NOAA Technical Memorandum NWS HYDRO 45

RELATIONSHIP BETWEEN STORM AND ANTECEDENT PRECIPITATION OVER KANSAS, OKLAHOMA, AND EASTERN COLORADO

Water Management Information Division
Office of Hydrology
Silver Spring, Md.
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D. James Baker, Under Secretary for Oceans and Atmosphere
National Weather Service
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RELATIONSHIPS BETWEEN STORM AND ANTECEDENT PRECIPITATION OVER KANSAS, OKLAHOMA, AND EASTERN COLORADO

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ABSTRACT

Antecedent and subsequent rainfall amounts were examined for storms with a daily precipitation amount equal to or greater than the 10-year 24-hour amount for Kansas, Oklahoma, and eastern Colorado. This investigation centered on the statistical relationships between an intense central precipitation event and its antecedent and subsequent precipitation within a small area (10 square miles or less). Daily precipitation sequences of 31 days centered on the maximum daily precipitation amount were used as the data base.

Some of the results from this study are: seasonally, storms with central rainfall amounts of 14.5 inches or more are most likely to occur in September or October in the central Plains; the larger central precipitation amounts tend to be associated with much shorter than average durations of the immediate antecedent dry period; as the central storm amount increases, the amount of precipitation contributed by the surrounding wet days increases; the distribution of total antecedent and subsequent precipitation is not symmetrical; and the ratio of the total antecedent and subsequent precipitation as a percent of the central storm decreases as the central precipitation increases. Statistically, the analysis of the daily rainfall indicates that for a 3- to a 5-day probable maximum precipitation event a reasonable antecedent precipitation amount would be 10 to 20 percent of the probable maximum precipitation amounts within a 31-day period centered on the day of maximum precipitation in the central Plains.

1. INTRODUCTION

The assessment of probable maximum flood (PMF) resulting from probable maximum precipitation (PMP) for a basin is a vital element in the hydrological analysis for the design of high-hazard dams. This assessment represents a major effort to minimize the risk of failure because of potential catastrophic consequences downstream. Computation of PMF involves selection of a sequence of meteorological and hydrologic conditions, such as the initial water levels in the basin and reservoir, the soil moisture, relevant snowpack, and other conditions. The dominant meteorological events include a principal storm of PMP magnitude with critical placement over the basin, and the associated antecedent and subsequent storms. Due to the relative lack of information on the antecedent and/or subsequent storms, many different assumptions have been adopted by various Federal agencies in computing floods used to evaluate hydrological safety of high-hazard structures. These assumptions on the magnitude of the antecedent storm can vary from enough precipitation to cause a 100-year flood to a storm that is 40 or more percent of the PMP amount (Newton 1983).

The goal of this investigation is to discover the pertinent relationships between an intense central precipitation event and its antecedent precipitation within a small area (10 square miles) through statistical analyses. The central event may have precipitation reaching a magnitude up to the appropriate PMP. A guiding principle for antecedent precipitation is that it could reasonably occur with the central event in real meteorological settings. Therefore, the probability of occurrence of the combined antecedent and central events should be virtually equivalent to the probability of the central event alone.

The term antecedent is frequently used to include all precipitation surrounding the central precipitation event regardless of when they occurred. It then depends on the context whether antecedent is being used inclusively or strictly in the sense of beforehand. In this investigation, unless specified otherwise, general reference to antecedent precipitation will refer to rainfalls both before and subsequent to the main storm.

There have been few works devoted to the topic of antecedent precipitation as related to the main storm. In an investigation to estimate PMP class precipitation for Tennessee River drainages, antecedent rainfall criteria were developed for the 21,400 square mile drainage above Chattanooga (Schwarz 1965). Part of that work was later extended to apply to drainages of 100 to 3000 square miles in the Tennessee Valley (Riedel et al. 1976). Miller and Ho (1980) did a pilot study on precipitation antecedent to the 24-hour PMP for small basins in Texas. In Hydrometeorological Report No. 56 (Zurndorfer et al. 1986), a section was devoted to antecedent rainfall for small and intermediate size basins in the Tennessee Valley which was in essence an updated version of the previous work by Riedel et al. (1976). All these works typically employ some maximization procedure to the antecedent precipitation and may sometimes even prescribe a fixed dry period separation between the antecedent and the main storms.

For example, Schwarz (1965) used the same percentage of main storm rainfalls for lesser storms and PMP resulting in a greater magnitude of antecedent rainfall in the PMP case. Riedel et al. (1976) applied storm transposition so that any major storm over the Tennessee Valley was transposed in such a manner that it was centered to get the greatest depth over the drainage. In one of the procedures, the annual maximum 3-day rain for stations in the Tennessee River Valley was determined; then the 6-day or 8-day adjoining rainfalls surrounding the annual maximum 3-day rain was also compressed into this 3-day period in an effort to maximize the antecedent rainfall. Miller and Ho (1980) assumed that precipitation events were symmetric with respect to a major storm. To achieve symmetry, the larger amount of the antecedent and subsequent rainfalls was replicated to replace the smaller of the two. This scheme therefore, could raise the antecedent precipitation up to twice the actual observed amount. They also defined a dry day as any day within a 10-day period that had less than 7.5 percent of the 10-day precipitation total. By this definition, it was quite possible that a rainy day with a precipitation depth greater than one inch could be designated as a dry day. Zurndorfer et al. (1986) proposed that the highest observed rainfalls for durations of 48 and 72 hours in the Tennessee Valley be selected to go with 24-hour PMP over small basins together with a 2 to 1 apportioning of antecedent versus subsequent precipitation. Storm transpositions over both times and a radius up to 300 miles were also employed.

Probable maximum precipitation or PMP is defined as the theoretical greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a certain time of the year (Hansen et al. 1988). By its very definition, PMP storms are so rare that they should never be observed. By maximization of the associated antecedent precipitation, the probability of the occurrence of the combined event of PMP and the antecedent precipitation would become an even rarer event.

An investigation of the relationships between the central precipitation event, which could reach PMP magnitude, and the antecedent precipitation, that can be reasonably associated with it, requires a completely objective approach without imposing a preconceived model. Correct relationships or models between antecedent and central precipitation can only emerge after thorough analysis of observational data. Therefore, the decision was made that no data maximization or modification would be permitted and observed data would be used without alteration. This guarantees that the antecedent events studied are real and observable in conjunction with the main storm. Since PMP events have not been observed within the limited length of available precipitation records, the study has been based upon observed maximum rainfalls. At the conclusion of this investigation, results will be extended by logical deduction to estimate antecedent precipitation reasonably associated with PMP.

The region under consideration consists of Oklahoma, Kansas, and the part of Colorado east of 105°W longitude as shown in Figure 1a. This area belongs to the drainages of several tributaries of the Mississippi River. These include the Platte, the Kansas, the Arkansas, and the Red Rivers. This region has no orographic barriers and is considered to be meteorologically homogeneous. It is possible that findings from this investigation will be relevant for other nonorographic areas with comparable precipitation climatologies.

Locations of stations whose precipitation data were used in the investigation are shown in Figure 1b. The number of stations in the figure are more numerous than those in the current observing network. For example, if a station existed for a few years in the early 1940's before being discontinued, it included in the sample, as long as its actual available precipitation record exceeds one year. Because of the large number of stations, 959 in all, some close-by points tend to cluster and merge in the figure. However, Figure 1b shows the general geographical distribution of available precipitation observations over the region.

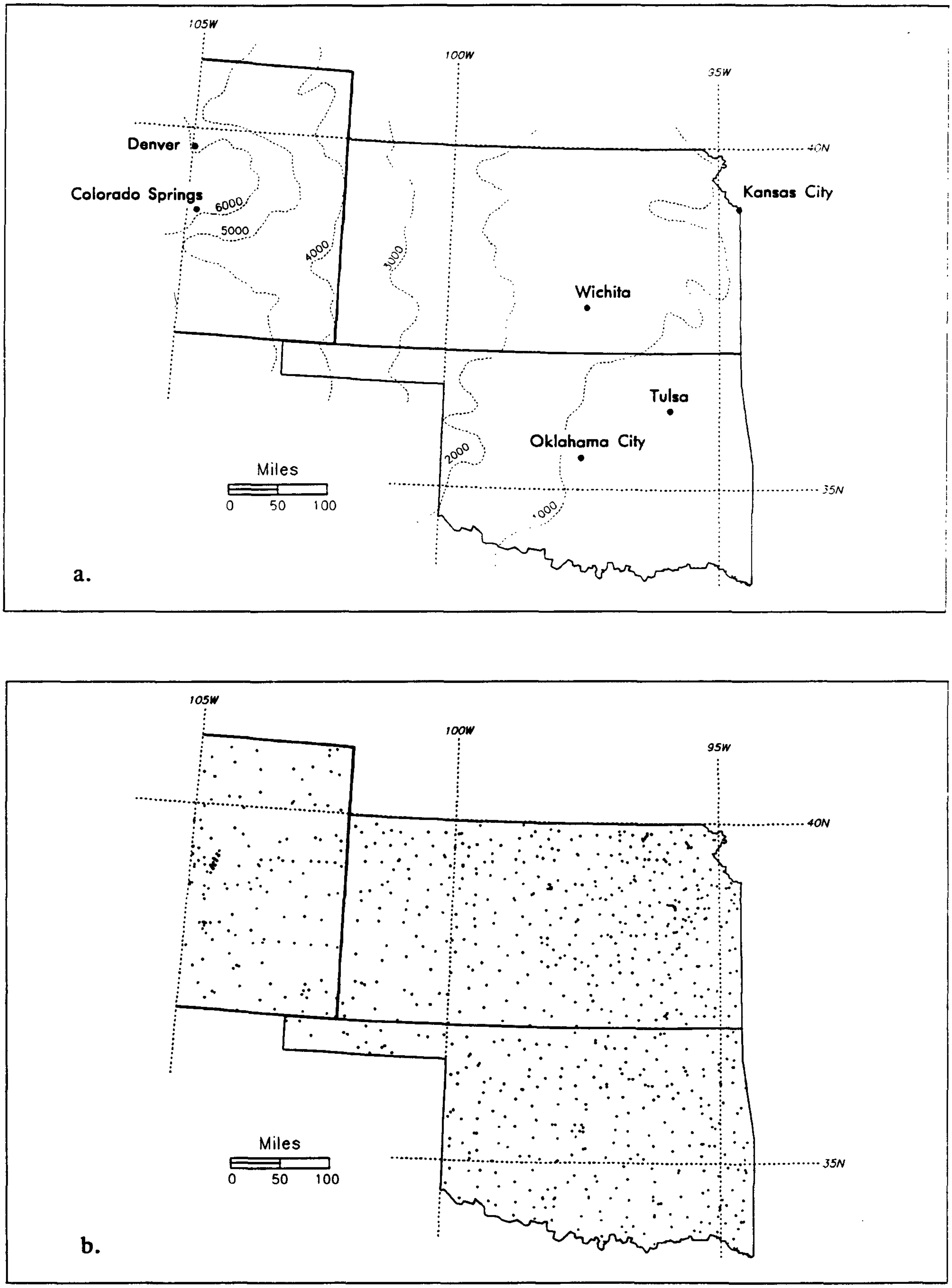

Figure 1.--Maps of a) study region, and b) stations used in study.

