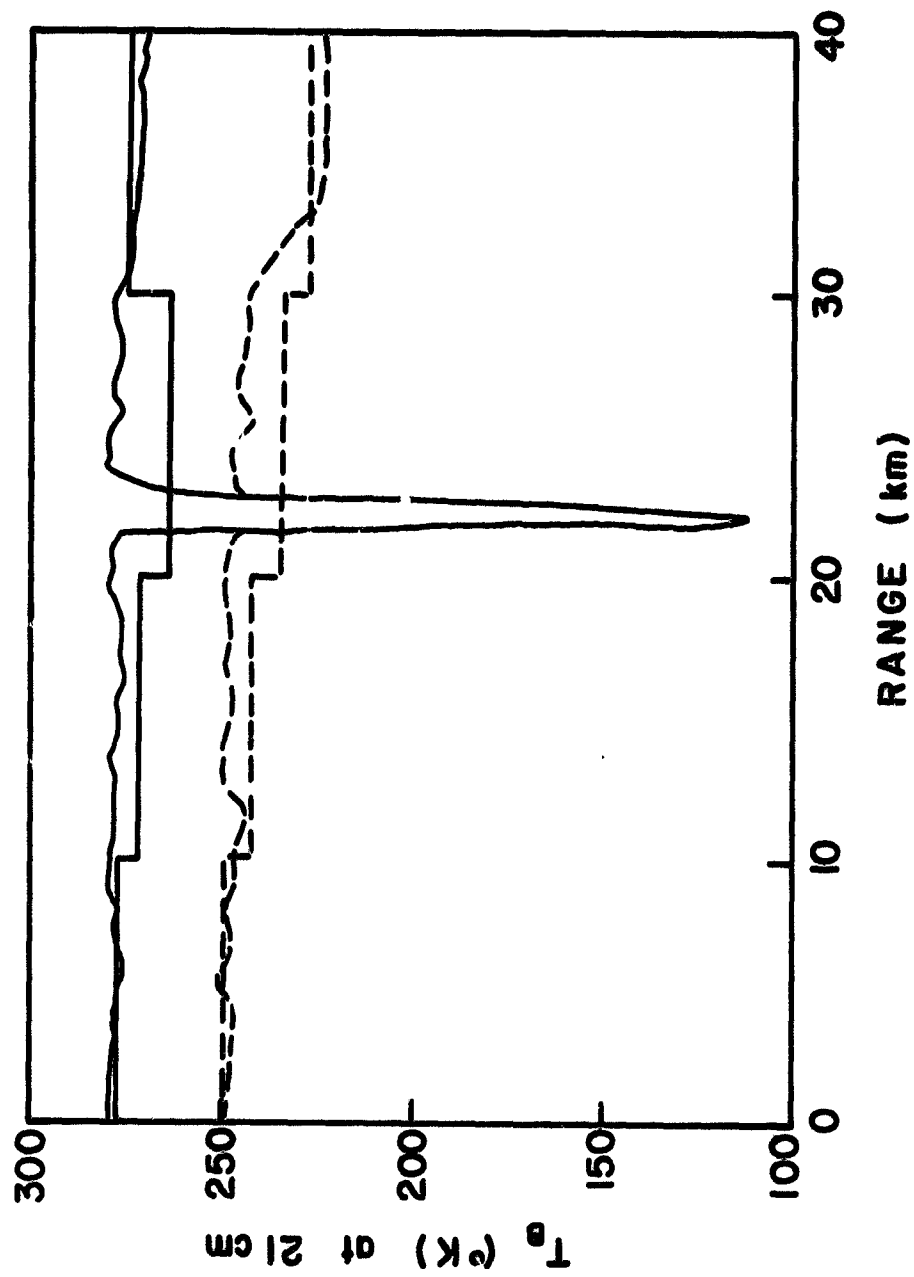


Figure 3-6b Simulated brightness temperatures at 21 cm along a scan line from Figure 3-6a (center, east-west) on 1 km x 1 km and 10 km x 10 km scales. Two background soil moisture conditions are assumed: solid lines for dry (5%) and dashed lines for wet (35%) conditions.

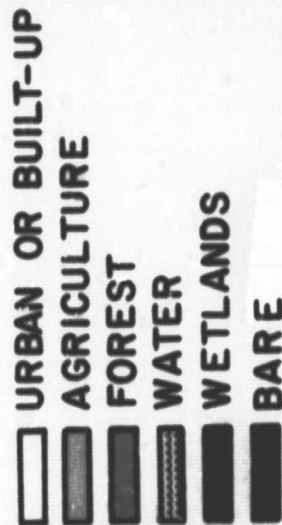
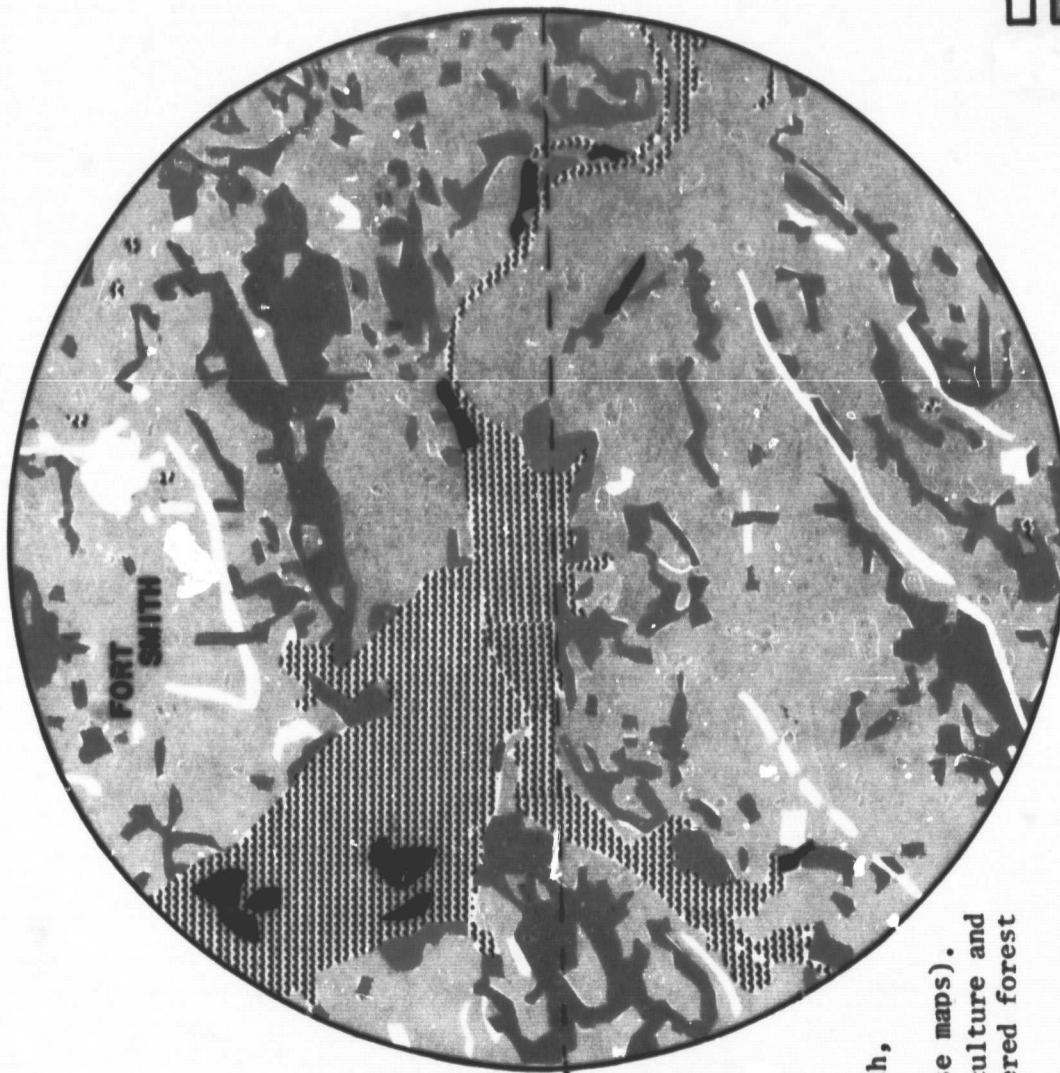
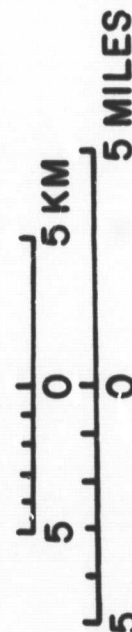


Figure 3-7a

Land use near Fort Smith,
Oklahoma area (USGS,
1:250,000 scale land use maps).
Main features are agriculture and
water areas with scattered forest
areas.



LAND USE, 1972
FORT SMITH, OKLA./ARK.

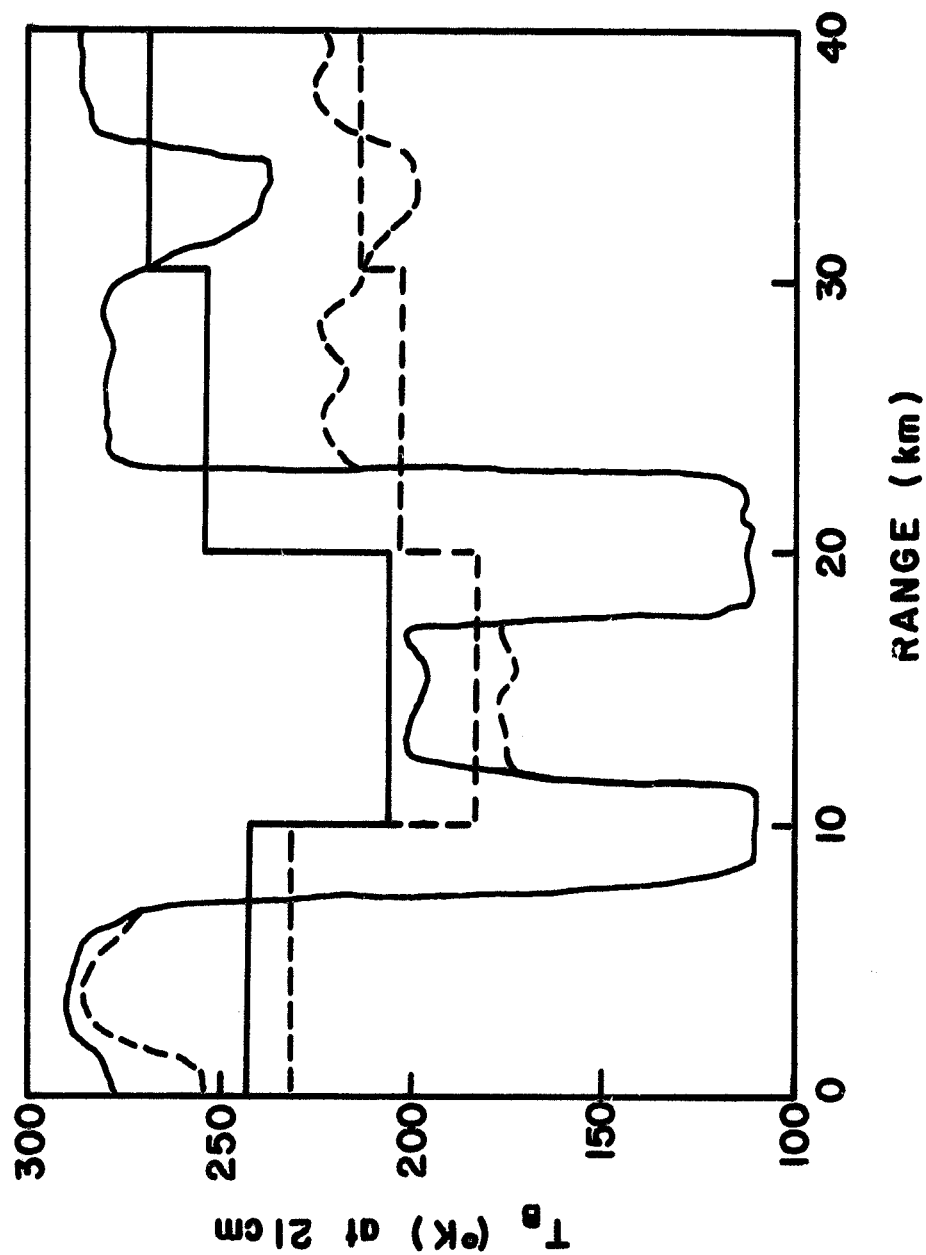


Figure 3-7b Simulated brightness temperatures at 21 cm along a scan line from Figure 3-7a (center, east-west) on 1 km x 1 km and 10 km x 10 km scales. Two background soil moisture conditions are assumed: solid lines for dry (5%) and dashed lines for wet (35%) conditions.