2. DATA AND PROCEDURE

The basic data used in this study were the daily precipitation observations from cooperative network stations in Kansas, Oklahoma, and the part of Colorado east of 105°W longitude extracted from the National Climatic Data Center (NCDC) TD-3200 tapes (National Climatic Data Center 1986). These data were augmented with the hourly precipitation data at recording stations not co-located with the daily observations. These hourly data were converted to daily data and combined with data from the TD-3200 tapes. The data were screened to eliminate any station with record length less than one year. The end result was precipitation data from 959 stations and a cumulative record length of 26,610 years with a data termination date of December 31, 1987. The average record length is 27 years and 9 months, while the longest station record is 95 years. Since station data are used directly without areal analysis, findings from this investigation apply to small areas up to 10 square miles. Any extension of the findings should be limited to small basins with areas less than 100 square miles in the region.

A quality assurance procedure was then carried out. Daily amounts greater than a threshold were checked against the NCDC monthly Climatological Data (CD). Any discrepancies found were resolved and errors corrected. In addition to assuring data quality, this step also eliminates the possibility that the results could be contaminated by a few grossly erroneous data.

Daily precipitation data were evaluated and for any daily amount equal to or greater than a threshold value of the 10-year 24-hour precipitation, a 31-day sequence was extracted centered on that day. The intensity of the 10-yr 24-hr precipitation amounts from Hershfield (1961) are shown in Figure 2a. They vary from just less than 3.0 inches in Colorado to 6.5 inches in southeast Oklahoma. The sequence begins 15 days prior to and ends 15 days after the day having an amount equal to or greater than the threshold value. If more than one day in the sequence satisfied the threshold criterion, the day with the largest amount was designated as the central day, or day 16 (P16), and the sequence was adjusted, if necessary, so it became centered on that day. The 'Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years' or Technical Paper No. 40 (Hershfield 1961), hereafter referred to as TP-40, was used to set the threshold value of 10-year, 24-hour depth at each station. A total of 1051 precipitation sequences were extracted from records totaling 26,610 station-years. This full set of 1051 31-day precipitation sequences, which is station-oriented, is designated as the primary data set, or PSQ. This is the primary data set used in this investigation. Additional data sets were also created by

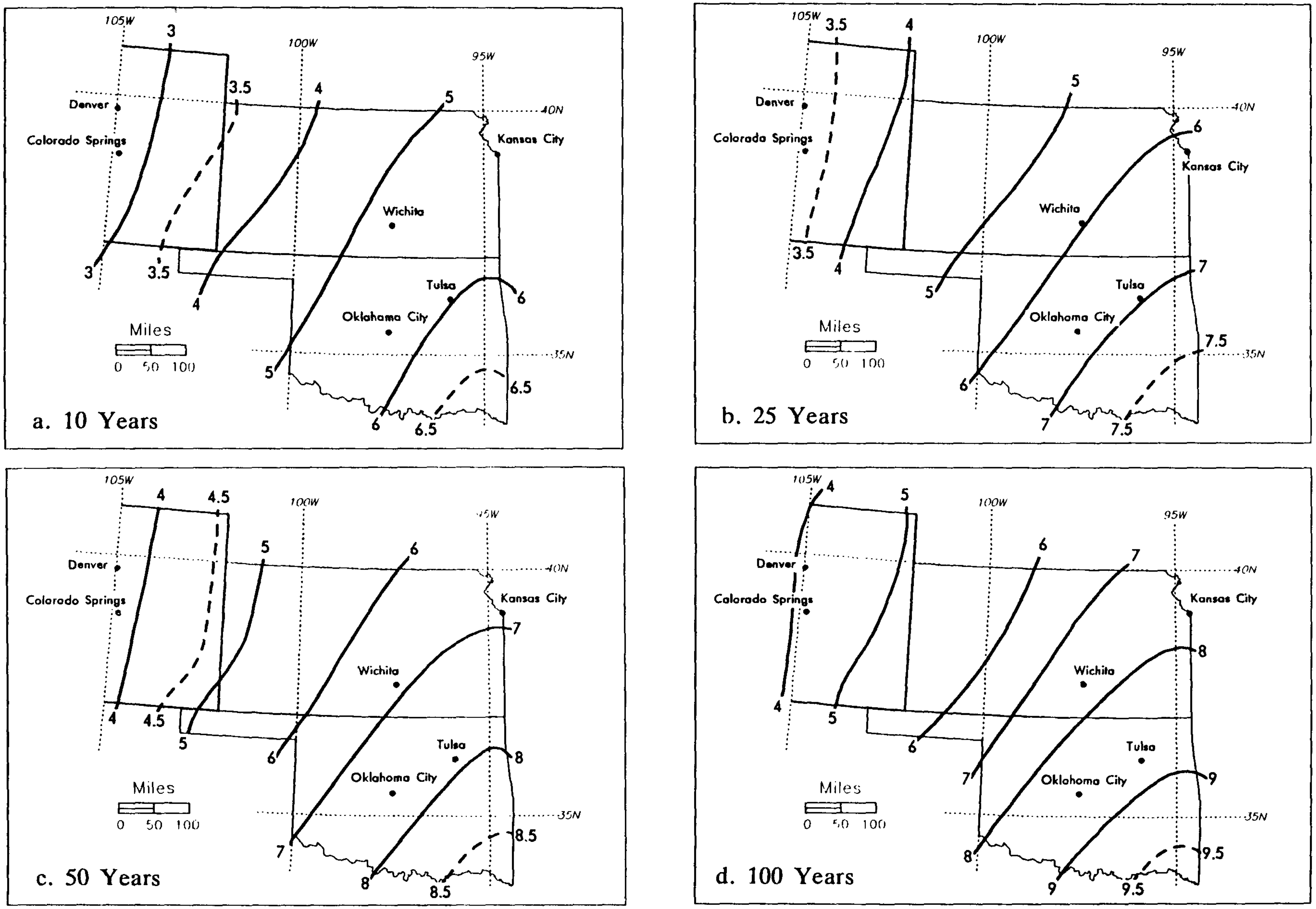

Figure 2.--Precipitation return frequencies from Herschfield (1961) for a) 10 years b) 25 years, c) 50 years, and d) 100 years.

adopting higher extraction threshold criteria such as 25-, 50-, and 100-year 24-hour precipitation from TP-40 (Figures 2b, 2c, and 2d). These data sets will be described in a later section.

The basic source data consisted primarily of observational day amounts. Measurement of precipitation at a fixed time may result in splitting some substantial amounts into two adjacent days in such a manner that the precipitation on neither day exceeds the threshold value. Furthermore, the selection thresholds adopted were the n-year 24-hour rain from TP-40 which is not exactly the same as the 1-day rain. There have not been many studies on the relations between fixed and true-interval precipitation values. Since the basic data structure adopted in this investigation is a time series, 31-day duration, the slight inconsistency between observational day and 24-hour precipitation is minimized. If a conversion factor with magnitude slightly greater than one were available to convert daily precipitation to 24-hour precipitation, it would not be wise to apply this factor to the whole sequence because it could lead to artificial maximization. If this same factor were applied to the central day or central period amounts only, then it could bias the data. Therefore, the daily precipitation data were used without adjustment.

The synoptic weather conditions associated with the central precipitation events were local convective storms, meso-scale upslope or frontal lifting, or synoptic scale cyclone passages. The typical length and time scales of a major extra-tropical cyclone are 10^3 kilometers and 10^2 hours, respectively. The passage of a major cyclone can conceivably produce precipitation exceeding the 10-year 24-hour threshold at a number of stations throughout the region and be represented by more than one sequence. The actual number of sequences produced is a function of the extent and severity of the cyclone and constitutes a storm weighting factor. Therefore, major storms over large areas of the region could be represented by more than one sequence and may be given more weight than a minor storm.

As just mentioned, there are instances when precipitation sequences, even though observed at different locations, represent manifestations of the same major storm, and in this sense are not totally independent. For some statistical applications using all this data from a major storm might cause concerns of possible data independence. To address this problem, a filtering procedure was applied to remove potential data dependence. The total data set, PSQ, was screened to detect if two or more sequences occur at different stations on the same day. When such a situation was detected, only the sequence with the largest precipitation in the central wet period was retained. All other sequences were excluded if they were within 5 degrees longitude or 4 degrees latitude. This operation reduced the full data set, PSQ, to a set consisting of 558 precipitation sequences designated as PSQR. In this reduced set a major storm with heavy precipitation covering a wide area only represented by one sequence per day, even if the precipitation exceeds local 10-year 24-hour thresholds at many stations. This reduced set, PSQR, could be characterized as storm-oriented. In addition, a variety of other data sets were also created from the basic precipitation source data to satisfy specific needs of the investigation. The characteristics of these data sets will be presented in appropriate sections.

2.1 Precipitation Parameters

A wealth of detail is contained in every precipitation sequence. To facilitate the analysis process, a set of precipitation parameters derived from such information are defined. In the following definitions "first" antecedent (subsequent) is counted from the center of the period. These abbreviations and others are repeated in Appendix A.

CDPOS	Position of day 16 in the central wet period counting from the beginning of that period. If there are m wet days immediately preceding day 16, then, CDPOS = m + 1.
CRTOA	Ratio of precipitation in the first antecedent wet period to the central amount. CRTOA = WAMTA/CSAMT.
CRTOS	Ratio of precipitation in the first subsequent wet period to the central amount. CRTOS = WAMTS/CSAMT.
CRTOT	Ratio of the total precipitation in the first antecedent and subsequent wet periods to the central amount. CRTOT = WAMTT/CSAMT.
CSAMT	Sum of precipitation in central wet period. CSAMT = P16 + CSAMX.
CSAMX	Sum of precipitation in central wet period excluding precipitation on day 16. CSAMX = CSAMT - P16.
CSLEN	Duration of central wet period.
DDLEN	Difference in lengths between the dry period immediately preceding and immediately following the central wet period. DDLEN = DLENA - DLENS.
DLENA	Duration of the dry period immediately preceding the central wet period.
DLENS	Duration of the dry period immediately following the central wet period.

DRAMT	Difference between the antecedent and subsequent precipitation excluding the precipitation in the first antecedent and subsequent periods. DRAMT = RAMTA - RAMTS.
DTAMT	Difference between the total antecedent and subsequent precipitation. DTAMT = TAMTA - TAMTS.
DTLEN	Difference of the total number of antecedent and subsequent dry days. DTLEN = TLENA - TLENS.
DWAMT	Differences in precipitation between the first antecedent wet period and the first subsequent wet period. DWAMT = WAMTA - WAMTS.
NBRDP	Number of dry periods in a sequence.
P16	Precipitation on day 16, the central day.
PSUMT	Sum of all precipitation in a sequence. PSUMT = CSAMT + TAMTT.
RAMTA	Sum of antecedent precipitation excluding precipitation in the first antecedent wet period or WAMTA.
RAMTS	Sum of subsequent precipitation excluding precipitation in the first subsequent wet period or WAMTS.
TAMTA	Total antecedent precipitation. TAMTA = WAMTA + RAMTA.
TAMTS	Total subsequent precipitation. TAMTS = WAMTS + RAMTS.
TAMTT	Total antecedent and subsequent precipitation. TAMTT = TAMTA + TAMTS.
TLENA	Total number of antecedent dry days.
TLENS	Total number of subsequent dry days.
TLENT	Total number of dry days in a sequence. TLENT = TLENA + TLENS.
TRTOA	Ratio of total antecedent precipitation to central amount. TRTOA = TAMTA/CSAMT.
TRTOS	Ratio of total subsequent precipitation to central amount. TRTOS = TAMTS/CSAMT.

TRTOT	Ratio of total antecedent and subsequent precipitation to central amount. TRTOT = TAMTT/CSAMT.
WAMTA	Precipitation in the wet period separated from the central wet period by one antecedent dry period.
WAMTS	Precipitation in the wet period separated from the central wet period by one subsequent dry period.
WAMTT	Total precipitation in the first antecedent and first subsequent wet period. WAMTT = WAMTA + WAMTS.
WLENA	Duration of the wet period separated from the central wet period by one antecedent dry period.
WLENS	Duration of the wet period separated from the central wet period by one subsequent dry period.

This set of parameters can be grouped into four different categories depending on which features of the precipitation sequences they measure or describe:

1. Depth: CSAMT, CSAMX, DRAMT, DTAMT, DWAMT, P16, PSUMT, RAMTA, RAMTS, TAMTA, TAMTS, TAMTT, WAMTA, WAMTS, WAMTT.
2. Duration: CSLEN, DDLEN, DLENA, DLENS, DTLEN, TLENA, TLENS, TLENT, WLENA, WLENS.
3. Ratio: CRTOA, CRTOS, CRTOT, TRTOA, TRTOS, TRTOT.
4. Count: CDPOS, NBRDP.

Unless stated otherwise, the unit for depth measurement used in this report is "inch", the unit for duration measurement is "day". A ratio parameter is expressed either as a fraction or as a percent, while a count is represented by a nondimensional number.

The conventional meteorological definition for reporting rain is followed in this report. A "wet" day is defined as a day with observed rainfall of .01 inch or more, while a "dry" day is a day with either no rain or only a trace.

Precipitation data are generally recorded up to a precision of one-hundredth of an inch. Durations are measured in days. In averaging processes, additional decimal digits are generated. It is believed appropriate to represent duration to two decimal places in fractions of a day in order to retain more information content. The premise is that it is always better to carry more, rather than less, information. The additional digit can always be easily rounded off if one so desires.

In assessing the linear correlations between precipitation parameters, the computed significance probabilities could be quite small, say .0001. Rounding off to .000 could be misinterpreted to indicate a degree of absolute certainty which is not justified. Thus, in correlation inquiries while the correlation coefficients are presented to three decimal places the significance probabilities are retained to four decimal digits.

In the case of testing any hypothesis, a significance probability of .02 is chosen as the threshold of acceptance. For example, in testing whether there is substantive difference between the expected values of two variables, only a significance probability less than or equal to .02 will lead to the rejection of the null hypothesis. This is a more stringent and more conservative criterion than the conventional threshold of a significance probability of .05.

For illustration purposes, a 31-day precipitation sequence and its associated parameters are presented.

The daily precipitation amounts for 31-day period are given in Figure 3. This sequence was observed at Broken Bow, Oklahoma, (34-1162), located at 34° 03'N and 94° 43.8'W, for the 31-day period from September 13 to October 13, 1980. The various parameters that will be used in this report are illustrated. The central storm amount of 11.67 inches (CSAMT) consists of the central day amount (P16) of 9.24 inches, plus the precipitation from the days surrounding P16 (CSAMX) or 2.43 inches. The total precipitation in the wet period immediately preceding the central rainfall amount is 0.02 inch (day 13) or WAMTA, while the total precipitation in the first subsequent wet period is 0.23 inch (day 25) or WAMTS. The wet periods is 0.25 inch (WAMTT equals WAMTA plus WAMTS). The difference between the immediate antecedent and subsequent precipitation is defined as DWAMT (DWAMT = WAMTA - WAMTS, or -0.21 inch). There is only one wet day subsequent to the central wet period, so that RAMTS or the total subsequent precipitation other than the first subsequent wet period is zero, while the total antecedent precipitation other than the first wet period (RAMTA) is 0.26 inch, which fell on days 5 (0.08 inch) and 8 (0.18 inch). The difference between the total antecedent and subsequent precipitation other than the immediate antecedent and subsequent period is defined as DRAMT, or RAMTA (0.26 inch) minus RAMTS (0.00 inch) is equal to 0.26 inch. The total amount of all antecedent and subsequent precipitation (TAMTT) is the total precipitation antecedent and subsequent to the central storm amount, or TAMTA plus TAMTS [TAMTA (0.28 inch) + TAMTS (0.23 inch) = TAMTT (0.51 inch)]. The difference between the total antecedent and subsequent precipitation is designated as DTAMT, (TAMTA - TAMTS) or 0.05 inch.

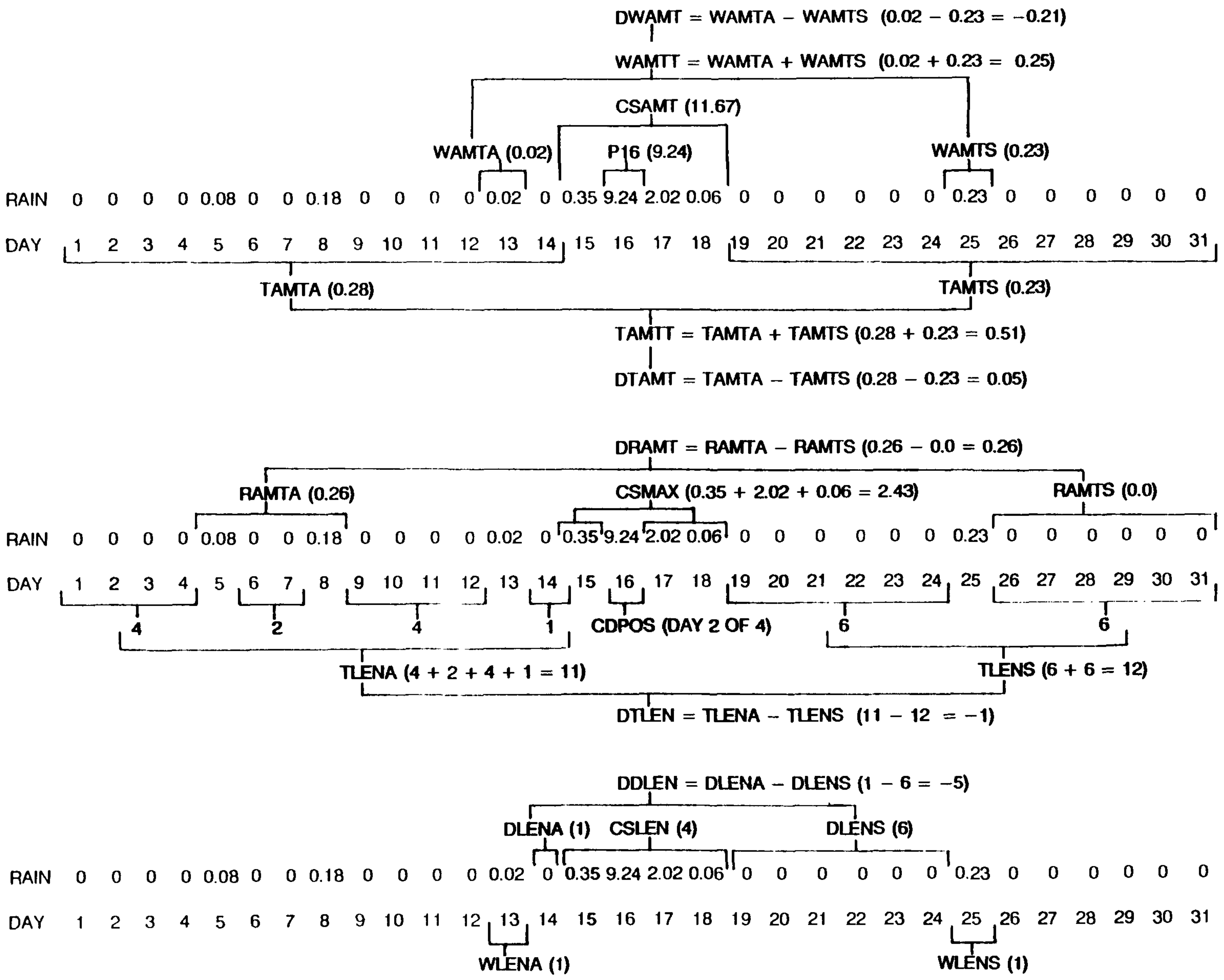

Figure 3.--Schematic depicting the parameters used to define amounts and number of days.

Various measurements of time are also used. These include the position of day 16 (CDPOS), or the highest precipitation amount in the central storm amount. For this sequence at Broken Bow the highest rainfall amount is the second day within the central rain event, therefore, CDPOS is designated as 2. The length of the central wet period is four days (CSLEN = 4). The length of the dry period immediately antecedent to the central wet period is defined as DLENA and for Broken Bow is 1. The length of the immediate subsequent dry period (DLENS) is 6. The difference between these two parameters is designated as DDLEN [DLENA (1 day) - DLENS (6 days) = DDLEN (-5)]. WLENA and WLENS defines the durations of the immediate antecedent and subsequent wet periods, which for Broken Bow are both one day. The total number of antecedent dry days and subsequent dry days are given by TLENA (11 days) and TLENS (12 days). The difference of these two lengths is defined as DTLEN. At Broken Bow this becomes TLENA (11 days) minus TLENS (12 days) equals DTLEN (-1).

Some other parameters, but not shown in Figure 3, which are used are the number of dry periods (NBRDP) within the 31-day sequence, which for Broken Bow is six. The total sum of all the precipitation (PSUMT) is equal to the central storm amount(CSAMT) plus the total antecedent and subsequent precipitation (TAMTT), or 11.67 + 0.51 = 12.18 inches. Ratios between various precipitation amounts are also used. Using the example from Broken Bow, they can be defined as follows:

$$\text{CRTOA} = \frac{\text{WAMTA}}{\text{CSAMT}} = \frac{0.02}{11.67} * 100 = 0.17 \text{percent}$$

$$\text{CRTOS} = \frac{\text{WAMTA}}{\text{CSAMT}} = \frac{0.23}{11.67} * 100 = 1.97 \text{ percent}$$

$$\text{CRTOT} = \frac{\text{WAMTT}}{\text{CSAMT}} = \frac{0.25}{11.67} * 100 = 2.14 \text{ percent}$$

$$\text{TRTOA} = \frac{\text{TAMTA}}{\text{CSAMT}} = \frac{0.28}{11.67} * 100 = 2.40 \text{ percent}$$

$$\text{TRTOS} = \frac{\text{TAMTS}}{\text{CSAMT}} = \frac{0.23}{11.67}*100 = 1.97 \text{ percent}$$

$$\text{TRTOT} = \frac{\text{TAMTT}}{\text{CSAMT}} = \frac{0.51}{11.67}*100 = 4.37 \text{ percent}$$

2.2 Precipitation Data Sets.

To meet the diverse needs of this investigation, a variety of data sets are created as the occasion arises. A listing of all data sets consisting of precipitation sequences follows.

N	Number of elements in a data set or any specified group.
PSQ	Primary data set consists of 31-day precipitation sequences centered on day 16 which has precipitation equal to or greater than the station 10-year 24-hour rain. N = 1051.
PSQA	A subset of PSQ with precipitation in the central wet period less than or equal to 6.00 inches: $\text{CSAMT} \le 6.00$ inches. N = 431.
PSQB	A subset of PSQ with precipitation in the central wet period greater than 6.00 inches, but less than 9.50 inches: $6.00 \text{ inches} < \text{CSAMT} < 9.50$ inches. N = 431.
PSQC	A subset of PSQ with precipitation in the central wet period equal to or greater than 9.50 inches, but less than 14.50 inches: $9.50 \text{ inches} \le \text{CSAMT} < 14.50$ inches. N = 151.
PSQD	A subset of PSQ with precipitation in the central wet period equal to or greater than 14.50 inches: $\text{CSAMT} \ge 14.50$ inches. N = 38.
PSQM	Modified data set of 31-day precipitation sequences derived from PSQ. Threshold for appreciable rain is raised from the conventional .01 inches to .21 inches. All daily precipitation less than .21 inches is set to 0. N = 1051.