1 km due to the areal variability. However, prediction of watershed runoff, a resource for irrigation and flood control, may be of more interest than soil moisture retrieval for areas of this type. The microwave brightness temperatures are high for low soil moisture content, rough surfaces, sandy soils and dense vegetation. All these conditions tend to reduce watershed runoff (Blanchard, 1974). For a specific drainage area, information on the type and roughness of the soil, the coverage of permanent water, and the regions of forest and dense vegetation can all be used as input to obtain an expected brightness temperatures applicable for the entire watershed drainage area under both saturated and dry conditions. These conditions can then be used as a minimum and maximum reference indicators for the watershed surface storage capacity. In this case, the resolution requirement can be greatly reduced.

The concluding remark for this watershed area, and similar ones, is that direct soil moisture information from satellite measurements should ideally be obtained at a spatial resolution of 1 km or less. Realistically, however, an "index" of the watershed surface storage capacity can be obtained more efficiently with a 10-km resolution provided the general land/water surface features for the season are known.

4. SOIL MOISTURE RESOLUTIONS FOR USE IN CROP YIELD AND HYDROLOGICAL MODELS

4.1 Current Soil Moisture Related Information

Present users of soil moisture information rely on gross estimates covering large geographic areas. The Palmer Index and Crop Moisture Index (CMI) is presented weekly during the growing season by the U.S. Dept. of Agriculture (USDA) and the National Oceanographic and Atmospheric Administration (NOAA). Both indices utilize Palmer's two-layer soil moisture model to evaluate the weekly moisture status (Palmer, 1965, 1968). An example of a map of CMI is given in Figure 4-1. The CMI and Palmer Index utilize temperature and precipitation data from approximately nine climatological divisions per state. There are 25-30 stations within each division which provide precipitation reports (Denny, 1979). The average area per station is $(50 \text{ km})^2$ but can be up to $(100 \text{ km})^2$ for station sparse area. A map showing the divisions used for a determination of the soil moisture index is shown in Figure 4-2. The two models are designed to provide indices which are indicative of agricultural drought and crop moisture stress.

Another agricultural drought monitoring program at NOAA is operated by their Environmental Data Service's Center for Climate and Environmental Assessment (CCEA). This Cumulative Precipitation program utilizes both climatological and current values of precipitation amount (Reid, 1977). The world-wide program does not use soil moisture information but it does use soil water-holding capacity data for rainfall stations (Reid, 1979).

Crop estimates, which are based on field reports, are reported by the USDA, Economics Statistical Cooperative Service (ESCS). The ESCS has been evaluating forecasting models to be applied in an operational program (Wilson, 1979). However, soil moisture data have not yet become part of an operational program.

Another major user of the soil moisture information is the Office of Hydrology of NOAA. The River Forecast Service of the office is responsible for river and water supply forecasts. Soil moisture is one parameter that can significantly improve the confident level of mathematical models.

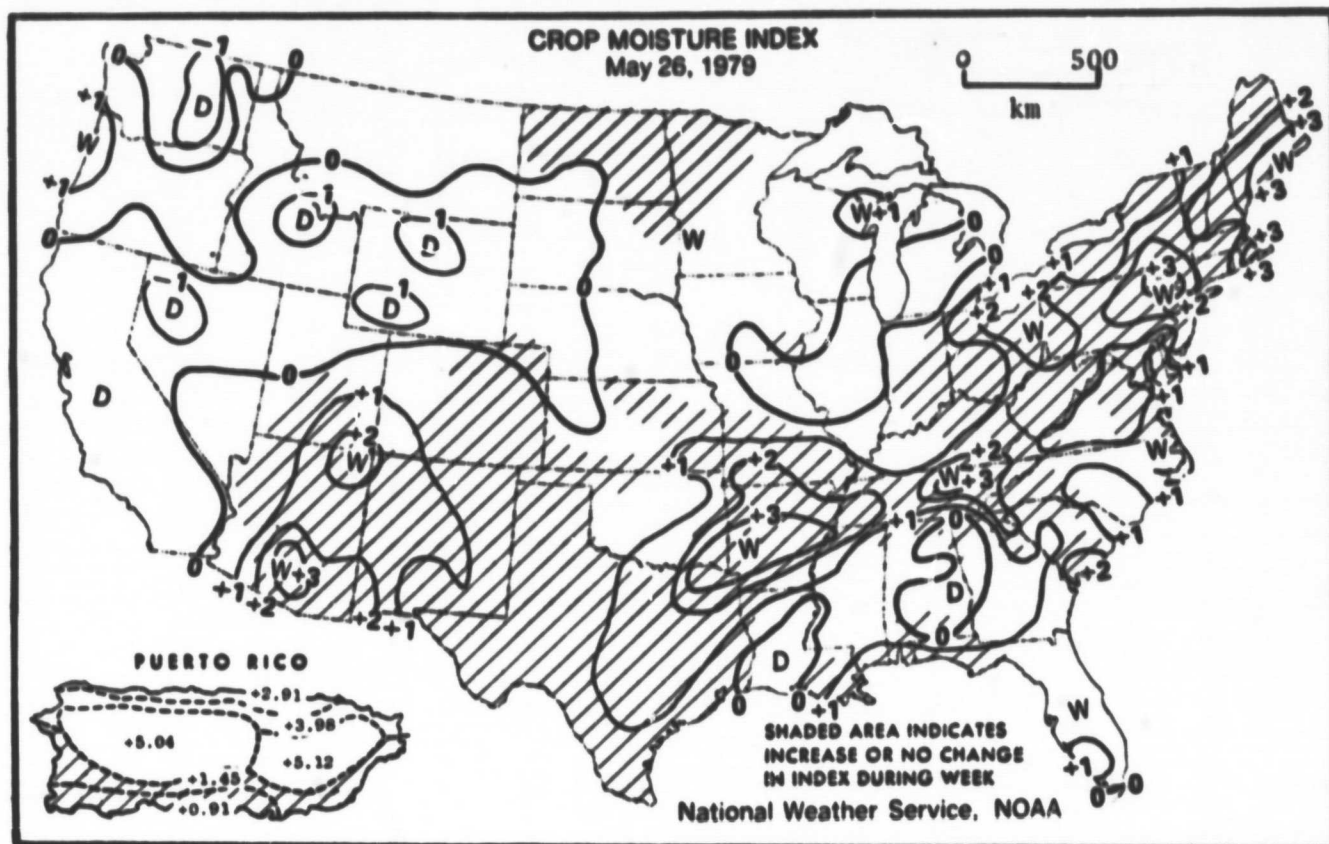


Figure 4-1A Sample of the Map of Crop Moisture Index (Weekly Weather and Crop Bulletin, NOAA Department of Commerce and Department of Agriculture)

Some general guidelines are as follows:

Unshaded Areas: Index Decreased

Above 3.0	Some drying but still excessively wet
2.0 to 3.0	More dry weather needed, work delayed
1.0 to 2.0	Favorable, except still too wet in spots
0 to 1.0	Favorable for normal growth and fieldwork
0 to -1.0	Topsoil moisture short, germination slow
-1.0 to -2.0	Abnormally dry, prospects deteriorating
-2.0 to -3.0	Too dry, yield prospects reduced
-3.0 to -4.0	Potential yields severely cut by drought
Below -4.0	Extremely dry, most crops ruined

Shaded Area: Index Increased or Did Not Change

Above 3.0	Excessively wet, some fields flooded
2.0 to 3.0	Too wet, some standing water
1.0 to 2.0	Prospects above normal, some fields too wet
0 to 1.0	Moisture adequate for present needs
0 to -1.0	Prospects improved but rain still needed
-1.0 to -2.0	Some improvement but still too dry
-2.0 to -3.0	Drought eased but still serious
-3.0 to -4.0	Drought continued, rain urgently needed
Below -4.0	Not enough rain, still extremely dry

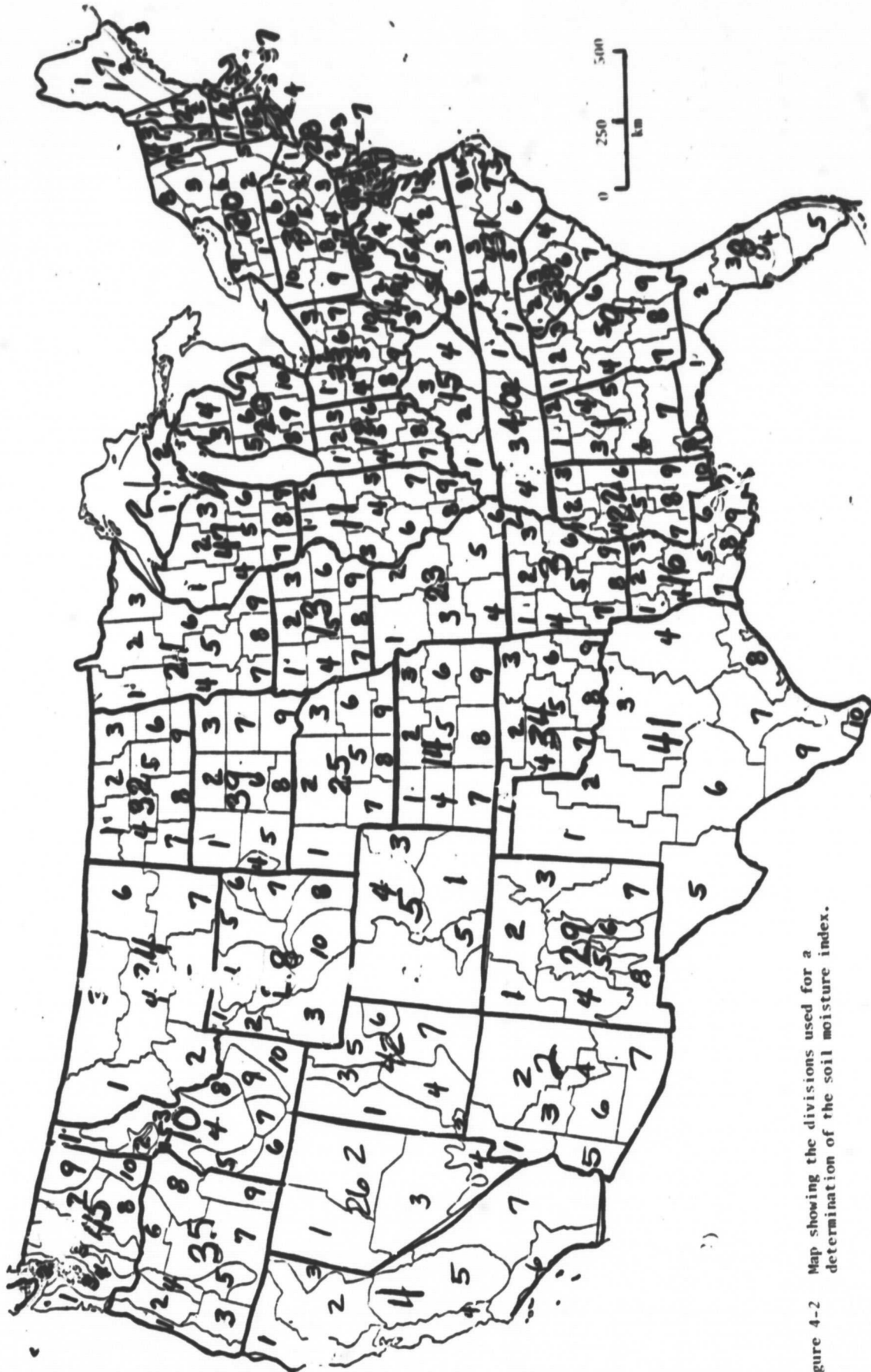


Figure 4-2 Map showing the divisions used for a determination of the soil moisture index.

ORIGINAL PAGE IS
OF POOR QUALITY

All the soil moisture information utilized by these various agencies is currently derived from precipitation reports or on-site direct measurements. Average spatial scale of the precipitation reports is 50 km or more. Direct measurements are usually carried out only for particular sites and the reports are less regular.

The Large Area Crop Inventory Experiment (LACIE) was performed by NASA in conjunction with NOAA and USDA to evaluate vegetative moisture stress using Landsat digital data (Thompson and Wehmanen, 1979). The remote sensing method showed a high degree of agreement with the CMI model. In the LACIE program, moisture condition was evaluated from vegetative stress rather than soil moisture.

4.2 Future Applications and Improvements of Soil Moisture Information

It is generally accepted that soil moisture estimates can improve crop yield and hydrological models. It was recognized at a Soil Moisture Workshop (NASA, 1978) that there are many potential users for soil moisture information. Once routine soil moisture information becomes available, operational programs would likely go through a period of development and evaluation of the new types of data.

Models using soil moisture budgeting should be a better predictor of crop yield than direct use of climatological data. Baier and Robertson (1968) claim higher correlation coefficients, lower coefficients of variation, and lower standard of errors of estimate for their soil moisture model versus models relying only on daily temperature and monthly rainfall.

Improvement of precipitation monitoring on a finer scale is another key to improving the accuracy of crop yield and hydrological models. Current soil moisture resolution over large areas is dependent upon the resolution of the climatological data. This study shows that the centers of maximum precipitation can occur within a 10-km diameter. Consequently, the incorporation of a dense rain-gage network could result in improved soil moisture information, and this would be of value for generating more accurate crop-yield models and forecasts.