PSQR	Reduced data set of 31-day precipitation sequences derived from PSQ by a filtering procedure that basically permits no more than one sequence to represent a storm on any given day. N = 558.
PSQRT	Truncated data set of 31-day precipitation sequences derived from PSQR by a truncation procedure that eliminates all sequences with CSAMT ≤ 6.00 inches. N = 304.
PSQT	Truncated data set of 31-day precipitation sequences derived from PSQ by a truncation procedure that eliminates all sequences with CSAMT ≤ 6.00 inches. N = 620.
PSQ21	Data set of 21-day precipitation sequences centered on day 11 which has precipitation equal to, or greater than, the station 10-year 24-hour rain. N = 1051.
PSQ13	Data set of 13-day precipitation sequences centered on day 7 which has precipitation equal to or greater than the station 10-year 24-hour rain. N = 1051.
PSQ25Y	Data set of 31-day precipitation sequences created by using 25-year 24-hour rainfall from TP-40 as selection threshold. N = 529.
PSQ50Y	Data set of 31-day precipitation sequences created by using 50-year 24-hour rainfall from TP-40 as selection threshold. N = 253.
PSQ100Y	Data set of 31-day precipitation sequences created by using 100-year 24-hour rainfall from TP-40 as selection threshold. N = 131.

Any general mention of precipitation data set in this report will mean the primary data set, PSQ, consisting of 1051 precipitation sequence unless specified otherwise.

This list is intended for use as a ready reference. Descriptions on the procedures employed to create each data set can also be found in the appropriate sections of the report.

3. GENERAL FEATURES OF SEQUENCES

3.1 General Features

Partial sums of precipitation in 5-day groups on both sides of the central day for data set PSQ are shown in Figure 4. For reference, the sum of precipitation on the central day in the PSQ data set is 6188.7 inches. It is evident that the amounts in the prior 5-day periods are greater than those in the corresponding subsequent 5-day periods. For example, total precipitation in the contiguous period 5 days before the centered rain amount (days 11-15) 1140.5 inches were while 1035.9 inches fell in the corresponding contiguous subsequent 5-day period (days 17-21). Similar situations exist when amounts in other pairs of corresponding 5-day periods are compared.

The percentages of days with rain for each individual day except day 16 in data set PSQ, are shown in Figure 5. The two days adjacent to the central day, days 17 and 15 have rains 57 and 49 percent of the times, respectively. These are followed by days 12, 13, 7, and 18 in descending order of proportions of rainy days. Of these four, only days 12 and 13 had rain fall more than 30 percent of the time. In none of the 30 non-central days in the sequence did rain occur less than 20 percent of the time.

The mean rainfalls averaged on days with rain on each day of the sequence except day 16, are depicted in Figure 6. Not surprisingly, the two adjacent days, day 15 and 17 had the highest average rainfalls of .856 and .780 inch, respectively. The lowest rainfall .386 inch occurred on day 11. These are to be compared with a mean of 5.888 inches that fell on day 16.
The durations of central wet periods vary from one day up to a maximum of 10 days; with a mean of 2.75 days. The most frequent duration or mode is two days. The four top frequencies of occurrences are 34.2, 22.9, 18.6 and 9.2 percent for wet durations of 2, 1, 3 and 4 days, respectively. Frequency distribution of the duration of the central wet period is shown in Figure 7. Approximately 15 percent of the central wet periods had durations of five days or longer with only three sequences having central wet periods of 10 days.

Every 31-day sequence contains alternating wet and dry periods. The observed number of dry periods varies from a maximum of 10 to a minimum of 2, with a mean of 5.5, a median of 5 and a mode of 6. All these features mentioned in this section are derived from the full data set PSQ. However, with only some minor changes in numerical values, they generally also apply to the reduced data set PSQR.

The cumulative distribution of precipitation amounts on day 16 for data sets PSQ and PSQR are shown in Figure 8, while similar distributions of precipitation in the central wet period (CSAMT) are shown in Figure 9. These distribution plots are characterized by heavy tails and are non-Gaussian. Table 1 lists numerical values for both parameters at selected quantiles for data sets PSQ and PSQR.

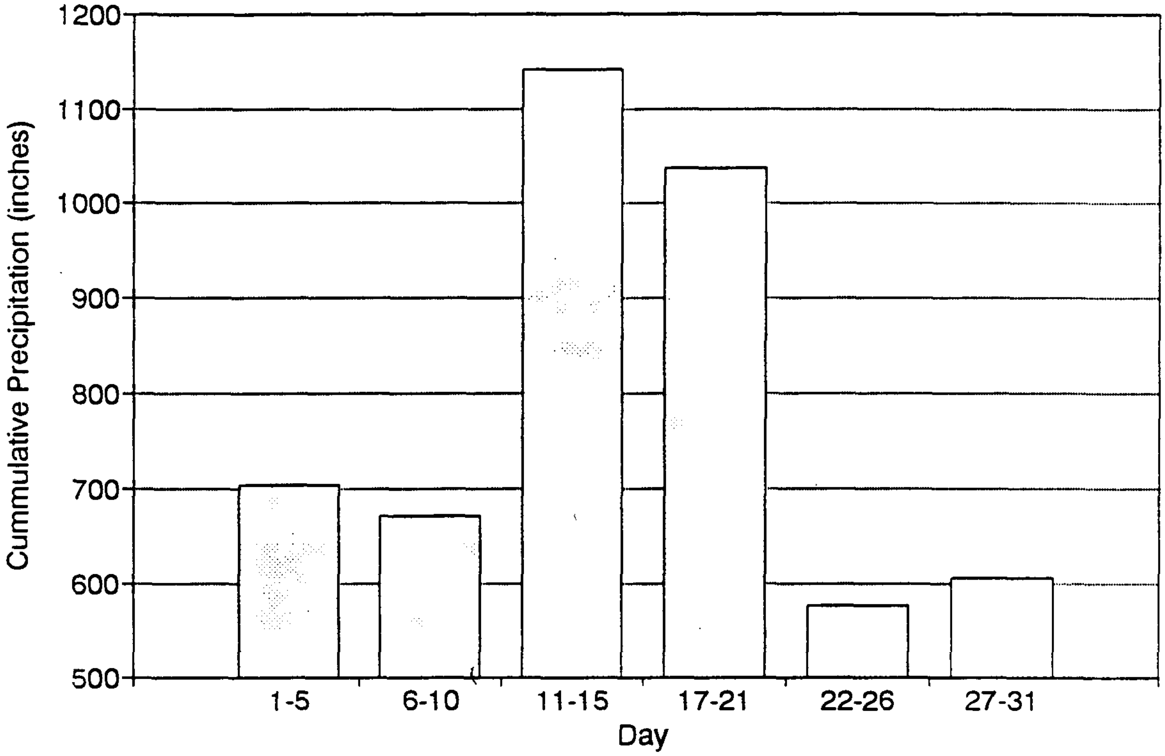

Figure 4.--Partial sum of precipitation in 5-day groups prior and subsequent to both sides of the central day or day 16.

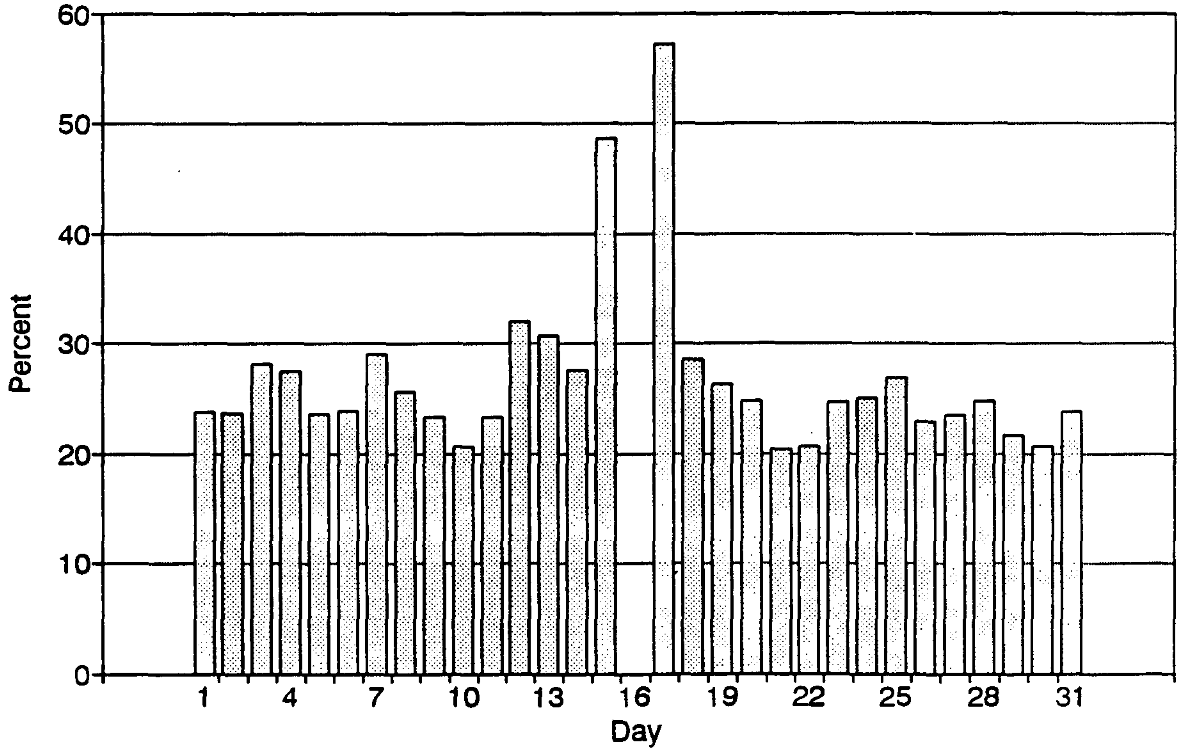

Figure 5.--Percentage of days with rain (excluding day 16).

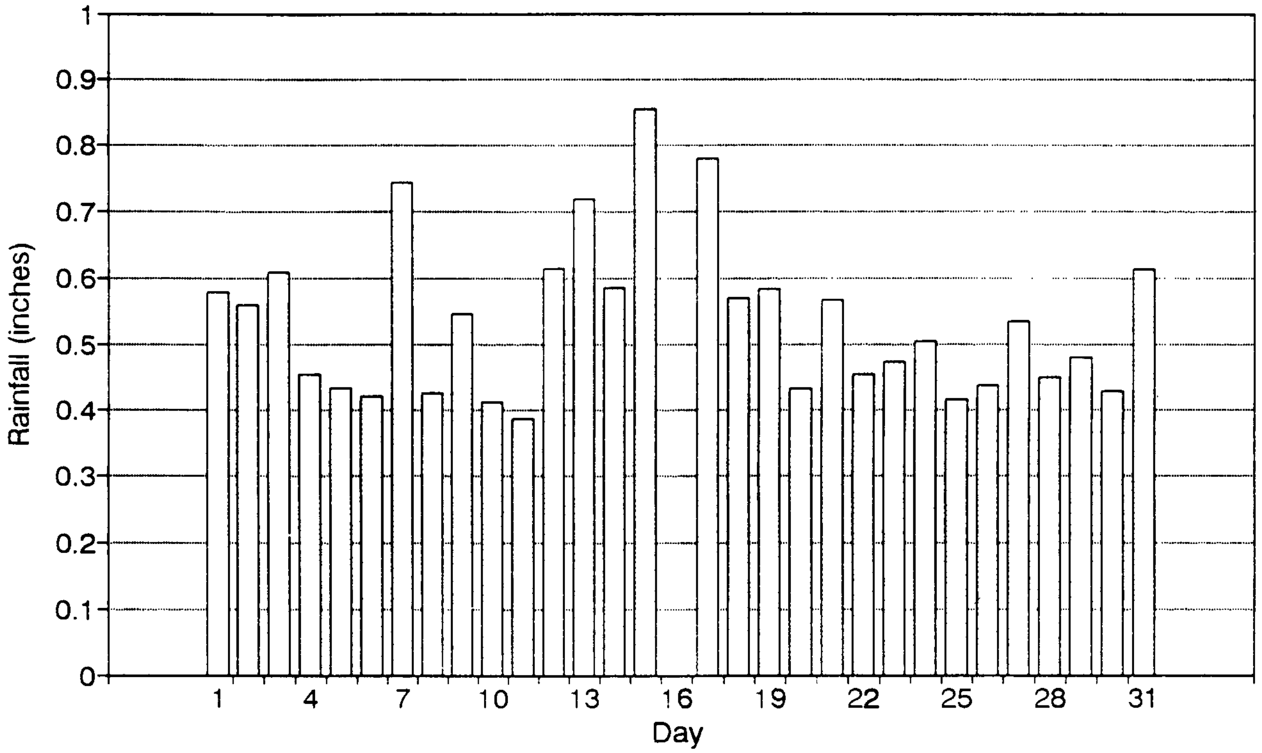

Figure 6.--Mean precipitation on days with rain (excluding day 16).