Both soil moisture and watershed models also require accurate prediction of evapotranspiration. It is recognized that the accuracy of

the Thornwaite equation for evapotranspiration is an inherent problem in the Crop Moisture Index (Denny, 1979). The potential evapotranspiration is usually calculated using the actual long-term mean monthly climatic temperatures. It is adjusted by the actual mean temperature and mean duration of sunlight of the past 10 to 30 days. Better accuracy of the climatological and meteorological information can certainly improve the estimate of the evapotranspiration.

The above summarizes the required improvements for soil moisture information. Soil moisture budgeting takes into account the soil texture and its capacity for holding water. Improvement of precipitation information leads to better input on the value of soil moisture. Evapotranspiration information plays a crucial part as a source of "depletion" of soil moisture. Among these factors, only precipitation information requires a fine spatial resolution of the order of 10 km. Present resolution of the order of a hundred kilometers for the other factors seem to be adequate for all users.

A satellite sensor system with a resolution of 10 km will be highly desirable for soil moisture monitoring. This is compatible with the ground information and meets the requirements of most users. A sensor with a resolution of 1 km would generate 100 times as many scenes for processing; other than specific interest groups which may have an interest in small areas, users of this fine-scale data cannot be easily identified.

Some of the government agencies that would benefit from a satellite sensor capable of detecting soil moisture on a 10-km resolution scale (NASA, 1978) include:

- 1) NOAA, for improving flood and water level forecasts
- 2) SRS (Statistical Reporting Service, or ESCS of USDA), for expanding areas for estimating and forecasting crop yields as present information is limited to specific research sites;
- 3) SCS (Soil Conservation Service) of USDA, for monitoring drought conditions and probable future moisture availability; and

- 4) AID (Agency for International Development), for anticipating drought and desertification in developing countries.

As can be seen, the capability of improving the monitoring of crop yield and drought/wetland areas from satellite microwave sensors on a 10-km resolution can benefit many major government agencies. Due to the current lack of data, applications and users for sensors of a 1-km resolution may appear once a system with a 10-km resolution is developed. Some of the potential users of data down to a 1-km resolution include:

- 1) USGS in their various water resource investigations;
- 2) ARS (Agricultural Research Service, or SEA) of USDA in local requirements of irrigation, drainage needs, and erosion;
- 3) the U.S. Water and Power Resources Service (formerly the Bureau of Reclamation) in their Irrigation Management Services Program; and
- 4) the U.S. Army Corps of Engineers in monitoring or predicting trafficability and mobility of military vehicles.

In general, these are operations and problems limited to local areas. As a result, data management and cost of operating a satellite sensor would be quite different from that of a system designed to monitor regional characteristics.

5. CONCLUSIONS

The intent of this study was to examine the usefulness of soil moisture observations at a 10-km and a 1-km resolution. Basic to this examination was an assessment of the problems inherent in the remote sensing of soil moisture by means of satellite-borne microwave radiometers.

The first item investigated was the rainfall amount patterns in the central regions of the U.S. The basic data were obtained from three networks of rain gages and the gages were separated by about 5 km. With this spacing it was not possible to obtain any useful information on scales of less than 5 km. However, from the correlation analysis of storm rainfall amounts, several previous investigators have demonstrated that the rainfall amounts at gages separated by about 5 km are correlated at the 0.9 level or higher. Thus, for the storm total rainfall amounts or the daily amounts used in this study, the patterns obtained from the networks having gage spacing of about 5 km are considered to be representative of the actual patterns with the exception that peak amounts and the gradients near the peak will generally be underestimated. Near the center of some storms where the gradients in rainfall amount are largest, a sensor with a 10-km resolution may underestimate the true value by about 20%. Beyond 5 km from the storm center, however, a 10-km resolution would lead to a good representation of the patterns for all the categories of storms.

The second item studied was an assessment of the problems associated with the remote sensing of soil moisture by means of a satellite-borne microwave radiometer. It has been shown in this study that the physical characteristics of the land features in the mid-western portions of the U.S. are such that microwave radiometers with resolutions on the order of 10 km can obtain representative and useful soil moisture measurements. This results was obtained from a combined analysis of the land features and the response to these land features by a 10-km resolution microwave radiometer.

The third major topic covered in the study was an assessment of the current uses of soil moisture information. Soil moisture information is essential for the generation of accurate results from crop yield and hydrological models. At present, soil moisture values are usually being

derived from temperature and precipitation reporting stations which are separated by distances on the order of 100 km. Since considerable variability in soil moisture can occur on scales of less than 100 km, crop yield and hydrological models would be improved with data having a finer resolution. The immediate users of soil moisture at scales of 10 km include agencies which are concerned with the prediction of crop yields at a regional or local level and for hydrologists responsible for the prediction of run-off on relatively small basins. Information at a 1-km resolution would be valuable in those areas which are dominated by small ponds or land features which have areas of less than about 25 km². However, users of this very fine resolution data are likely to be confined to a small number of specific interest groups who are concerned with the details of soil moisture over very small regions.

6. REFERENCES

- Baier, W. and G.W. Robertson, 1968: The Performance of Soil Moisture Estimates as Compared With the Direct Use of Climatological Data for Estimating Crop Yields, Agr. Meteorol., 5, 17-31.
- Blanchard, B.J., 1974: Passive Microwave Measurement of Watershed Run-off Capability, Ph.D. Dissertation, Univ. of Oklahoma, Norman, Oklahoma.
- Brady, P.J., 1975: Matching Rain Gauge Placement to Precipitation Patterns, Presented at Nat. Symposium on Precipitation Analysis for Hydrologic Modeling, Davis, California.
- Changnon, S.A., Jr. and F.A. Huff, 1980: Review of Illinois Summer Precipitation Conditions, Bull. 64, Illinois State Water Survey, Urbana, Illinois, 160 p.
- Choudhury, B.J., T.J. Schmugge, A. Chang and R.W. Newton, 1979: Effect of Surface Roughness on the Microwave Emission from Soils, J. Geophys. Res., 84, 5600.
- Crane, R.K., 1979: Automatic Cell Detection and Tracking, IEEE Transactions on Geoscience Electronics, GE-17, No. 4, 250-262.
- Crane, R.K. and K.R. Hardy, 1981: The HIPLEX Program in Colby-Goodland, Kansas: 1976-1980, Final Report, Environmental Research & Technology, Inc. for Water and Power Resources Service, Dept. of Interior under Contract No. 14-06-D-7673, 134 p.
- Denny, L., 1979: Personal Communication, NOAA, National Weather Service, Washington, D.C.
- Eagleson, P.S., 1978: Climate, Soil, and Vegetation - 2, The Distribution of Annual Precipitation Derived from Observed Storm Sequences, Water Resources Res., 14, 713-721.
- Eddy, A., 1976: Optical Rain Gauge Densities and Accumulation Times: A Decision-Making Procedure, Report to the Bureau of Reclamation under Contract No. 14-060-D-7633, 28 pp.
- Eddy, A. and L. Hembree, 1978: The Effects of Rain Gauge Densities on the Analysis of Storm Total Rainfall from Convective Complexes, Final Report, Amos Eddy Inc. Contract No. 7-07-83-V007, 82 p.
- Fogel, M.M. and L. Duckstein, 1969: Point Rainfall Frequencies in Convective Storms, Water Resources Res., 5, 1229-1237.
- Huff, F.A., 1971: Evaluation of Precipitation Records in Weather Modification Experiment, Advances in Geophysics, Vol. 15, Academic Press, N.Y., 59-135.

- Huff, F.A., 1979: Spatial and Temporal Correlation of Precipitation in Illinois, Circular 141, Illinois State Water Survey, Urbana, Illinois, 14 p.
- Huff, F.A. and W.L. Shipp, 1969: Spatial Correlations of Storm, Monthly and Seasonal Precipitation, J. of Appl. Meteor., 8, 542-550.
- Lilly, D.K., 1975: Severe Storms and Storm Systems: Scientific Background, Methods, and Critical Questions, Pure and Applied Geophysics, 113, 713-734.
- Ludlam, F.H., 1976: Aspects of Cumulonimbus Study, Bull. Am. Meteorol. Soc., Vol. 57, 774-779.
- Mignogno, M.J., C.E. Duchon, A.G. Eddy and A.D. Nicks, 1980: An Investigation of the Dependence of Mesoscale Rainfall Parameters on Pixel Size, School of Meteorology, U. of Oklahoma, 75 p.
- NASA, 1978: Soil Moisture Workshop, edited by J.L. Heilman, V.I. Myers, D.G. Moore, T.J. Schmugge and D.B. Freidman, NASA Conference Publication, 2073.
- National Atlas of the USA, 1970: USGS, Washington, D.C.
- Palmer, W.C., 1965: Meteorological Drought, U.S. Dept. of Commerce, Weather Bureau, Research Paper No. 45, 58 p.
- Palmer, W.C., 1968: Keeping Track of Crop Moisture Conditions, Nationwide: The New Crop Moisture Index, Weatherwise, 156-161 (August 1968).
- Reid, M., 1977: A Comparison of Three Operational Drought Programs, Proc. of the 2nd Annual NOAA Climate Diagnostics Workshop, Oct. 18-20, 1977, 4.1 - 4.11.
- Reid, M., 1979: Personal Communication, NOAA, EDS Center for Climatic and Environmental Assessment, Washington, D.C.
- Schmugge, T.J., 1977: Remote Sensing of Surface Soil Moisture, Second Hydrometeorology Conference, Toronto, Canada.
- Serebreny, S.M., R.M. Trudeau and R.G. Hadfield, 1975: A Statistical Analysis of United States Surface Water Area Measurements Obtained from ERTS-1 Data, Final Report Contract NA5-21949, Stanford Research Institute, Menlo Park, California.
- Thompson, D.R. and O.A. Wehmanen, 1979: Using Landsat Digital Data to Detect Moisture Stress, Photogrammetric Engineering and Remote Sensing, Vol. 45, 201-207.
- Water and Power Resources Service, a: Contour Plotting and Grid Interpolation User Guide, Division of Data Processing User Support Branch, Engineering and Research Center, Denver, Colorado.
- Wilson, W., 1979: Personal Communication, USDA, Economic Statistical Cooperative Service, Washington, D.C.

ACKNOWLEDGMENTS

This study was made possible through the cooperative efforts of Dr. Arlin D. Nicks of the Agriculture Research Service in Chickasha, Oklahoma and Mr. Fran Politte and Richard Eddy of the Water and Power Resources Service. Dr. Nicks kindly provided a copy of the rain gage records for the Oklahoma network and Mr. Politte and Mr. Eddy arranged for the use of the HIPLEX rain gage records for the Texas and Kansas networks. We are grateful to these individuals for their help. Dr. Thomas J. Schmugge provided a careful review of an earlier draft of this report and we appreciate his efforts in improving the overall value of the material presented.

APPENDIX A

**FORMAT FOR THE INFORMATION
EXTRACTED FOR EACH STORM CELL
AND LISTING OF THE CELL DATA**

VAR	DESCRIPTION	NO. DIGITS	FORMAT	INCLUSIVE COLUMNS	EXAMPLE
SITE	1=OK; 2=TX; 3=KS	1	F1.0	1	1
DATE	YYMMDD	6	F6.0	2-7	770704
CID	CELL ID NUMBER	4	A4	8-11	C112
SFC	SFC WX TYPE ¹	2	1X, F1.0	12-13	2
kPa50	500 mb WX TYPE ²	2	F2.0	14-15	03
MAXP	MAX PRECIP ³	4	1X, F3.2	16-19	1.30
VAR7	5 km (360) ³	4	1X, F3.2	20-23	.50
VAR8	5 km (90)	3	F3.2	24-26	.40
VAR9	5 km (180)	3	F3.2	27-29	.30
VAR10	5 km (270)	3	F3.2	30-32	.20
VAR11	10 km (360)	4	1X, F3.2	33-36	.10
VAR12	10 km (90)	3	F3.2	37-39	.06
VAR13	10 km (180)	3	F3.2	40-42	.04
VAR14	10 km (270)	3	F3.2	43-45	.02
VAR15	STORM DURATION(min)	5	1X, F4.0	46-50	1440

Sites include: 1 Oklahoma
2 Texas
3 Kansas

¹Code for Surface Weather Types

- 1 AIRMASS
- 2 UPSLOPE
- 3 SQUALL LINE
- 4 SQUALL ZONE
- 5 COLD FRONT
- 6 WARM FRONT
- 7 SFC HIGH
- 8 SFC LOW
- 9 STATIONARY FRONT
- 0 NONE OF ABOVE

²Code for 500 mb Types

- 1 TROF W
- 2 TROF E
- 3 RIDGE
- 4 SWLY FLOW
- 5 SELY FLOW
- 6 W FLOW
- 7 NW FLOW
- 8 LOW
- 0 NONE OF ABOVE

³Maximum precipitation and values at 5 and 10 km are in units of 0.01 inches.