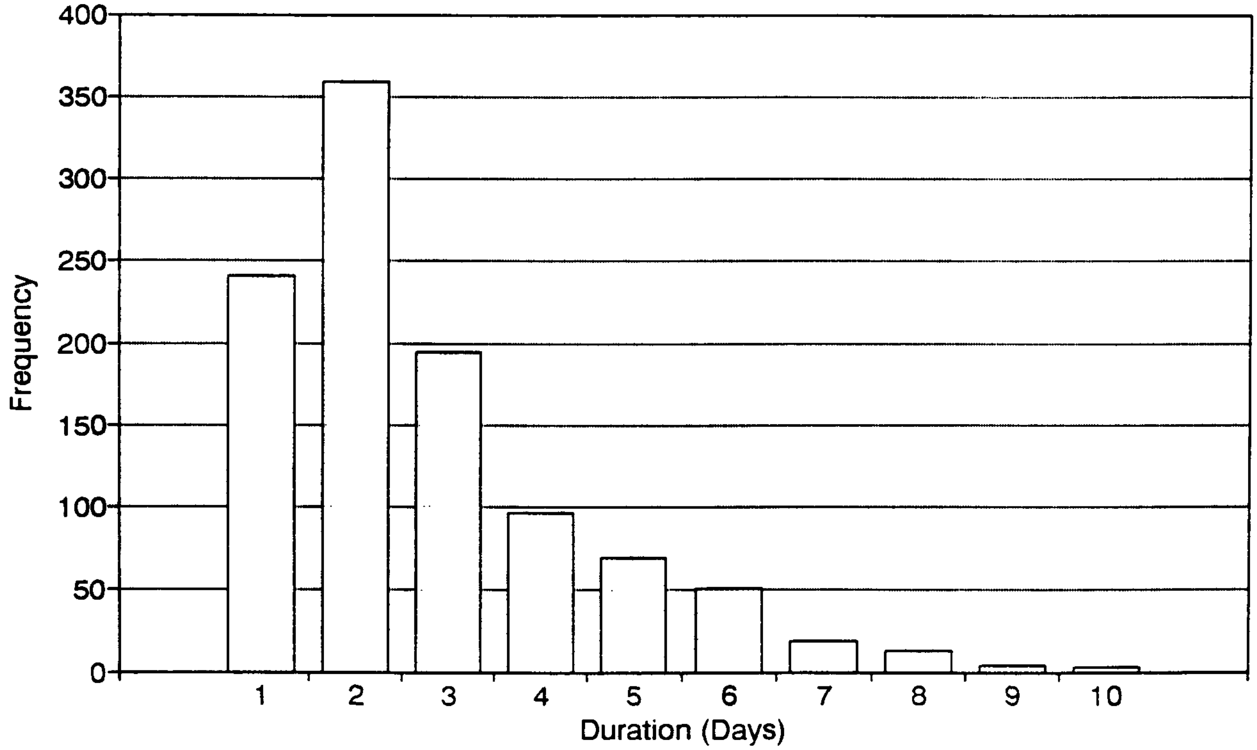

Figure 7.--Frequency distribution of the duration of the central wet period.

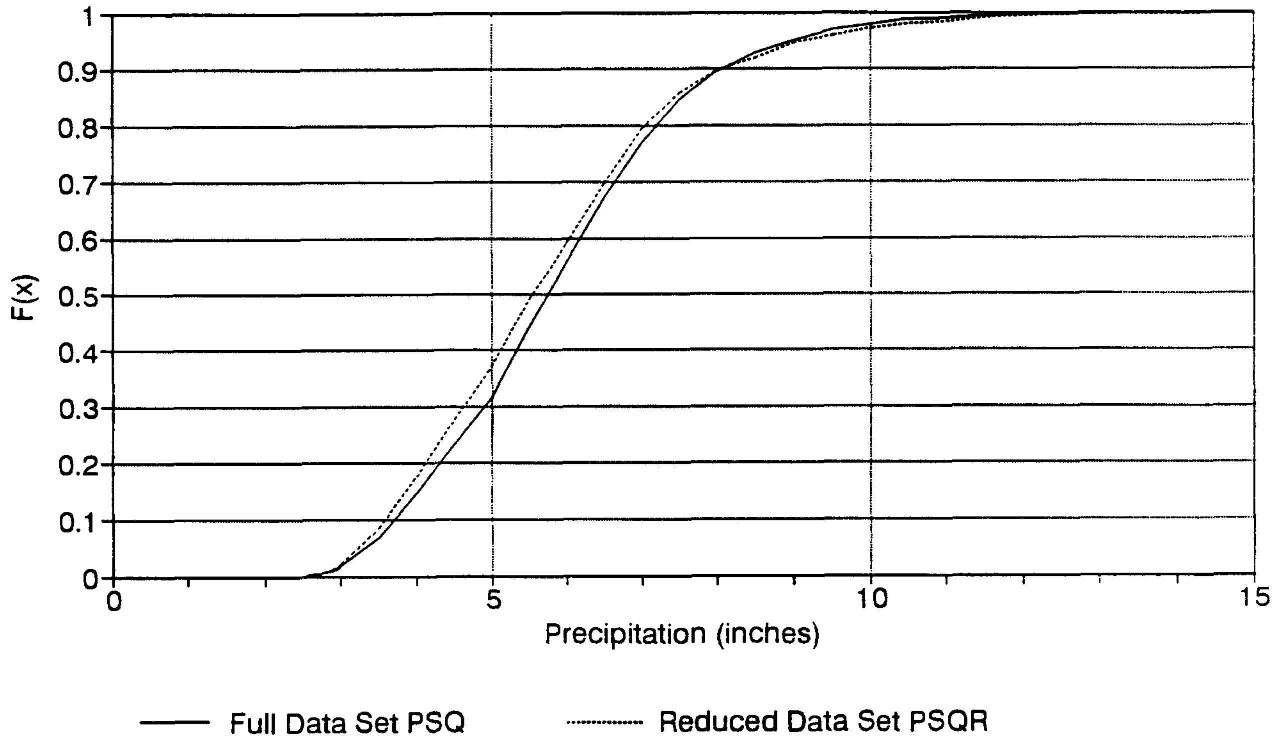

Figure 8.--Cumulative distribution of central day precipitation, P16, for the full and reduced data sets.

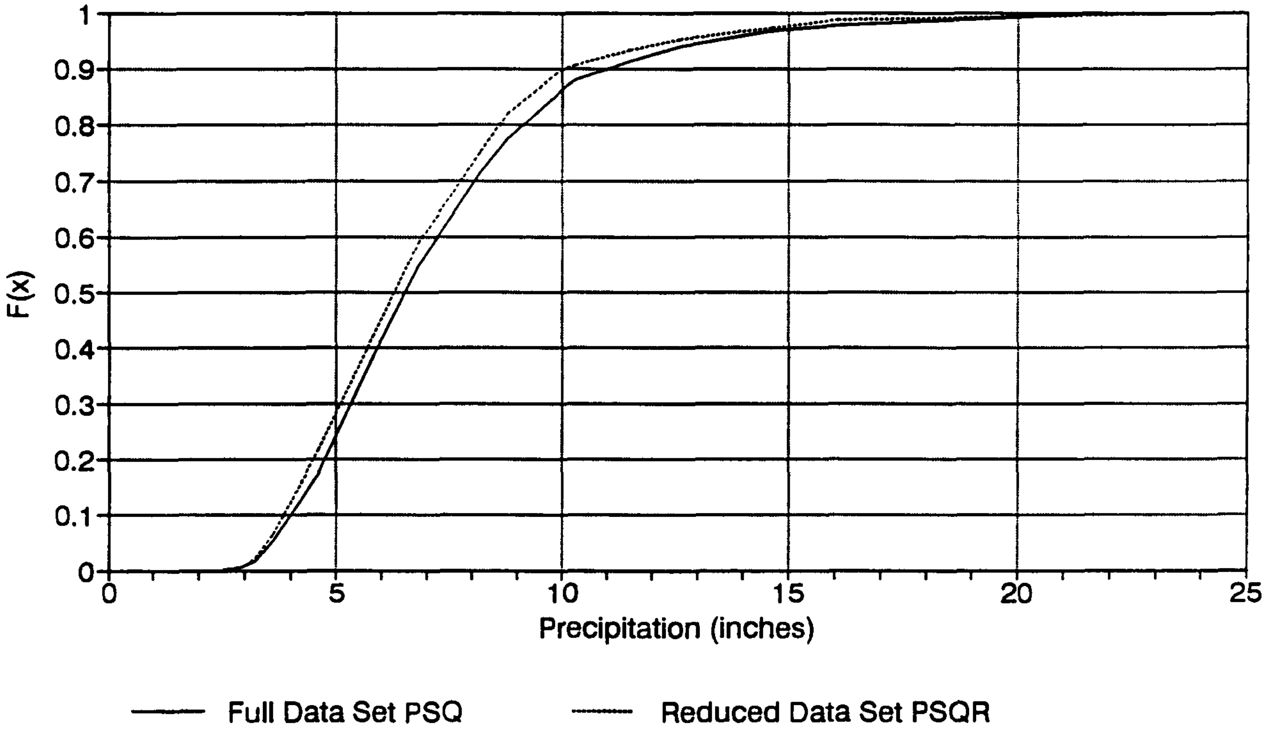

Figure 9.--Cumulative distribution of central wet period precipitation, CSAMT, for the full and reduced data sets.

Table 1. Central day precipitation (P16) and total precipitation in the central wet period (CSAMT) at selected quantiles for full data set PSQ and reduced data set PSQR. Units are inches.

	min	.10	.25	Quantiles median	.75	.90	.95	max
				Data set PSQ (N=1051)				
P16	2.43	3.70	4.60	5.76	6.93	8.07	9.00	15.68
CSAMT	2.43	4.09	5.17	6.55	8.49	11.18	13.31	24.95
				Data set PSQR (N=558)				
P16	2.54	3.59	4.35	5.57	6.75	8.05	9.13	15.68
CSAMT	2.54	3.86	4.84	6.26	8.17	10.48	12.12	24.95

3.2 Seasonal Distributions of Sequences

The distributions of precipitation sequences in the data sets PSQ and PSQR according to the seasons are shown in Table 2. Spring is defined as March through May. The other seasons are defined in 3-month periods in similar fashion.

For both data sets, the season with the most frequent occurrence is summer, followed by fall, spring, and winter. For the fall season, there are moderate differences in relative frequencies; 33.8 percent versus 26.0 percent for data sets PSQ and PSQR, respectively. This indicates that proportionally more fall observations were removed from the full data set PSQ by the filtering procedure to arrive at the reduced data set PSQR.