EXAMPLE:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	7	7	0	7	0	4	0	1	1	2		2	0	3		1	3	0			5	0		4	0

27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
	3	0		2	0		0	1	0		0	6		0	4		0	2		1	4	4	0						

1760205C001	704	06	34	30	53	30	-99-99-99-99
1760205C002	704	35	30	25	29	26	-99-99-99-99
1760205C003	704	30	27	24	22	27	-99-99-99-99
1760210C004	604	05	05	04	05	04	-99-99-99-99
1760210C005	604	03	002000000	03	-99-99-99-99	-99-99-99-99	
17602110006	716	04	-99-99000	02	-99-99-99-99	-99-99-99-99	
1660210C007	716	02	-99	01	01	01	-99-99-99-99
1760303C008	504	145	-99	97125105	-99	80120102	-99-99-99-99
1760303C009	504	124	46	69	80	74	53 55-99 51
1760303C000	504	111	82	40102	52	110 20 59 54	-99-99-99-99
1760303C011	504	59	49	20	46	36	20 17 19 08
1760304C012	614	06	000	01	03	02	-99-99-99-99
1763304C013	614	06	04	03-99	05	-99-99-99-99	-99-99-99-99
1760304C014	614	06	04-99000	03	-99-99-99-99	-99-99-99-99	
1760304C015	614	05	-99	05	03	05	-99-99-99-99
1760307C016	706	140	136122136118	-99-99-99-99	-99-99-99-99	-99-99-99-99	
17603070017	706	129	122110-99100	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760307C018	706	114	108109100	90	-99-99-99-99	-99-99-99-99	
1760307C019	706	110	101102104	92	-99-99-99-99	-99-99-99-99	
17603080020	614	131	100100110110	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760308C021	614	130	127114125118	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1700308C022	614	102	92	90	90	80	-99-99-99-99
1763308C223	614	102	93	83	90	96	-99-99-99-99
1760311C024	614	71	70	20-99-99	-99-99-99-99	-99-99-99-99	
1760311C025	614	70	29	15	60	48	-99-99-99-99
1760311C026	614	54	52	35	52	30	-99-99-99-99
7760311C027	614	63	40-99	56	07	-99-99-99-99	-99-99-99-99
176032480289999	16	05	03	03	01	-99-99-99-99	-99-99-99-99
1760329C2299999	104	60	30	52	52	50 25 82 27	-99-99-99-99
166032CC0309999	90	72	10	70	50	80 10 70 12	-99-99-99-99
1700329 0319999	78	40	28	63	32	-99-99 50 24	-99-99-99-99
1760329C0399999	85	15	18	10	34	14 19 10 70	-99-99-99-99
1760328C0339999	30	18	24	16	12	-99-99-99-99	-99-99-99-99
1760328C0349999	25	18	14	10	16	-99-99-99-99	-99-99-99-99
1760407C0399999	285	198130140120	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760407C0369 99	150	130118118122	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760407C0379999	183	170162127119	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760007C0889999	145	40133110-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760412C3399999	26	04	13	05	14	-99-99-99-99	-99-99-99-99
7760414C0409999	09	09	08	06	06	-99-99-99-99	-99-99-99-99
1760414C0419999	09	08	07	07	06	-99-99-99-99	-99-99-99-99
1760414C0429999	08	06	03	04	05	-99-99-99-99	-99-99-99-99
1764414C4439999	07	02	04	02	03	-99-99-99-99	-99-99-99-99
1760415C0449999	231	182189210215	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760415C0499999	221	190200170-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760415C0469999	212	180208180-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760415C0479999	210	209172180180	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760416C0489999	24	22	16	18	16	14 13 18 12	-99-99-99-99
1760416C0999999	24	21	18	18	17	17-99 17 14	-99-99-99-99
1760416 0509999	23	20-99-99	18	19-99-99	18	-99-99-99-99	-99-99-99-99
1760416C0519999	23	20	14	14	16	19 17-99 14	-99-99-99-99
176041700529999	228	150210140-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
176041 C0539999	04	02	01	01	03	-99-99-99-99	-99-99-99-99
1760418C0549999	04	01	01	03000	-99-99-99-99	-99-99-99-99	
1760419C0559999	260	170180220137	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760419C0569999	216	-99140176134	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760419C0599999	189	137149140	94	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760419C0589999	188	172-99150118	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760420C0599999	48	10	35	23-99	-99-99-99-99	-99-99-99-99	
1760420C0609999	25	01	03	08000	-99-99-99-99	-99-99-99-99	
1760428C0619999	147	146112100100	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760428C0229999	139	93129136097	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760428C0639999	142	119110120107	-99-99-99-99	-99-99-99-99	-99-99-99-99	-99-99-99-99	
1760428C0649999	136	125102	82	85	-99-99-99-99	-99-99-99-99	

ORIGINAL PAGE IS
OF POOR QUALITY

1760430C0669999	29	20	23	22	25	-99-99-99-99
1660505C0679999	89	78	38	76	34	-99-99-99-99
1760505C0689999	55	28	99	99	28	-99-99-99-99
1760505C0699999	41	15	99	25	14	-99-99-99-99
7760555C0709999	40	28	16	25	25	-99-99-99-99
1760566C0719999	10	05	02	06	04	-99-99-99-99
176 506C0729999	07	04	01	04	01	-99-99-99-99
1760509C0739999	45	30	40	99	99	-99-99-99-99
1760510C0749999	26	-99	20	14	10	-99-99-99-99
1760512C0759999	89	88	40	99	99	-99-99-99-99
7760522C0769999	79	-99	62	10	65	-99-99-99-99
1760512C0779999	45	07	28	12	20	-99-99-99-99
1760512C0789999	37	19	99	99	28	-99-99-99-99
1760522C079 314	108	80	70	60	100	75 55-99 97
1760522C080 114	100	-99	62	33	64	-99 81 72 61
1760522C08 314	95	46	30	40	46	80 27 65 45
1760222C082 314	88	47	60	45	64	-99-99 77 48
1760523C0 3 314	30	23	25	24	26	-99-99-99-99
1760523C084 314	24	18	19	17	16	-99-99-99-99
1760525C085 714	111	87	70	95	70	-99-99-99-99
17605250086 714	107	46	80	89	55	-99-99-99-99
1760525C087 714	95	55	55	67	40	-99-99-99-99
1760525C088 714	87	70	74	75	70	-99-99-99-99
1760526C089 584	359	200	150	120	60	-99-99-99-99
1760526C090 584	149	140	99	120	100	-99-99-99-99
1760526C091 884	133	70	88	100	58	-99-99-99-99
1760526C092 584	126	63	68	124	70	-99-99-99-99
1760529C993 837	40	37	20	30	-99	-99-99-99-99
1660529C994 837	22	05	10	01	06	-99-99-99-99
1760530C095 536	100	60	30	22	36	-99-99-99-99
1760530C096 536	86	78	38	58	25	-99-99-99-99
1760530C097 536	82	68	50	18	45	-99-99-99-99
1760530C098 536	68	47	25	47	23	-99-99-99-99
1760531C0999999	44	32	20	30	32	32 20 22 35
1765531 1009999	43	25	20	39	28	22 33 37 28
1760531C1019999	42	33	35	33	37	32 28 26 36
1760531C1029999	38	30	30	37	-99	27 30 34-99
1700901C103 714	91	10	30	14	20	-99-99-99-99
1760901C104 714	65	48	01	04	08	-99-99-99-99
1760901C105 714	30	09	19	25	07	-99-99-99-99
1760901C106 714	23	02	02	13	21	-99-99-99-99
1760908C107 114	252	90	150	250	164	-99-99-99-99
1760908C108 514	220	130	100	110	69	-99-99-99-99
1760908C1095514	189	50	38	116	100	-99-99-99-99
1760908C110 114	196	119	78	56	-99	-99-99-99-99
1760909C111 784	31	25	-99	18	10	-99-99-99-99
1760912C112 814	199	173	-99	188	163	-99-99-99-99
1769912C 13 814	194	164	146	150	143	-99-99-99-99
1760912C114 814	189	162	105	162	160	-99-99-99-99
1760912C115 114	187	142	109	134	118	-99-99-99-99
1700913C116 114	139	100	100	110	92	-99-99-99-99
1760913C117 614	127	90	-99	-99	95	-99-99-99-99
1760913C118 614	106	105	80	94	90	-99-99-99-99
176 914C119 614	109	78	10	200	00	30000000000
1760914C120 614	93	60	09	000	04	40-99 02000
7760914C121 614	53	08	20	03	10	-99000 23 09
1760917C122 706	07	04	04	02	02	-99-99-99-99
1760917C223 706	06	03	-99	03	01	-99-99-99-99
1760919C124 514	65	25	54	06	22	-99-99-99-99
1660920C125 714	17	15	14	14	12	-99-99-99-99
1760927C126 714	14	09	07	07	08	-99-99-99-99
1761003C127 114	20	16	12	05	10	-99-99-99-99
1761003C128 814	20	06	11	15	06	-99-99-99-99
1761003C129 814	16	01	12	12	-99	-99-99-99-99
1761009C1308A14	15	08	12	13	02	-99-99-99-99

1761005C1328A84	68	46	30	48	22	40	20	25	40
1761005C133	884	60	45	42	40	38	-99-99	40	21
1761005C134	884	42	32	39	27	20	-99-99	22-99	
1761005C135	884	20	09	10	08	10	14	03-99-99	
1761007C136	784	64	-99-99	52	58	-99-99-99-99			
1761007C137	784	58	47	53-99	50	-99-99-99-99			
1761007C138	784	52	50	42	45	41	-99-99-99-99		
7761017C139	784	52	42	45	36	43	-99-99-99-99		
1761015C1405514		51	30	34	43	28	-99	20	30
1761015C141	114	48	42	18-99-99		40	10	29-99	
1761015C142	514	49	33	07	41	35	-99000	10-99	
1761010C143	516	10	08	07	06	06	-99-99-99-99		
1761018C1445516		10	10-99	09	05	-99-99-99-99			
1661018C145	516	10	08	03	08	08	-99-99-99-99		
1761018C146	116	10	06	07	06	06	-99-99-99-99		
1761019C147	786	11	06	06	04	08	-99-99-99-99		
161019C148	786	11	07	06	06	05	-99-99-99-99		
1761019C149	786	09	05	05	05	04	-99-99-99-99		
1761023C150	504	26	16	12	11	09	15-99-99	10	
17610231151	504	18	17	11	15	11	12	14	16
1761023C152	504	16	14	16	14	16	05	12	09
1761020C153	816	20	18	19	15	20	-99-99-99-99		
1761026C154	116	14	09	13	08	10	-99-99-99-99		
1760026C555	816	14	07	10	10	11	-99-99-99-99		
1761026C156	116	17	12	11-99	11	-99-99-99-99			
1761227C157	716	24	14	17	16-99	-99-99-99-99			
1761027C158	716	15	06	09	13	11	-99-99-99-99		
1761027C159	716	14	05	13	05	12	-99-99-99-99		
1761028C16	714	11	08	06	04	05	06	02-99	07
1760028C661	714	10	06	01	04	05	08	04-99	02
1760028C162	714	10	08	05	05	05	08	08-99-99	
1761028C163	714	09	08	04	07	05	05	05	08
1761029C164	714	195	150150150160	-99-99-99-99					
1761029C165	714	180	160145146145	-99-99-99-99					
1661029C166	714	173	158158156155	-99-99-99-99					
1761029C167	714	168	160140130123	-99-99-99-99					
1761030C1687727		05	04-99	03	02	-99-99-99-99			
17110301169	727	05	03-99	04	04	-99-99-99-99			
1761030C170	27	05	03	04	02	03	-99-99-99-99		
1761030C171	727	05	03	04	03	02	-99-99-99-99		
1761111C172	706	17	12	13	10	13	03-99	08	12
161111C173	706	12	11	10	10	05	07-99-99	03	
1761111C774	706	10	07	06	08	07	-99-99	08	04
17111131175	114	09	05	08	03	06	-99-99-99-99		
1761113C176	714	08	03	07	03	06	-99-99-99-99		
1761113	177	714	08	04	06	05-99	-99-99-99-99		
1761114C178	386	07	05	04	05	06	-99-99-99-99		
1761120C779	727	08	04	04	05	01	01-99	04-99	
1711205C180	004	64	40-99	60	55	-99-99-99-99			
1761205C181	704	62	52	51-99	40	-99-99-99-99			
1761205C1827704		60	40	50	49	34	-99-99-99-99		
77612	5C183	704	52	50	50	48	49	-99-99-99-99	
1761206C144	714	25	15	20	22	16	12	19	22
17112101185	526	08	06	02	07	05	-99-99-99-99		
1770106C1869999		10	09	06	08	04	-99-99-99-99		
1770106C1879999		09	08	05	09	06	-99-99-99-99		
170010811889999		50	35	45	48	07	-99-99-99-99		
1770108C1899999		40	-99-99	03	29	-99-99-99-99			
1770108C1999999		29	10	10	12	03	-99-99-99-99		
1770109C1919999		55	05-99	20	10	-99-99	30	14	
1770109C1929999		35	21	19	14	20	-99	15	10
177010911939999		32	30	16	22	12	30	10	13
1770109C1949999		30	22	10	18	17	04	20	29
1770112C195	716	30	25	22	13	19	-99-99-99-99		
17701121196	716	25	23	17	23	21	-99-99-99-99		

1770113C199	814	09	07-99	08	05	-99-99-99-99
1770113C20	814	08	05000	05-99		-99-99-99-99
1700122C201	736	09	06	05-99	05	-99-99-99-99
1770122C002	736	07	04	06	06	02 -99-99-99-99
1770122C203	736	05	03	04	04	03 -99-99-99-99
1770123C204	506	09	-99	05	07	04 -99-99-99-99
1770123C205	506	05	04	03	02	02 -99-99-99-99
1770202C206	227	09	06-99-99	04		-99-99-99-99
1770202C207	127	06	02	03	05	04 -99-99-99-99
1770203C208	727	09	-99	08	08	08 -99-99-99-99
17702 3C209	727	09	06-99-99-99			-99-99-99-99
17002032210	727	09	06-99-99	03		-99-99-99-99
1770111C211	114	190	150170155126	134155150118		
1770211 212	114	148	130140-99120	128122-99-99		
1770211C113	114	146	-99120125123	-99-99119126		
1772222C114	816	16	12	15-99	07	-99-99-99-99
1770226C215	814	34	20	33-99-99		-99-99-99-99
1770226C216	814	30	22	16-99	20	-99-99-99-99
1770226C217	114	28	22	21	18	16 -99-99-99-99
1770266C218	814	26	17	19	20	14 -99-99-99-99
1770227 219	826	19	15	02	10	18 -99-99-99-99
1770227C220	826	12	09	03	07	05 -99-99-99-99
1770227C221	826	11	50	50	60-99	-99-99-99-99
1770302C222514	133	19-99	90	15	13-99	01 21
1770302C223	514	126	50	10	50	30 50-99 45 50
1770302C224	114	103	37	25-99	55	30 03-99 74
1770310C225	114	100	49	57	64	23 -99-99-99-99
1770310C226	114	59	57	24	30	30 -99-99-99-99
17003262227	514	51	50	44	46	32 -99-99-99-99
1773327C228	514	61	59	51	48	41 -99-99-99-99
1770377C229	514	52	31	27	33	34 -99-99-99-99
1770401C230	814	69	50	20	43	01 -99-99-99-99
1700401C2318814	33	-99-99	20	15		-99-99-99-99
7770413C232	914	78	15	16	53	50 -99-99 06 28
1770413C233	914	23	21	01	19	09 21 04 20 02
1770113C244	914	23	15	09	09000	0000000-99000
1770414C235	514	32	27	14	24	14 -99-99-99-99
1774414C236	514	31	21	20	30	16 -99-99-99-99
1770415C23	884	50	40	46	40	38 -99-99-99-99
1774415C238	884	50	50-99	50	45	-99-99-99-99
1 70415C2398884	43	30	40	35	30	-99-99-99-99
1770415C240	884	42	35	37	35	30 -99-99-99-99
1770416C241	584	54	-99	30	25	30 -99-99-99-99
1774416C242	584	52	45	40	38	39 -99-99-99-99
1770416C243	584	46	-99	36	40-99	-99-99-99-99
1770416C244	584	31	30	24	30	22 -99-99-99-99
1770417C445	885	15	08	07	10-99	-99-99-99-99
1770417C246	885	15	08	05	11000	-99-99-99-99
1770418C247	885	28	11	06	02	04 11-99 02 04
1770418C248	885	26	01	02	00-99	00 00-99-99
1770418C249	885	26	-99-99-99	00		-99-99-99000
1700419C2505514	32	24	13	00	01	-99-99-99-99
1770420C251	514	464	440340280390			-99-99-99-99
1770420C252	14	402	315175265320			-99-99-99-99
1770420C253	514	319	140200205190			-99-99-99-99
1770420C254	514	241	200	85	75100	-99-99-99-99
17704212255	584	09	05	06	08	06 -99-99-99-99
1770421C256	584	09	-99	06	06-99	-99-99-99-99
1774421C557	584	08	07	06-99	06	-99-99-99-99
1770422C258	787	26	18-99	13	08	16-99-99 10
1770422C259	787	24	20	02	20	20 07 02 15 06
1770422C260	787	24	12	20	07	05 10 07 07-99
1770422261	787	24	20-99-99	14		20-99-99 09
1774429C662	516	250	75	55200170		-99-99-99-99

ORIGINAL PAGE IS
OF POOR QUALITY

1770422C264	516	35	30	20	12-99	-99-99-99-99
1770229C265	516	35	30	20	12-99	-99-99-99-99
1770430C266	884	55	35	08	06-99	-99-99-99-99
17705012267	887	223	115	50145	60	-99-99-99-99
7770511C268	887	145	105	52	26 04	-99-99-99-99
1770501C269	887	122	000	75	50 25	-99-99-99-99
1770500C270	887	113	-49	09102	-99	-99-99-99-99
1775502C771	826	110	45100100	-99	-99-99-99-99	
7770522C222	826	107	40	80	65-99	-99-99-99-99
1770502C273	826	100	80	78	50-99	-99-99-99-99
1770503C274	1126	134	38	78100	60	25 75 48 96
1770503C775	126	96	54	68	49 90	25134 31 33
1770503C276	126	80	36	50	26 40	25 40 17 56
1770504C277	114	43	40	35	00 24	-99-99-99-99
1770504C288	114	39	35	30	36 30	-99-99-99-99
17705052279	814	225	210145	-99	-99	-99-99-99-99
1770505C280	814	84	60	22	61 30	-99-99-99-99
1770505C281	814	78	59	55	55 30	-99-99-99-99
1770513C2827714	149	80	08	30	52	-99-99-99-99
1770513C283	714	134	50	50	70 10	-99-99-99-99
1770513C284	714	72	10	22	65 55	-99-99-99-99
1770514C285	114	186	168	-99	-99100	-99-99-99-99
1770515C2869914	50	45	20	21	24	28 03 20 05
177051C28	914	42	21	10	15 19	37 05 05 00
1770515C288	914	39	31	10	20 15	10 07 38 00
17705152289	914	35	-99	-99	20 10	-99-99 15 09
1770516C290	914	178	-99120130160	-99	-99-99-99-99	
1770516C291	914	22	20	08	15 14	-99-99-99-99
1770517C2929914	49	20	30	32	10	-99-99-99-99
1770517C293	914	37	32	15	06 08	-99-99-99-99
1770519C294	914	394	280	-99	-99310	-99-99-99-99
177051 C295	914	306	300285	-99	235	-99-99-99-99
1775520C296	914	578	530415500400	-99	-99-99-99-99	
1770520C277	914	244	235130220190	-99	-99-99-99-99	
17705202298	914	229	200160220170	-99	-99-99-99-99	
1770521C299	884	07	03	02	02 04	-99-99-99-99
17705213300	884	07	06	-99	04 03	-99-99-99-99
1770526C301	914	465	300240390275	200225231214		
1770526C302	914	425	390200300280	330151267263		
1770527C303	114	148	95	95130105	-99-99-99-99	
1770527C3049914	141	125110	85120	-99-99-99-99		
1770527C30	914	77	48	55	45 60	-99-99-99-99
1770527C366	914	59	30	34	30 41	-99-99-99-99
1770530C307	006	297	200	95270200	-99-99-99-99	
1770530C308	506	266	190140150125	-99-99-99-99		
1770530C009	506	231	180145110150	-99-99-99-99		
17705313310	707	247	210100100	-99	-99-99-99-99	
1770531C311	707	214	200	60	80110	-99-99-99-99
1770531C312	707	211	115100100	70	-99-99-99-99	
1770904C113	116	74	60	-99	10 10	-99-99-99-99
17709043314	816	25	20	-99	20 15	-99-99-99-99
1779905C115	537	121	85	80113110	61 55-99 78	
17709053316	537	104	60	85	75 85	62 95 56100
1770905C317	537	89	50	60	65 62	46 61-99 40
1770906C318	730	190	50	-99	-99 70	-99-99-99-99
1770910C319	737	40	-49	20	15 35	-99-99-99-99
1779910C320	337	31	17	00	18 05	-99-99-99-99
1770912C321	814	148	135	-99	-99-99	-99-99-99-99
17709123322	114	69	60	50	35 25	-99-99-99-99
1770912C323	814	55	15	40	50 14	-99-99-99-99
1770913C324	527	144	110	60	-99 90	106 21-99-99
1770913C325	527	114	100	-99	-99 60	69-99-99 33
1770913C326	527	85	55	55	-99 10	18 15-99 05
1770928C327	936	48	-49	-99	14 21	-99-99-99-99
1779928C228	936	30	25	11	-99 08	-99-99-99-99

ORIGINAL PAGE IS
OF POOR QUALITY

1771000330	537	50	50	40	35	46	44	38	32
1771000331	537	32	30	25	30	22	30	30	29
77710220332	514	252	225	210	225	225	-99	-99	-99
17710220333	514	170	90	110	150	155	-99	-99	-99
17 10220334	114	106	85	55	63	90	-99	-99	-99
17710220335	514	49	-99	30	24	35	-99	32	10
17710220336	514	40	32	22	27	23	31	18	22
17710220377	514	37	28	16	30	25	28	13	31
17711010338	814	34	22	27	30	25	-99	-99	-99
17711010399	814	17	08	06	05	10	-99	-99	-99
17711023340	887	82	60	62	70	68	-99	-99	-99
17711073341	514	57	55	20	56	45	45	20	35
17711070342	514	45	42	25	-99	43	-99	28	40
17711070343	514	36	30	25	27	21	21	25	25
17711080344	514	100	70	75	62	62	-99	-99	-99
17711080345	114	97	-99	-99	65	70	-99	-99	-99
17711080346	514	85	70	62	56	58	-99	-99	-99
17 11090347	527	30	22	14	26	16	18	14	15
17711090348	527	30	21	14	15	15	22	16	14
17711093349	527	30	12	11	20	17	15	14	16
17711280550	714	29	-99	-99	24	17	-99	-99	17
1771128035	714	20	19	16	20	18	15	12	18
17722000552	816	30	-99	17	20	-99	-99	-99	-99
17712290353	806	10	09	09	08	07	-99	-99	-99
17712290354	806	10	06	06	03	02	-99	-99	-99
1771229035	806	10	06	05	03	02	-99	-99	-99
27706010356	737	197	110	130	-99	100	78	80	-99
22706010357	73	139	90	80	80	80	83	70	65
27706010358	737	112	80	78	80	80	58	60	65
27706010359	737	122	50	50	60	60	28	18	70
27706120360	116	115	90	83	75	87	90	65	55
22706120361	916	111	98	85	75	90	-99	72	61
27706120362	966	67	57	35	39	40	61	25	28
2770612036	916	63	55	47	42	47	59	45	34
27706210364	914	148	130	110	104	118	120	90	85
27706210365	914	138	95	95	98	90	70	75	95
27706210366	914	136	128	120	120	124	120	115	100
27706210367	914	101	98	90	90	88	90	78	70
27706223368	914	199	160	170	140	130	145	162	110
27706220369	914	115	88	90	83	70	70	75	70
27706220370	914	103	60	58	70	58	50	38	59
27706220371	914	110	85	85	85	81	81	85	-99
27706220372	914	231	90	90	118	100	50	48	110
27706220373	914	226	140	110	100	100	150	70	50
27706220374	914	161	100	80	105	110	82	40	90
27706220375	914	555	60	80	110	70	38	60	120
27707080376	227	222	118	100	120	108	98	58	100
27707080377	527	189	100	103	118	90	65	60	130
27707080378	527	183	140	150	100	118	120	160	70
27707080399	527	169	90	90	85	85	80	65	58
27708200300	036	158	95	98	95	90	78	90	77
27708200381	036	119	70	80	85	80	50	70	80
2770 200322	036	85	80	70	65	70	65	57	54
27702270383	514	671	500	500	450	450	42	-99	32
27708770384	514	565	460	450	440	440	43	40	38
27708200385	514	498	430	430	430	410	-99	420	420
27708270386	514	364	270	280	280	280	230	250	240
27710040387	836	20	14	15	16	16	11	13	-99
27700040888	836	55	13	13	13	13	13	11	-99
27710040389	836	12	09	09	08	09	09	08	06
27710070390	514	36	24	28	25	28	18	24	20
27805000391	78	198	1160	160	170	158	148	139	165
27855000392	784	194	158	140	158	150	144	115	137
27805000393	884	186	158	150	140	150	142	120	130
27800000344	78	158	137	132	120	125	130	118	98