Table 2. Seasonal distributions of precipitation sequences

	PSQ (N=1051)		PSQR (N=558)	
	N	Percent	N	Percent
Spring	191	18.2	116	20.8
Summer	486	46.2	286	51.3
Fall	355	33.8	145	26.0
Winter	19	1.8	11	2.0

Monthly distributions of sequences in the full data set PSQ are depicted in Figure 10a with relative frequencies shown in Figure 10b. This distribution is defined by the location of the central day. For example, if a sequence is centered on October 25, then it is assigned to the month of October, even though the full sequence extends over the first 10 days of November. The five months containing the greatest number of sequences are September, July, June, May and October in descending order.

The full data set PSQ is stratified into four subsets according to the magnitude of the central precipitation. Subset PSQA consists of 431 sequences with central amount less than, or equal to, 6.00 inches; subset PSQB comprises 431 sequences with central amount greater than 6.00, but less than 9.50 inches; subset PSQC includes 151 sequences with central amount equal to, or greater than, 9.50 inches, but less than 14.50 inches and subset PSQD consists of 38 sequences having central precipitation greater than 14.50 inches. A detailed distribution of the sequences in these four subsets of PSQ, according to the months of the year, is shown in Table 3. The partition of the precipitation sequences into four subsets is empirical, but does provide a meaningful stratification.

Table 3. Monthly distributions of precipitation sequences

	PSQA $P \leq 6.0$	PSQB $6.0 < P < 9.5$	PSQC $9.5 \leq P < 14.5$	PSQD $P \geq 14.5$	PSQ
N	431	431	151	38	1051
January	0	3	1	0	4
February	1	2	0	0	3
March	0	3	1	0	4
April	17	8	0	1	26
May	85	56	18	2	161
June	74	77	21	1	173
July	87	76	25	3	191
August	78	41	3	0	122
September	58	108	31	6	203
October	29	37	35	24	125
November	2	16	9	0	27
December	0	4	7	1	12

Table 3 also shows a progression of the median month of occurrence from July to October as the threshold level of central precipitation of the data sets increase from PSQA to PSQD. This progression may be a realistic feature of the climatology of precipitation distribution. There is no doubt that storms with heavier rainfall tend to occur more frequently in the months of September and October in the region of interest. However, in the case of PSQD, the extreme concentration of sequences in the month of October; 24 out of a total of 38 or 63 percent perhaps may

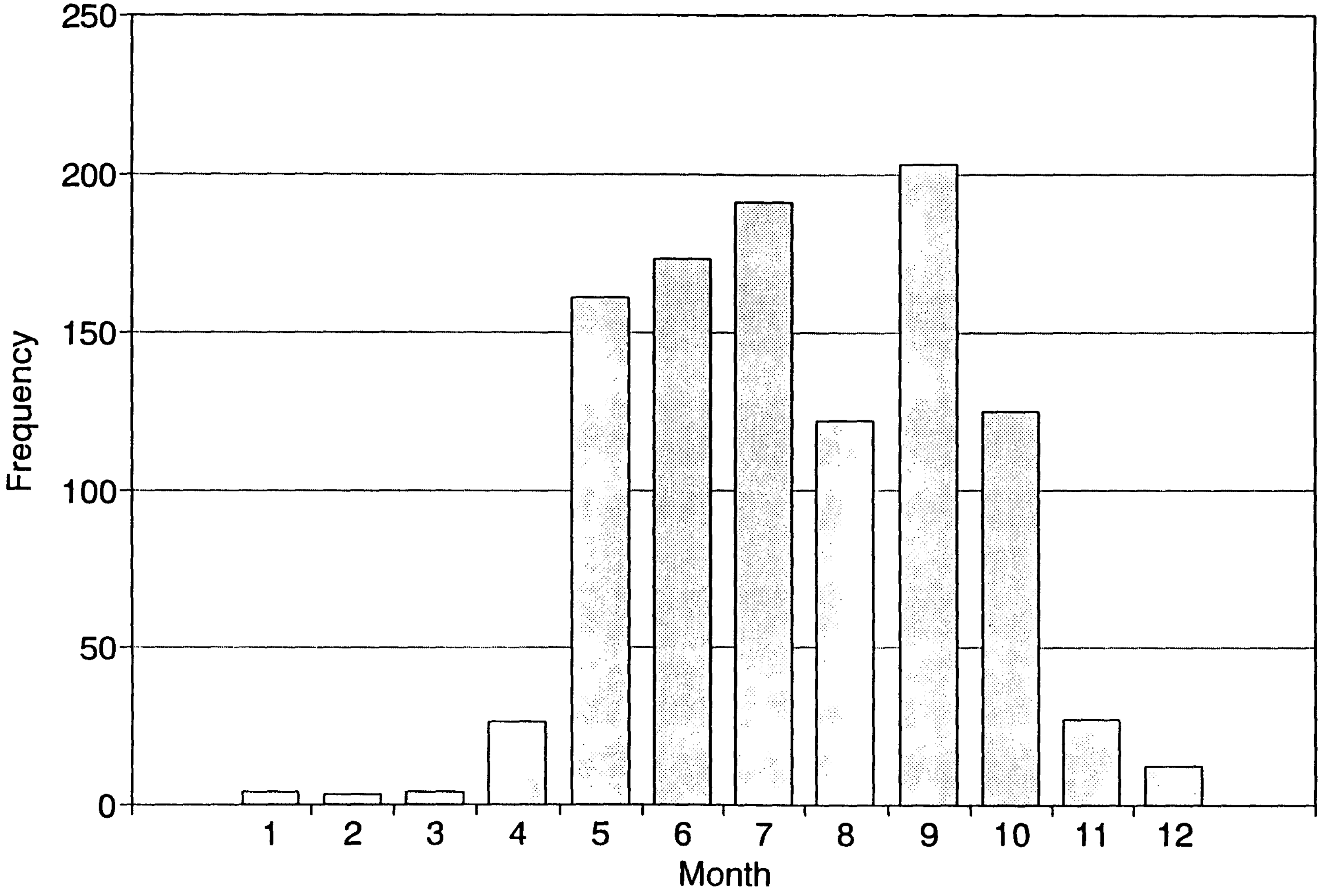

Figure 10.--Monthly distribution of precipitation sequences.

also be partly explained as a result of sampling fluctuations. Another interesting feature is the presence of a local minimum in August in the distribution of events for the three subsets PSQB to PSQD.

3.3 Monthly Distribution of Amounts

The distributions of three amount parameters; precipitation on the central day (P16), sum of precipitation in the central wet period (CSAMT), and total antecedent and subsequent precipitation (TAMTT) according to the month of the year is shown in Table 4. Table 4 should be viewed in conjunction with Table 3. Three characteristics are obvious. The first is the great disparity in the monthly distributions of the sequence, it varies from a low of 3 in February to a high of 203 in September. In view of this fact, interpretation of results in months when very few cases were present should be done with caution. The second is the fact that three precipitation measurements; the central day amount, the central wet period amount and the total antecedent and subsequent amount all had their absolute minima in the month of April. This indicates that storms taking place over the region of interest in the month of April are generally quite moderate compared with those in the other months. The third feature is the presence in August of not only the "local" minima of all three precipitation parameters, but also a "local" minimum in the number of sequences as compared with those in the adjacent months. These realities constitute an integral part of the precipitation climatology over the region of investigation.

Table 4. Monthly distributions of the means of three precipitation parameters. Units are inches.

	N	P16 (inch)	CSAMT (inch)	TAMTT (inch)
January	4	7.94	9.04	3.22
February	3	5.60	5.64	4.63
March	4	7.17	8.68	2.29
April	26	4.95	5.49	1.60
May	161	5.55	6.54	3.25
June	173	5.60	6.74	3.57
July	191	5.59	6.75	3.26
August	122	5.12	5.62	2.14
September	203	6.16	7.53	3.58
October	125	6.98	10.21	3.29
November	27	7.28	8.58	1.63
December	12	9.00	10.75	3.97

3.4 Components of Precipitation in the Central Wet Period

Precipitation in the central wet period consists of two components; namely precipitation on the central day and on the rest of the days, or CSAMT = P16 + CSAMX. Figures 11 and 12 are scatter diagrams of CSAMT versus P16 and CSAMX respectively for the full data set PSQ. In cases where the central amount is relatively small, for example less than 5 inches, the dominant contribution comes from P16 as expected due to the selection threshold used. However, as central amount CSAMT increases, it can be associated with a wider and wider range of P16s as shown in Figure 11, while at the same time the contributions from CSAMX become increasingly more important. For values of central precipitation 16 inches and greater, CSAMT and CSAMX have less scatter (Figure 12).

For data set PSQ, 81.54 percent of the precipitation in the central wet period fell on day 16, while precipitation on all other days in the central wet period contributed 18.46 percent. For data set PSQR, the proportions are 83.83 and 16.17 percent, respectively. For the four subsets of PSQ, (PSQA, PSQB, PSQC, PSQD), the percent contributions to CSAMT of precipitation on days other than day 16 are 6.62, 13.13, 30.82 and 49.28 percent, respectively. Table 3 shows the relative contribution by precipitation on days other than the central day becomes more crucial as the central amount grows. In subset PSQD, composed of 38 sequences with central amounts equal to, or greater than, 14.5 inches, approximately half of these amounts are due to precipitation on days other than day 16.

3.5 Duration of Central Wet Period

Distributions of amount parameters including precipitation on day 16 (P16), central precipitation excluding P16 (CSAMX), central precipitation (CSAMT) and total antecedent and subsequent precipitation (TAMTT), and duration parameter DLENA denoting duration of the immediately preceding dry period, with respect to duration of the central wet period (CSLEN), are summarized in Table 5.

As the central wet duration increased from 1 day successively to 6 days, the amount on the central day (P16) increased accordingly. P16 then decreased as the central wet duration exceeded 6 days. This pattern is mirrored in the behavior of CSAMX, which grew as the central wet duration lengthened to 6 days and then became smaller. Therefore, the total central precipitation (CSAMT) also showed a similar trend. The distribution of the mean total antecedent and subsequent

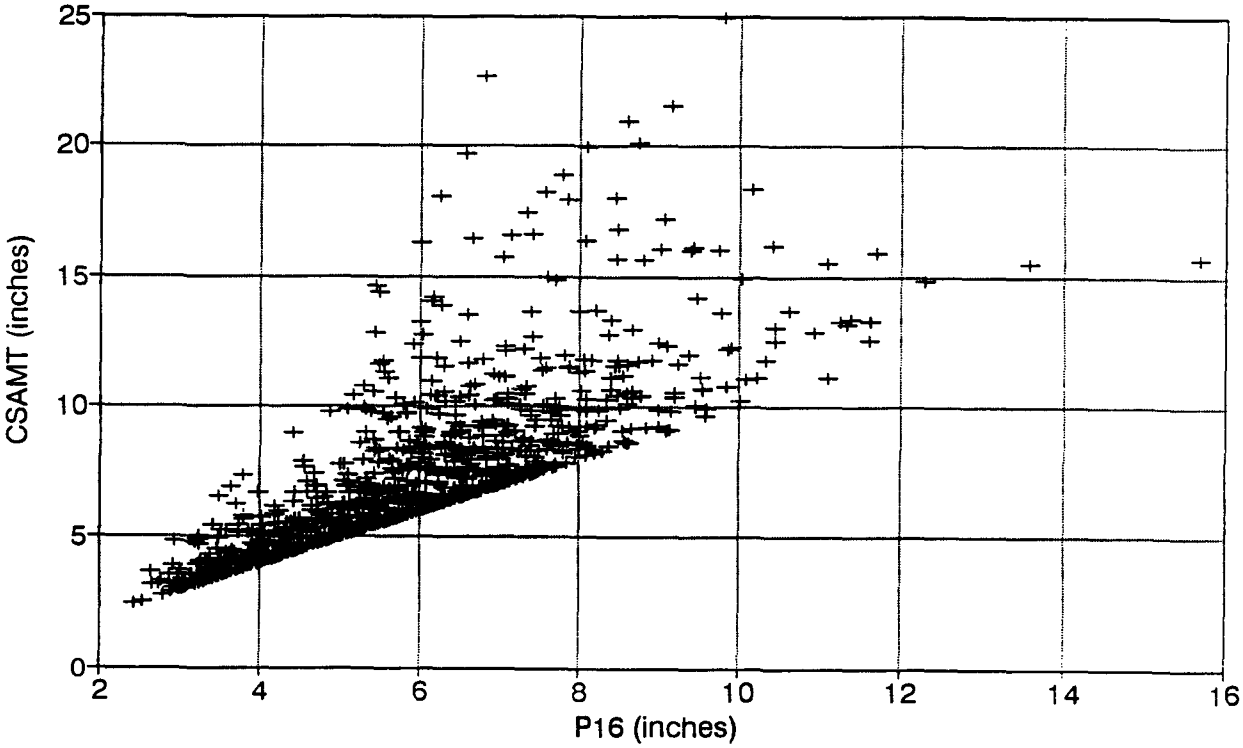

Figure 11.--Scatter diagram of central wet period precipitation, CSAMT, and central day precipitation.