589

589

589

589

508

508

508

508

542

542

542

542

2474

2474

2474

2474

2153

2153

2153

1202

1202

1202

1386

1386

1386

1618

1618

1618

1618

316

316

316

406

666

666

666

666

2780520C397	7064016	370330300330	-99-99-99-99	2352
780520C39	706405	340340300250	-99-99-99-99	2352
2780520C399	914669	160150140130	14010011080	456
7780508C400	914230	140120163168	11040160148	456
2780520C401	914220	135122102100	118987068	456
2780520C4029914	147	1101008582	100885850	456
2780520C4039999	21	150160160140	-99-99-99-99	216
2780520C4049999	154	95629890	-99-99-99-99	216
2780520C4059999	126	84806060	-99-99-99-99	216
7780520C4069999	58	50353835	-99-99-99-99	216
2780630C407	9142214	140100118120	-99-99-99-99	719
7780600C408	914129	90707070	-99-99-99-99	719
2707034009	537213	140120140150	12212090123	730
2780703C41	537156	10611011090	908512538	730
2780103C411	337133	80706160	70584030	730
2780703C412	5371131	90909380	70707958	730
2780803C413	785100	60705550	-99-99-99-99	668
2780901C414	70448	25252925	-99-99-99-99	748
2880901C415	70426	18131918	-99-99-99-99	748
2780920C416	51430	24242424	-99-99-99-99	635
2780920C41	51420	13131110	-99-99-99-99	635
2780900C418	51416	14120911	-99-99-99-99	635
2780920C419	11415	08080708	-99-99-99-99	635
2780921C420	726508	440400430430	430340500380	1629
2780920C421	726457	350390350250	360380310150	1629
27009214422	726351	280280250240	260240240290	1629
2780921C4237726	327	240240200240	17023050190	1629
2780924C444	707276	238230218218	230203200218	3179
2780924C425	777259	210180200200	190120200180	3179
278092444267707	339	218204200210	218160180198	3179
27809244427	707227	177158160160	160120140138	3179
3770518C428	51467	45-994842	-99-99-99-99	329
37705184429	514558	42303230	-99-99-99-99	329
3770520C430	114661	345300330-99	-99-99-99-99	1607
3770520C431	514551	300280330-99	-99-99-99-99	1607
3770520C432	514329	300310310318	-99-99-99-99	1607
3770520C433	514353	160158155160	-99-99-99-99	1607
3770525C4344914	125	85657868	80755870	1186
3770525C435	914110	8888-9960	10182-9968	1186
37705254436	914102	83608575	75659060	1186
3770525C4379914	87	58627268	70756065	1186
3770526C438	91455	55404240	52482834	238
3705264439	91474	50-997268	25-996260	238
3770526C440	91471	55575447	42-994038	238
3770528C441	81444	55504855	-99-99-99-99	538
3770528C442	81451	3842-9940	-99-99-99-99	538
3770520C443	81448	30353530	-99-99-99-99	538
37706114444	33577	62625561	-99-99-99-99	523
3770611C445	33571	62555150	-99-99-99-99	523
3770611C446	53561	4353-9948	-99-99-99-99	523
3770613C447	537223	-9997100114	-99-99-99-99	821
3770714C448	93170	11013011080	851038070	1038
3770714C44	934133	806265110	685258110	1038
3770714C450	934102	58709070	53688560	1038
3770724C45	534236	14080200120	13080190100	1492
37707244452	534215	12010013070	1208520041	1492
3770724C453	534200	130130125120	12011014090	1492
3770724C454	534162	11070110117	9055100108	1492
3770720C455	004113	55884060	-99-99-99-99	415
3770728C456	00487	40805558	-99-99-99-99	415
3770728C457	00447	25203020	-99-99-99-99	415
3778804C458	80751	-99331025	-99-99-99-99	718
3770110C459	586166	100100130128	87100130122	562
37008104460	586159	128140120142	8013090120	562

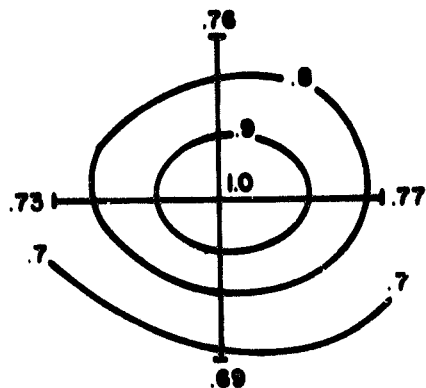
ORIGINAL PAGE IS
OF POOR QUALITY

3770810C461	586	156	120130130110	120110110105	562
3770810C462	586	147	130-99118110	125-99105120	562
3770810C463	53	174	125105 95110	-99-99-99-99	325
370810C464	534	113	109 90 95-99	-99-99-99-99	325
3770810C465	534	88	60 62 50 82	-99-99-99-99	325
3770810C466	534	661	48 38 42 53	-99-99-99-99	325
37 0816C467	506	35	20 25 28 15	-99-99-99-99	663
37 08214068	027	81	63 70 30 42	-99-99-99-99	446
3770821C499	027	77	65 62 40 72	-99-99-99-99	446
7770821C470	027	45	35 33 18 15	-99-99-99-99	446
37008214471	027	30	15 12 12 12	-99-99-99-99	446
3780430C4729990	159	142143142125	-99-99-99-99	2042	
3784430C4739999	154	120136135118	-99-99-99-99	2042	
3780505C774	806	183	105103143119	102103130140	1551
3780505C4758806	153	122120125122	108102139121	1551	
7780555C476	806	143	104119122-99	103130121-99	1551
3780518C477	816	148	121 70 95 90	-99-99-99-99	740
3780518C478	816	103	70 78 90-99	-99-99-99-99	740
3780518C479	816	96	75 63 78 70	-99-99-99-99	740
3780518C480	816	991	60 58 70 78	-99-99-99-99	740
3780604C481	706	355	220220250270	150210220140	656
3780604C48	706	299	265222258263	200245250-99	656
3700604C483	706	770	220240-99260	185150-99250	656
3780604C484	706	2247	160210210190	150240241205	656
388060CC485	716	250	204150 90 80	180130 50120	440
378060CC486	716	2200	80 70180120	120100 80 70	440
37806054487	716	186	125 80120115	100180 90110	440
3780605C4887716	133	118	70100110	90 50 90102	440
3780627C489	714	141	120 78 95 95	70 30 88 80	742
3780627C490	714	95	58 70 78 59	40-99 80 42	742
37006274491	714	88	60 64 50 60	50 61 44 80	742
3700720C4928806	97	80	90 88 87	-99-99-99-99	593
3780721C493	814	73	65 50 45 51	63 48 41 45	1758
3780221C494	814	58	35 25 53 30	33 30 35 25	1758

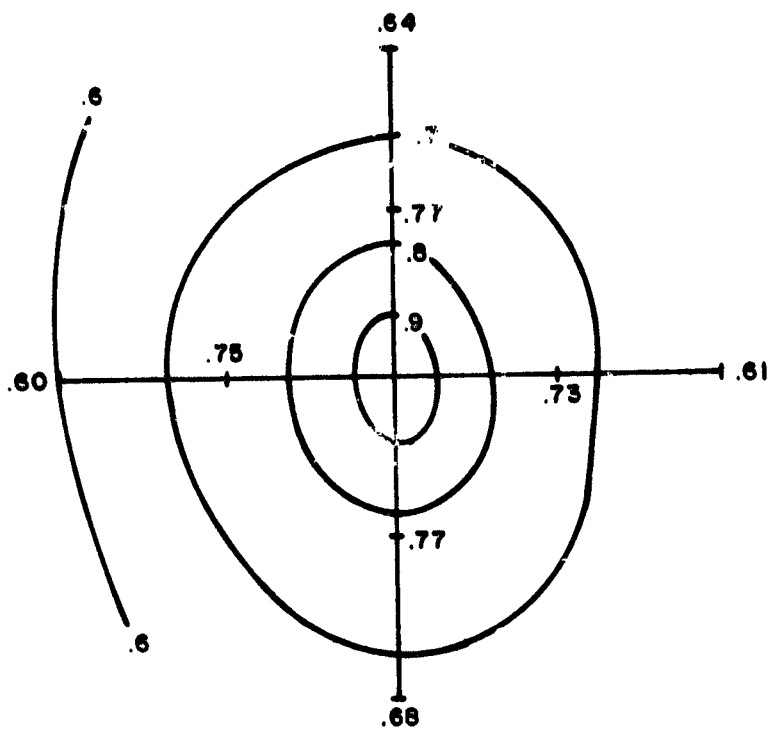
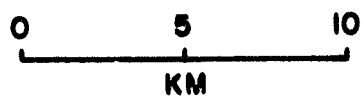
APPENDIX B
NORMALIZED RAINFALL AMOUNT PATTERNS

APPENDIX B

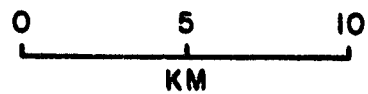
The 22 patterns in this appendix are the result of separating the storms by four synoptic types and various storm-center rainfall amount categories for the rain gage network in Oklahoma and the networks in Kansas and Texas. The range of the maximum storm rainfall amounts included in each pattern is indicated to the right of the pattern. The patterns have been normalized to the rainfall amount of the gage showing the maximum for the storm. The number of storms in each of the categories is indicated by the letter N. The direction of storm motion, as indicated by the 700 mb wind, is in the vertical upward direction for all patterns.

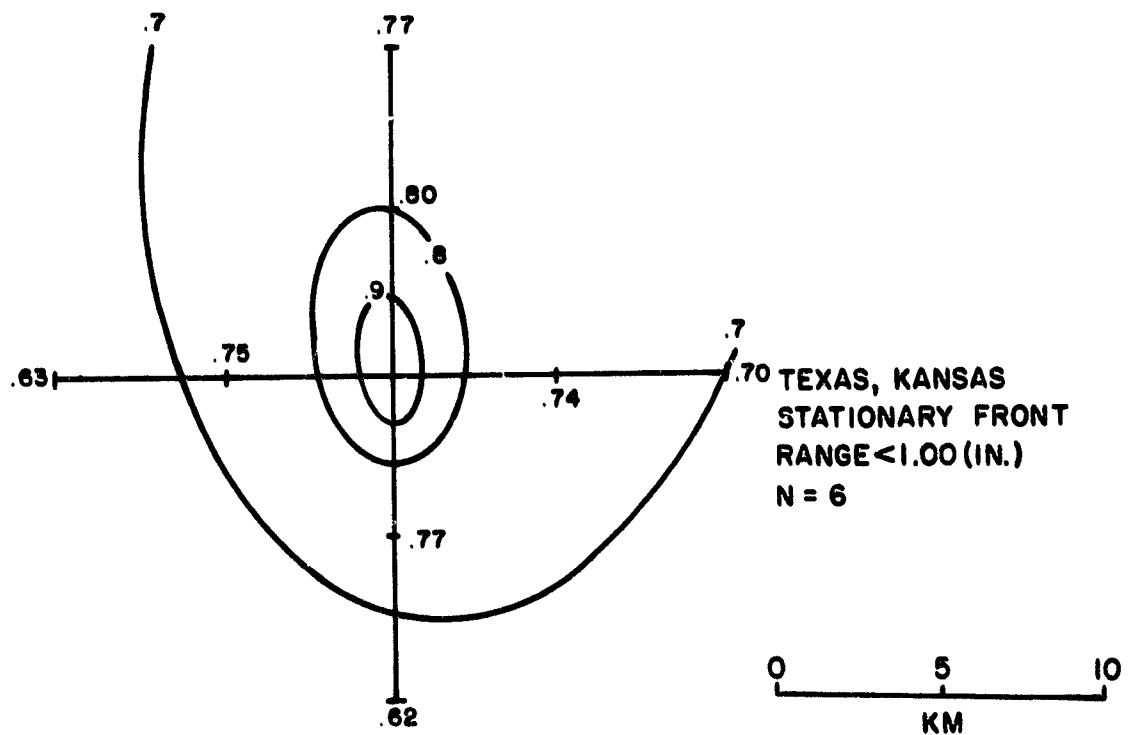
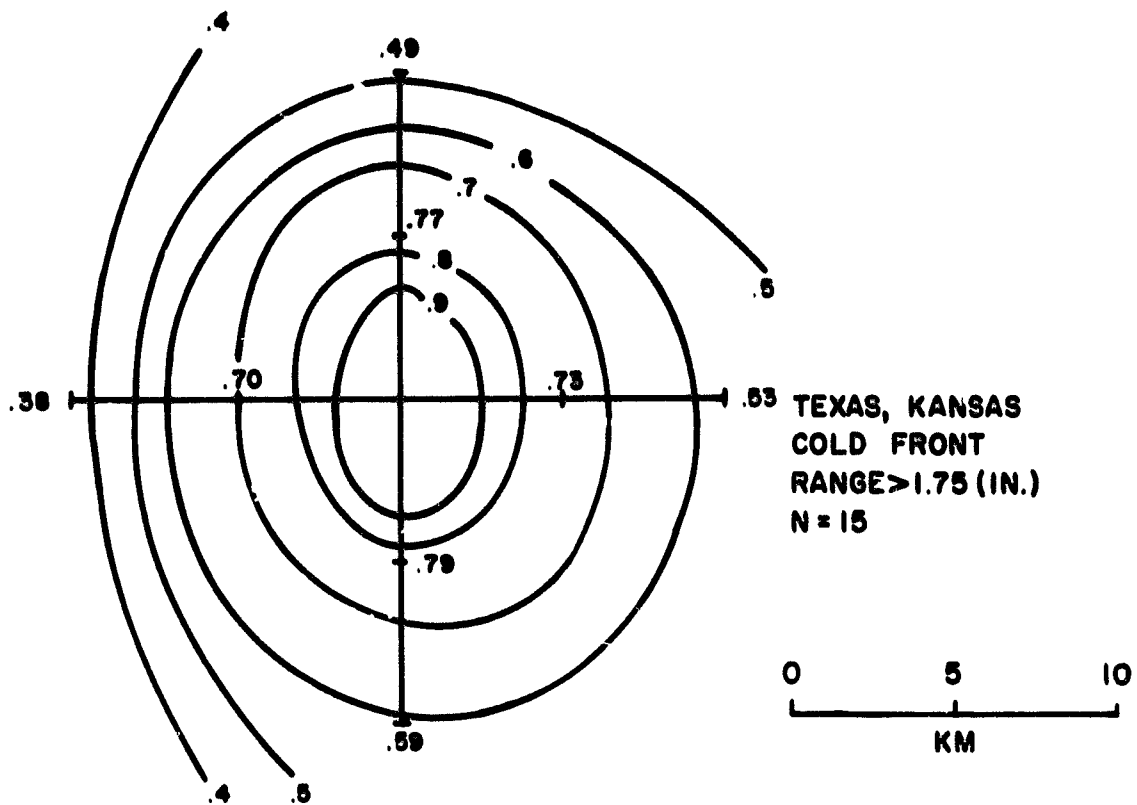


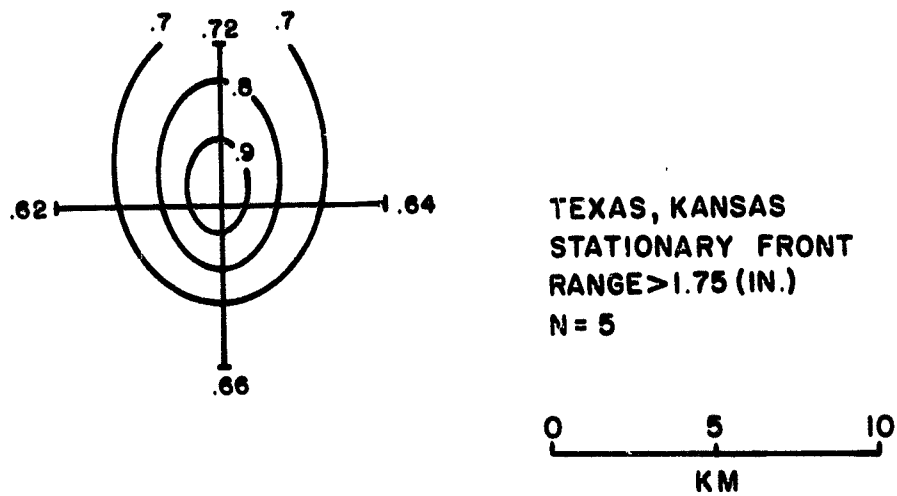
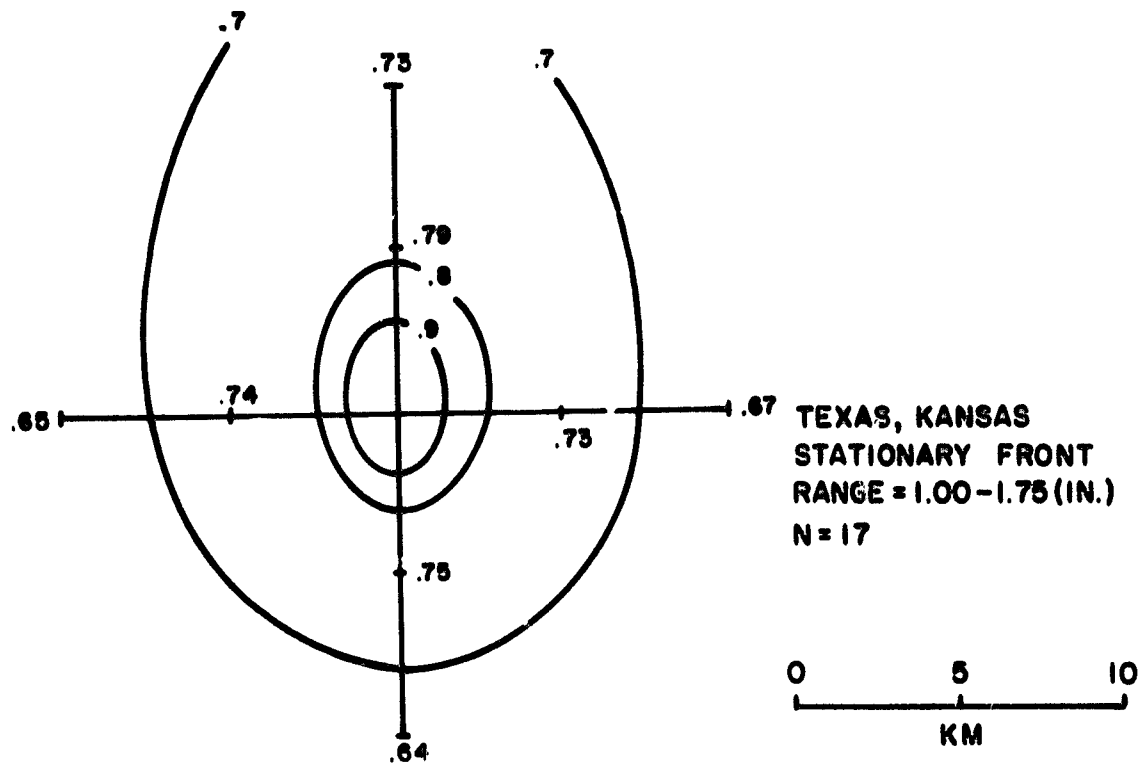
TEXAS, KANSAS
COLD FRONT
RANGE < 1.00 (IN.)
N = 13

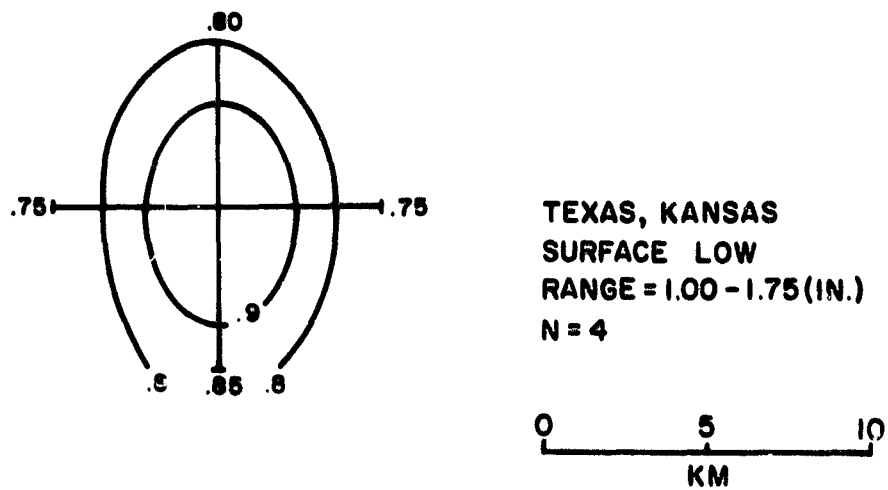
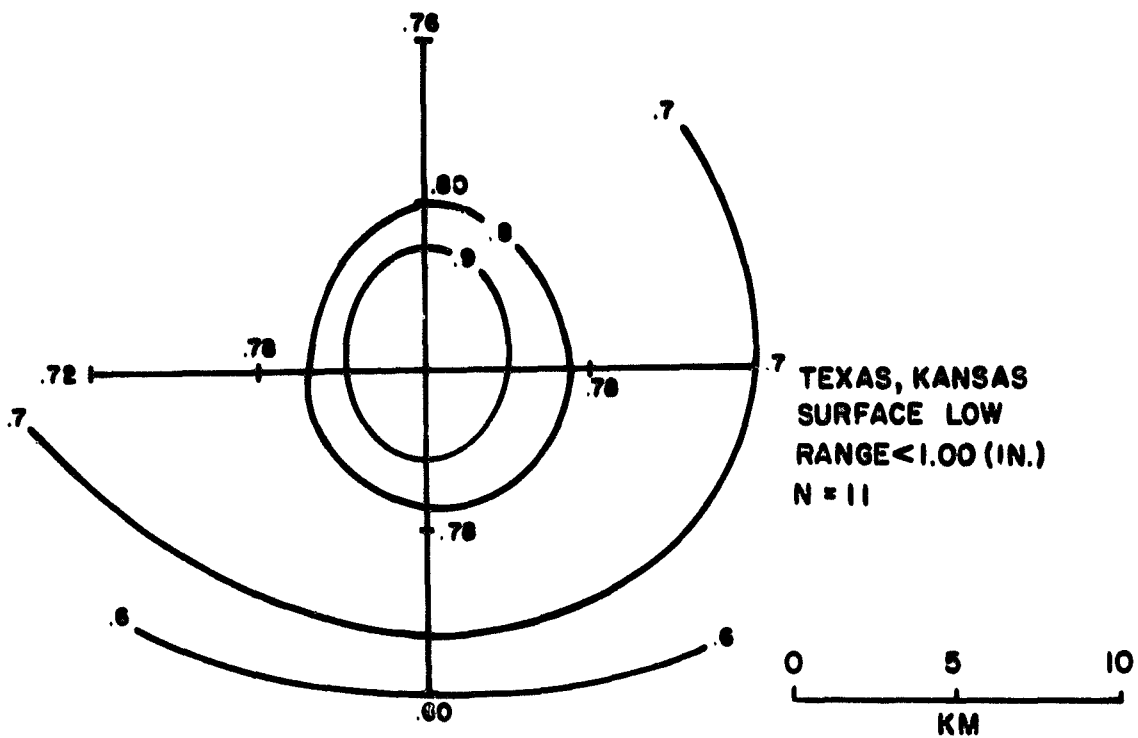


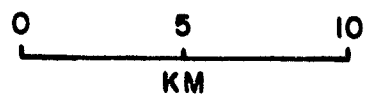
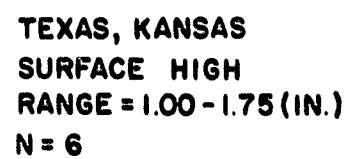
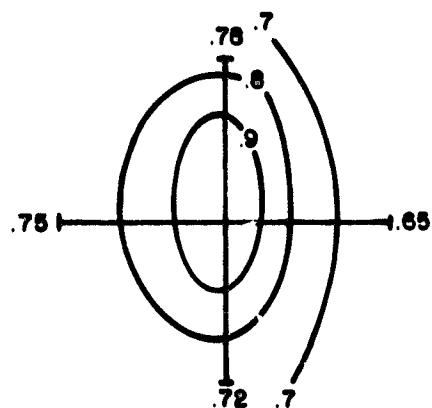
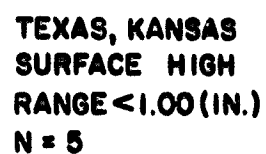
TEXAS, KANSAS
COLD FRONT
RANGE = 1.00-1.75 (IN.)
N = 11

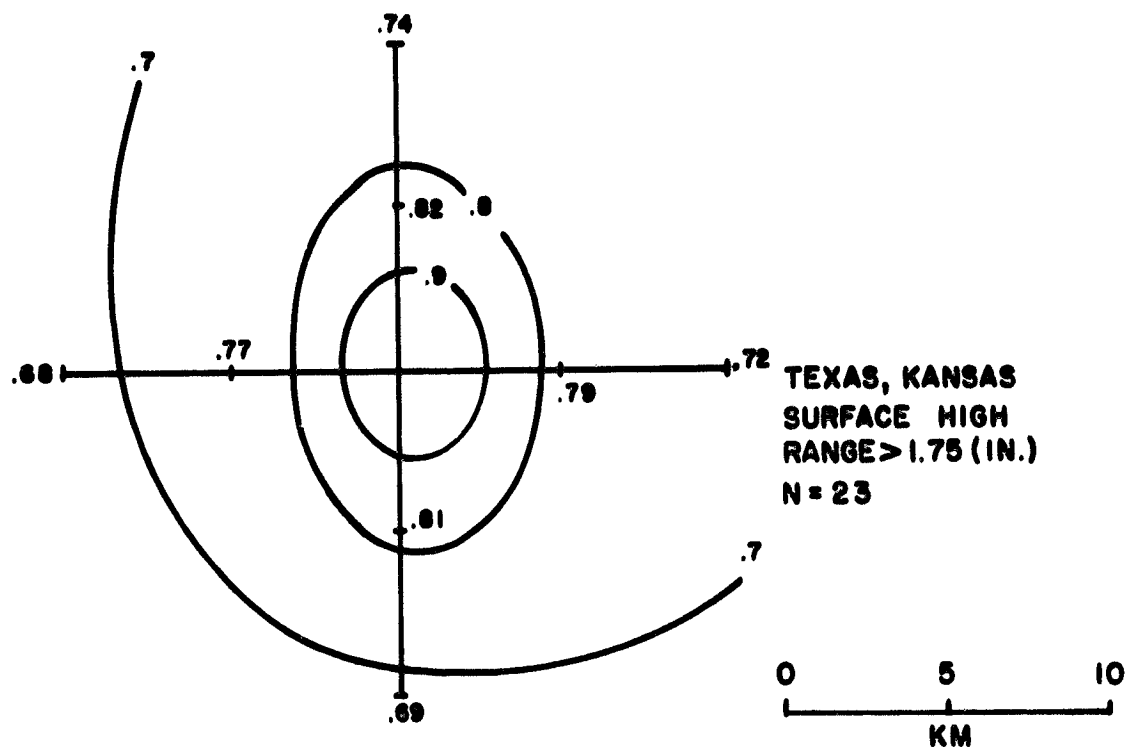


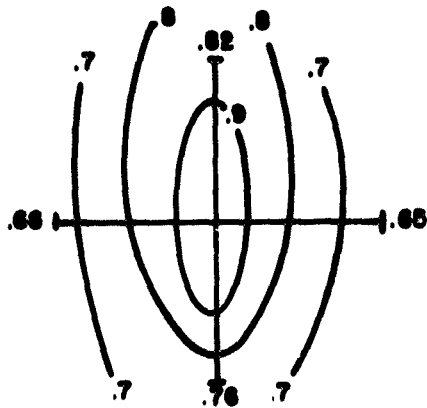




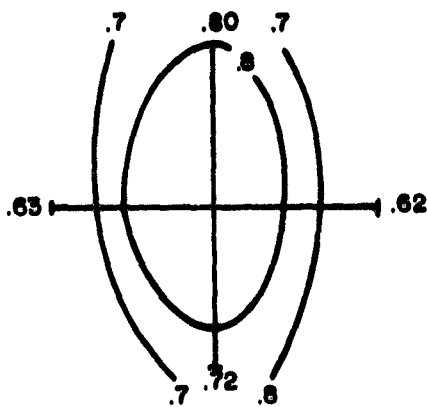
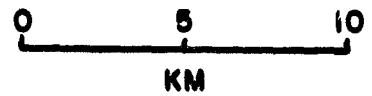