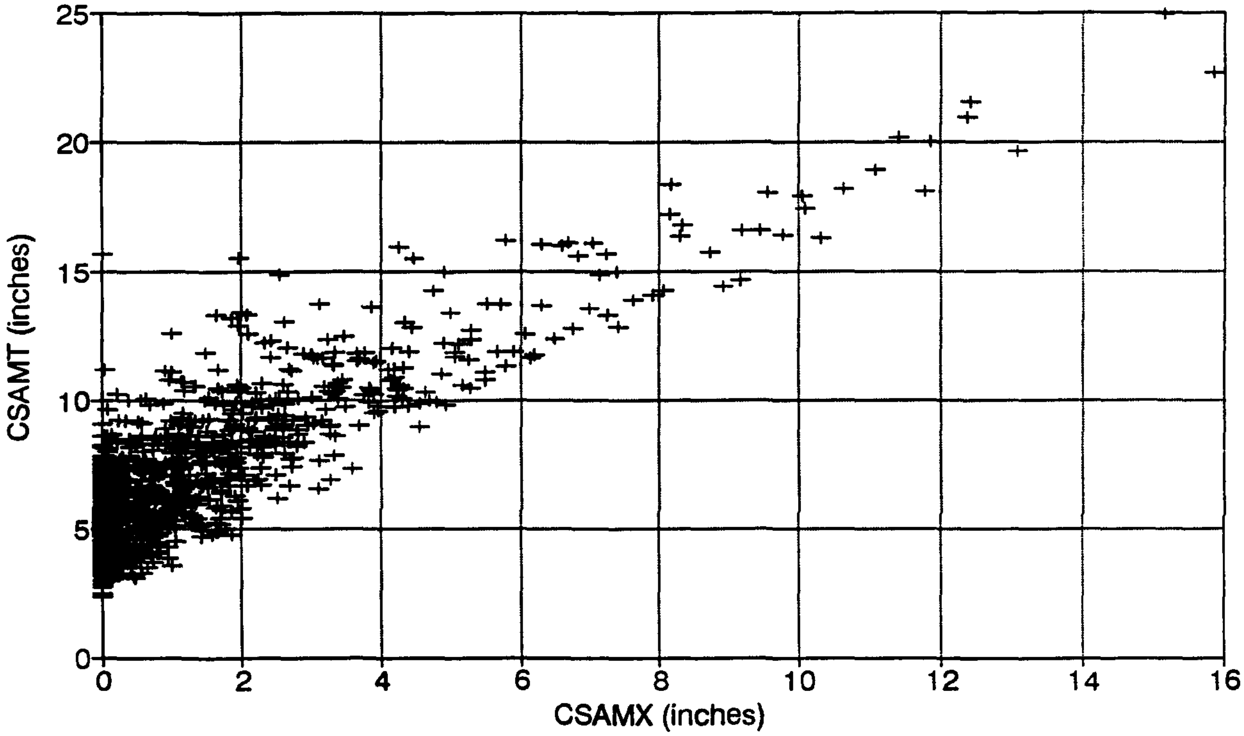

Figure 12.--Scatter diagram of central wet period precipitation, CSAMT, and central wet period precipitation excluding day 16, CSAMX.

precipitation (TAMTT) displays two local maxima at 2 and 5 days. The contiguous antecedent dry period duration (DLENA) shows a steady decline as the duration of central wet period increases from 1 to 6 days. However, it then shows a slight increase as central wet duration grows to 7 days or longer.

Table 5. Distribution of selected parameters of PSQ with CSLEN.

CSLEN (day)	N	P16 (inch)	CSAMX (inch)	CSAMT (inch)	TAMTT (inch)	DLENA (day)
1	241	5.41	0	5.41	3.07	5.60
2	359	5.82	.70	6.52	3.50	4.61
3	195	6.01	1.52	7.53	3.05	4.52
4	97	6.13	2.05	8.18	3.03	4.44
5	69	6.55	3.19	9.74	3.10	4.02
6	51	6.65	5.30	11.95	2.66	3.33
≥7	39	6.13	4.25	10.38	2.53	3.49

4. CHARACTERISTICS OF PRECIPITATION SEQUENCES

4.1 Antecedent versus Subsequent Contiguous Dry Periods

A comparison between the durations of the contiguous antecedent dry periods and those of the corresponding subsequent dry periods revealed an interesting tendency for the former to be of shorter duration. This observation led to the question: "Are the expected values of the durations of the immediate antecedent dry period (DLENA) and of the durations of the immediate subsequent dry period (DLENS) equal?" Usually, to test the equality of means between two equal-sized samples with size n from normal populations, the most powerful test is the Student t-test with degree of freedom 2n-2. Additional prerequisites for applying the Student-t test are that the two samples are independent and have equal variance. Since the complete absence of meteorological dependence between DLENA and DLENS can not be assured, direct application of the Student t-test would be inappropriate. Instead, the derived parameter DDLEN was examined where:

$$\text{DDLEN} = \text{DLENA} - \text{DLENS}.$$

DLENA and DLENS are the immediate antecedent and subsequent dry periods, respectively, and DDLEN is the remainder after DLENS is subtracted from DLENA through pairwise operations. It is found that DDLEN is approximately normally distributed. Furthermore, even though there may be correlation between DLENA and DLENS in the same sequence, there should be no correlation between DLENA of one sequence and DLENS of a different sequence. With these conditions satisfied, a paired-sample Student t-test with degree of freedom reduced to n-1 was applied to DDLEN. Test results are shown in Table 6.

Table 6. Results of paired-sample Student t-Test for null hypothesis that no difference exists between durations of immediate antecedent and immediate subsequent dry periods, or DDLEN=0.

mean	s.d.	sum	s.e.m.	c.v.	skew	t	s.p.
		Data set PSQ (N=1051)					
-.8592	5.6208	-903	.1734	-654.205	.0874	-4.96	.0001
		Data set PSQR (N=558)					
-.6183	5.6170	-345	.2378	-908.488	-.0099	-2.60	.0096

Here s.d. stands for standard deviation, sum is the cumulative sum for DDLEN in the data set, s.e.m. the standard error of the mean, c.v. the coefficient of variation and s.p. is the significance probability. Throughout this work, a significance probability of .02 is chosen as the threshold in hypothesis testing. This is a more stringent and more conservative criterion than the conventional .05.

For the primary data set PSQ of 1051 sequences, DDLEN sums to -903 days, with a mean of -.8592, a standard error of the mean of .1734, a coefficient of variation of -654.205, and skewness .0874. The computed Student t-statistic is -4.96. If the durations of the contiguous antecedent and subsequent dry periods are the same, then the mean and sum of DDLEN would be zero. The fact that they are substantially different from zero suggests that DLENA and DLENS do not have the same duration. Under the null hypothesis that DDLEN is zero, the probability of getting a Student t-statistic with absolute value larger than 4.96 is .0001 for data set PSQ; while the probability of getting one with absolute value larger than 2.60 is .0096 for data set PSQR. Therefore, the null hypothesis should be rejected for both data sets. The alternate hypothesis that the expected duration of the contiguous antecedent dry period is significantly shorter than that of the contiguous subsequent dry period is accepted. Thus, the number of days between the central wet period and the antecedent rain is significantly shorter than the number of days between the central wet period and the start of any subsequent rain. This conclusion is valid for both the station-oriented full data set PSQ and the storm-oriented reduced data set PSQR.

In order to determine if the differences in durations between the contiguous dry periods are related to the central rainfall, the distribution of durations of immediate antecedent dry period (DLENA), and of immediate subsequent dry period (DLENS), are shown in Table 7. Differences of (DDLEN) for the four PSQ subsets are also shown in Table 7.

Not only do significant differences exist between the mean durations of the contiguous antecedent and the corresponding subsequent dry periods for the sample PSQ, but when the data are stratified, Table 7 shows a tendency for this difference to become more marked as the central rainfall amount grow. As the central amounts increase from PSQA through PSQD, the duration of the immediate subsequent dry period (DLENS) actually diminishes slightly. This small reduction is more than compensated by the steep decrease in the duration of the immediate antecedent dry period (DLENA), leading to a larger negative DDLEN. For the subset PSQD with central rainfall equal to, or greater than, 14.50 inches, the mean immediate antecedent dry period is shorter by about two and one-third days than the mean immediate subsequent dry period. This difference is significant.

Table 7. Distribution of antecedent and subsequent contiguous dry periods DLENA and DLENS and their difference DDLEN at selected quartiles, units are days.

	mean	min	.25	median	.75	max
PSQA (N=431), CSAMT ≤6.0 inches						
DLENA	5.08	1	2	3	7	15
DLENS	5.59	1	2	4	8	15
DDLEN	-.51	-14	-4	0	3	14
PSQB (N=431), 6.0 inches < CSAMT < 9.5 inches						
DLENA	4.72	1	1	3	7	15
DLENS	5.58	1	2	5	8	15
DDLEN	-.86	-14	-4	-1	2	14
PSQC (N=151), 9.5 inches ≤ CSAMT < 14.5 inches						
DLENA	3.85	1	1	2	6	15
DLENS	5.34	1	2	4	7	15
DDLEN	-1.49	-13	-5	-1	2	12
PSQD (N=38), CSAMT ≥ 14.5 inches						
DLENA	2.53	1	1	2	3	11
DLENS	4.87	1	2	5	7	15
DDLEN	-2.34	-11	-5	-2.5	1	3

4.2 Correlations Between CSAMT, CSLEN and Other Precipitation Parameters

The central precipitation (CSAMT) and the corresponding duration of central wet period (CSLEN) are the two key parameters that describe a precipitation sequence. It is important to examine if any pertinent relations exist among these two key parameters and all other parameters. The Pearson correlation coefficients between CSAMT and other parameters are shown in Table 8, while those between CSLEN and the same parameters are shown in Table 9.

Due to the relatively large sample sizes, a more stringent significance probability of .01 is chosen as the threshold value in order to uncover definitive correlations. Cases with significance probabilities greater than .01 are considered not to be significant. Furthermore, only parameters showing significant correlations with CSAMT or CSLEN in **both** the full data sets PSQ and the reduced data set PSQR are considered truly significant. These steps are intended to keep the correlation results conservative and are adopted throughout this work.