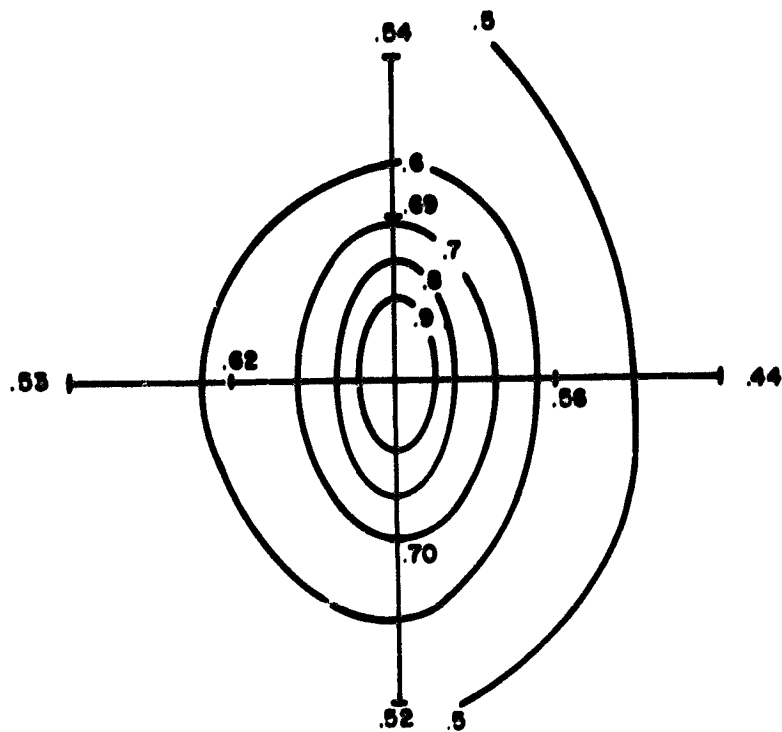


OKLAHOMA
COLD FRONT
RANGE < .25 (IN.)
N = 11



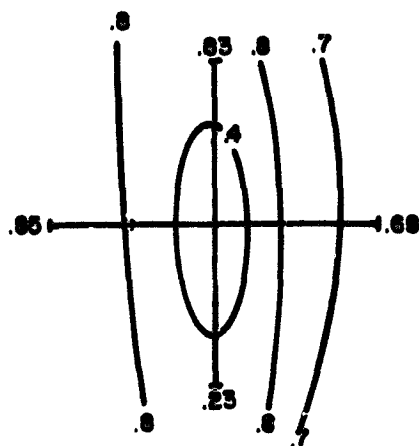
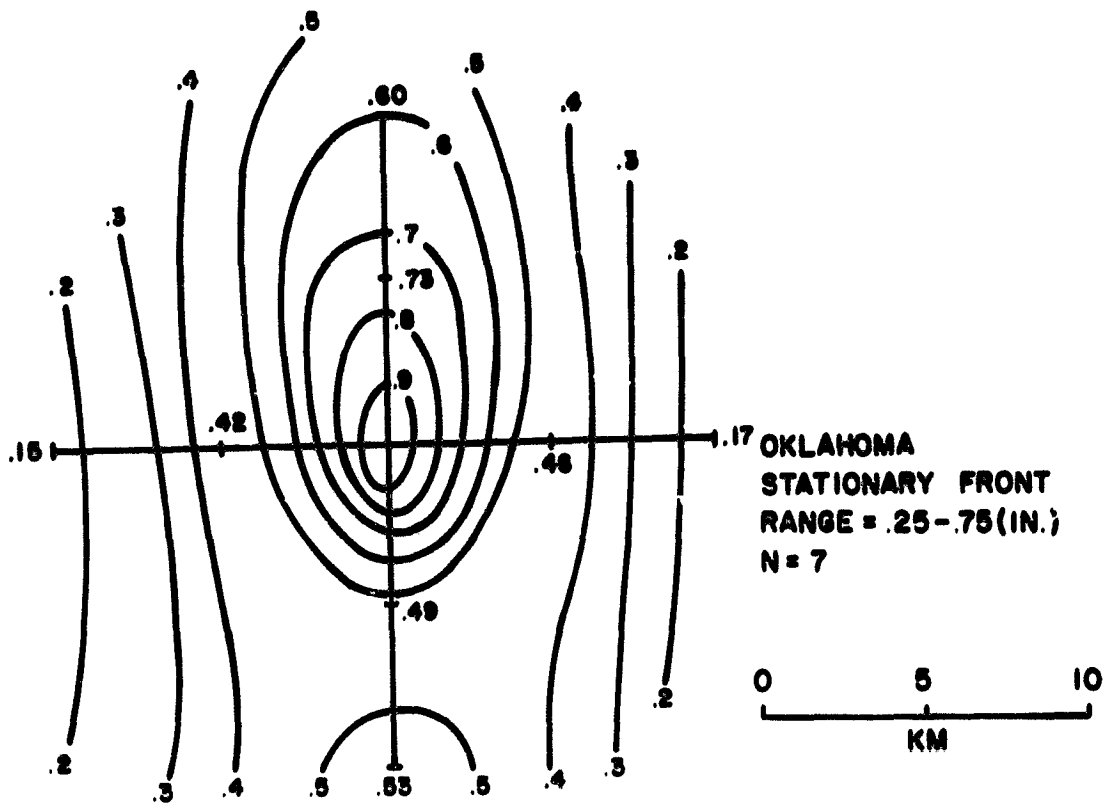
OKLAHOMA
COLD FRONT
RANGE = .25 - .75 (IN.)
N = 29

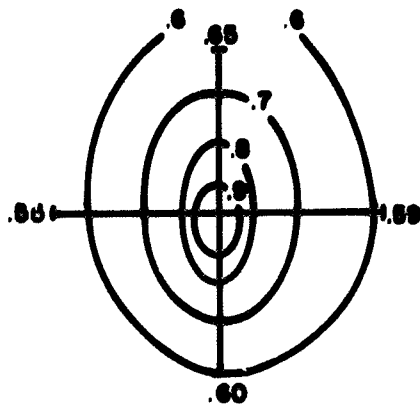




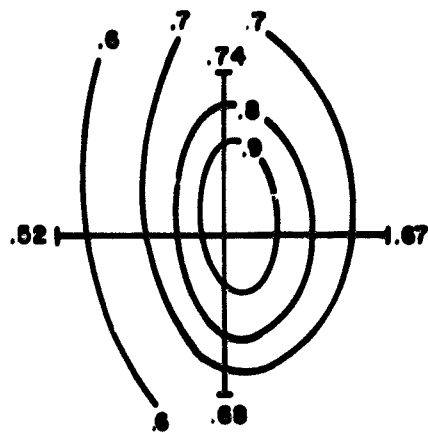
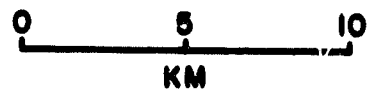
OKLAHOMA
COLD FRONT
RANGE > .75 (IN.)
N = 9

0 5 10
KM

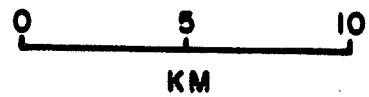


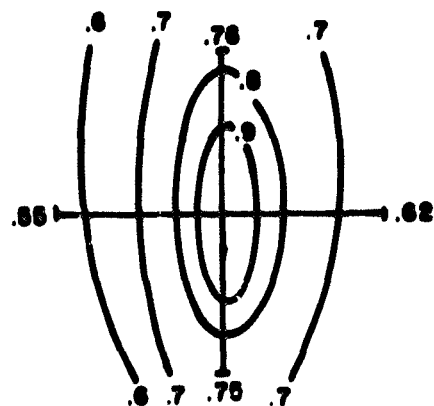


OKLAHOMA
SURFACE LOW
RANGE < .25 (IN.)
N = 24

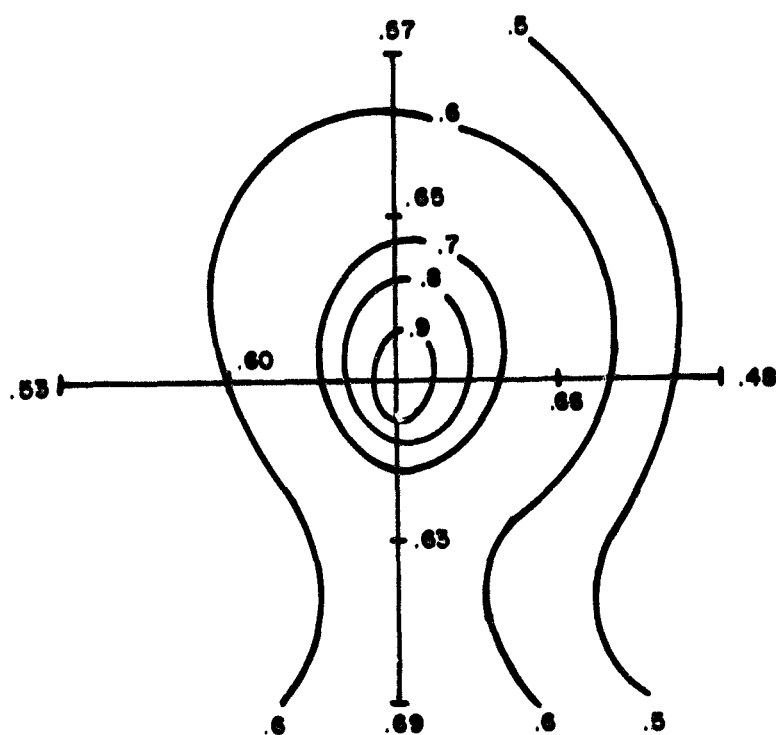


OKLAHOMA
SURFACE LOW
RANGE = .25 - .75 (IN.)
N = 20



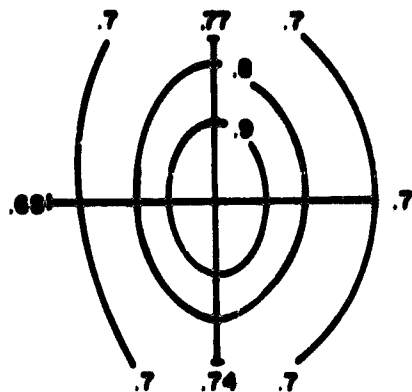


OKLAHOMA
SURFACE LOW
RANGE > .75 (IN.)
N = 14

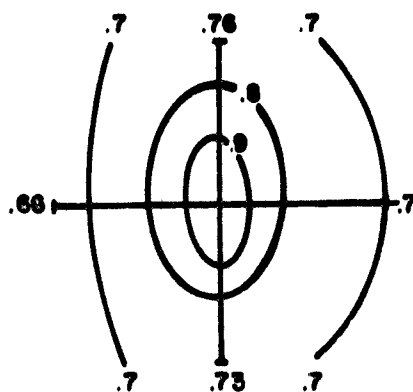


OKLAHOMA
SURFACE HIGH
RANGE < .25 (IN.)
N = 9





OKLAHOMA
SURFACE HIGH
RANGE = .25 - .75 (IN.)
N = 16



OKLAHOMA
SURFACE HIGH
RANGE > .75 (IN.)
N = 18