Table 8. Correlations between CSAMT and selected parameters

	PSQ (N = 1051)		PSQR (N = 558)	
	Correlation Coefficient	Significant Probability	Correlation Coefficient	Significant Probability
P16	.773	.0001	.795	.0001
CSAMX	.848	.0001	.805	.0001
WAMTA	.110	.0003	.173	.0001
WAMTS	.113	.0002	.146	.0005
WAMTT	.153	.0001	.215	.0001
RAMTA	.089	.0040	.121	.0043
RAMTS	-.020	.5186	.032	.4512
TAMTA	.145	.0001	.200	.0001
TAMTS	.055	.0756	.113	.0075
TAMTT	.139	.0001	.204	.0001
NBRDP	-.028	.3662	-.008	.8593
CSLEN	.522	.0001	.465	.0001
CDPOS	.402	.0001	.297	.0001
DLENA	-.164	.0001	-.134	.0015
DLENS	-.032	.3027	-.044	.2951
WLENA	.071	.0214	.094	.0264
WLENS	.066	.0320	.073	.0842
TLENA	-.230	.0001	-.179	.0001
TLENS	-.156	.0001	-.179	.0001
TLENT	-.255	.0001	-.227	.0001
CRTOA	-.109	.0004	-.090	.0333
CRTOS	-.119	.0001	-.063	.1371
CRTOT	-.156	.0001	-.104	.0138
TRTOA	-.165	.0001	-.125	.0031
TRTOS	-.203	.0001	-.141	.0008
TRTOT	-.249	.0001	-.177	.0001

As expected there are strong positive correlations between the central precipitation (CSAMT) and its components P16 and CSAMX. In addition there are slight, but statistically significant, positive correlation between CSAMT and the following parameters denoting rainfall amounts: WAMTA and WAMTS, rainfall amounts in the two closest wet periods straddling the central wet period; and their sum WAMTT; TAMTA, sum of antecedent amounts; and TAMTT, sum of all antecedent amounts.

There are modest correlations between CSAMT and CSLEN and CDPOS. This is to be expected, since CSLEN denotes the length of the central wet period and CDPOS denotes the position of day-16 counting from the beginning of the central wet period. If there are m wet days immediately preceding day 16, then CDPOS = m + 1. There also exist slight, but significant negative correlations between CSAMT and the following duration parameters: the total number of antecedent dry days (TLENA); the total number of subsequent dry days (TLENS); and the total number of all dry days in a sequence (TLENT), and the immediate antecedent dry period duration (DLENA). The relations between CSAMT and parameters representing number of dry days have a clear physical interpreta-

Table 9. Correlations between CSLEN and selected parameters

	PSQ (N = 1051)		PSQR (N = 558)	
	Correlation Coefficient	Significance Probability	Correlation Coefficient	Significance Probability
P16	.173	.0001	.132	.0018
CSAMX	.635	.0001	.608	.0001
CSAMT	.522	.0001	.466	.0001
WAMTA	-.023	.4540	.036	.3960
WAMTS	-.039	.2048	.003	.9441
WAMTT	-.042	.1762	.025	.5546
RAMTA	-.028	.3688	-.030	.4770
RAMTS	-.060	.0512	-.052	.2188
TAMTA	-.038	.2223	-.004	.9322
TAMTS	-.069	.0246	-.037	.3825
TAMTT	-.072	.0189	-.028	.5157
NBRDP	-.055	.0747	-.048	.2562
CDPOS	.723	.0001	.645	.0001
DLENA	-.136	.0001	-.132	.0018
DLENS	-.115	.0002	-.144	.0006
WLENA	-.022	.4674	.068	.1075
WLENS	.051	.0996	.090	.0329
TLENA	-.323	.0001	-.268	.0001
TLENS	-.388	.0001	-.446	.0001
TLENT	-.472	.0001	-.456	.0001
CRTOA	-.132	.0001	-.094	.0272
CRTOS	-.140	.0001	-.099	.0191
CRTOT	-.187	.0001	-.135	.0014
TRTOA	-.194	.0001	-.147	.0005
TRTOS	-.194	.0001	-.159	.0002
TRTOT	-.264	.0001	-.204	.0001

tion which is anticipated. Therefore, it is interesting to notice the presence of the slight, but significant negative correlations between the central rainfall amount and the duration of the dry period immediately preceding the central wet period.

When total antecedent precipitation (TAMTT) and its ratio to central amount (TRTOT) are examined, a notable duality is evident in Table 8. The slight positive correlation between CSAMT and TAMTT is more than matched by the negative correlation between CSAMT and TRTOT. In other words, as central precipitation increases, the total antecedent amount would tend to increase marginally on the average, but at the same time its ratio to the central amount would decrease significantly. This finding led to the question of how these parameters are distributed in the subsets of PSQ which is addressed in section 6.

With regard to the central wet period duration (CSLEN), it has significant positive correlations with the following parameters: precipitation on the central day (P16), precipitation in the central wet period (CSAMT), their difference (CSAMX) and position of day 16 in the central wet period (CDPOS). The comparatively high correlation with CDPOS is no surprise, since CDPOS measures that part of CSLEN from the beginning of the central wet period up to day 16. CSLEN has significant negative correlations with the following parameters: duration of the immediate antecedent dry period (DLENA), duration of the immediate subsequent dry period (DLENS), their difference (DDLEN), number of antecedent dry days (TLENA), number of subsequent dry days (TLENS), and their sum (TLENT); all of which represent various dry durations. Central wet period duration (CSLEN) is negatively correlated with the following ratio parameters: ratio of the sum of precipitation in the first antecedent and first subsequent wet periods to the central precipitation (CRTOT), ratio of the antecedent precipitation to the central amount (TRTOA), ratio of the subsequent precipitation to the central amount (TRTOS), and ratio of the total antecedent and subsequent precipitation to the central amount (TRTOT).

4.3. Distributions of CSLEN, CDPOS, TAMTT and TRTOT

The distributions of several important parameters, such as the duration of the central wet period (CSLEN), the position of central day or day 16 in the central wet period (CDPOS), total antecedent and subsequent precipitation (TAMTT), and the ratio of total antecedent and subsequent precipitation to central amount (TRTOT) with respect to the four subsets of the full data set PSQ are treated in this section. Table 10a shows the detailed distribution of CSLEN over PSQ and its subsets. Table 10b shows the distribution of the respective means of the four parameters over the four subsets of PSQ.

Table 10a. Distribution of duration of central wet period CSLEN (days) over subsets of PSQ, P represents CSAMT

CSLEN	PSQA $P \leq 6.0$	PSQB $6.0 < P < 9.5$	PSQC $9.5 \leq P < 14.5$	PSQD $P \geq 14.5$	PSQ
1	165	74	1	1	241
2	163	164	30	2	359
3	58	103	28	6	195
4	29	37	29	2	97
5	10	23	29	7	69
6	4	15	15	17	51
≥7	2	15	19	3	39
Total	431	431	151	38	1051

Table 10b. Distribution of means of Central Wet Duration (CSLEN), Position of Central Wet Day in Central Wet Period (CDPOS), Precipitation in Central Wet Period (CSAMX), and Central Wet Day (P16) in subsets of PSQ.

	CSLEN (Days)	CDPOS (Days)	CSAMX (Inch)	P16 (Inch)
PSQA (N=431)	2.02	1.50	.31	4.42
PSQB (N=431)	2.74	1.77	.98	6.45
PSQC (N=151)	4.27	2.52	3.45	7.75
PSQD (N=38)	5.00	3.26	8.53	8.78
PSQ (N=1051)	2.75	1.82	1.33	5.89

There are 241 sequences with central wet period consisting of one day only and all except two had less than 9.5 inches of rain. A majority of the sequences in data sets PSQA and PSQB have CSLEN of 2 days or less, while most of the sequences in data sets PSQC and PSQD have CSLEN of 3 days or more. This is due to the increasingly important contributions made by precipitation in wet days surrounding day 16 as the total precipitation in the central wet period CSAMT increases beyond 9.50 inches

Since the four subsets PSQA to PSQD are grouped according to the magnitude of their central precipitation which is the sum of P16 and CSAMX, their well-behaved increases from PSQA to PSQD is expected. The two parameters denoting central wet duration (CSLEN) and position of central day within the central wet period (CDPOS) also indicate a clear trend of growth from PSQA to PSQD. It should be noted that subset PSQD has a mean central wet duration (CSLEN) less than three quarters of a day longer than that for subset PSQC, but the mean precipitation in the surrounding days of the central wet period (CSAMX) is more than 5 inches greater than that of PSQC.

To shed more light on the apparent duality mentioned earlier, the distributions of total antecedent (TAMTT) and subsequent (CSAMT) central storm amounts with respect to the stratified subsets of PSQ are shown in Table 11. There is no evidence that a larger mean central rainfall amount (CSAMT) tends to associate with a somewhat proportionally larger sum of antecedent and subsequent precipitation (TAMTT) in the 31 day precipitation sequence. For example, data subsets PSQB, PSQC, and PSQD having mean central amounts of 7.42, 11.20, and 17.30 inches are associated with mean total antecedent and subsequent precipitation of 3.63, 3.51, and 3.14 inches, respectively. There is almost a faint suggestion of inverse linkage between them. However, subset PSQA which has the smallest central amount also has the smallest sum of antecedent and subsequent precipitation among the four subsets.

Table 11. Distribution of Total Antecedent (TAMTT) and Subsequent (CSAMT) Precipitation Central Storm Amount in subsets of PSQ

		TAMTT		CSAMT
	min (inch)	mean (inch)	max (inch)	mean (inch)
PSQA (N=431)	0	2.60	10.34	4.73
PSQB (N=431)	0	3.63	14.14	7.42
PSQC (N=151)	0	3.51	9.88	11.20
PSQD (N=38)	.61	3.14	7.55	17.30

These facts do not contradict the previous finding that a slight positive correlation exists between CSAMT and TAMTT in the full data set PSQ. Table 11 shows that despite the existence of this weak correlation for the whole population, the mean TAMTTs of the stratified subsets do not necessarily follow a commensurable relationship with the corresponding mean CSAMTs. This fact indicates that the apparent positive correlation is mainly due the presence of the lesser storms (PSQA). For the data set PSQ as a whole, this correlation is very tenuous.

There is also no evidence that the magnitudes of the maximum antecedent precipitation are in any way positively correlated with the corresponding mean central precipitation. For example, the maximum antecedent precipitation of 14.14 inches is found in PSQB, while the smallest of the four maxima, 7.55 inches, is found in PSQD, a subset characterized by the largest central rainfall amount.

For data set PSQD, characterized by the largest central rainfall, there is at least some observed antecedent rainfall in every sequence. For the other three data sets, there are sequences where no rain is observed besides that in the central wet periods. Actual occurrences of such sequences are, however, relatively rare. Sixteen cases were found out of a population of 1051, or 1.5 percent of the time.

4.4 Distribution of TAMTT in Subsets of PSQ

To describe more fully the distribution of the total antecedent and subsequent precipitation (TAMTT) in the subsets of PSQ, it is convenient to classify TAMTT into five groups T1 to T5 according to the magnitude as follows:

T1; $0 \le \text{TAMTT} \le 0.75$ inches
T2; 0.75 inches $< \text{TAMTT} \le 1.75$ inches
T3; 1.75 inches $< \text{TAMTT} \le 3.00$ inches
T4; 3.00 inches $< \text{TAMTT} \le 5.00$ inches
T5; 5.00 inches $< \text{TAMTT}$.

Table 12. Distribution of selected parameters on TAMTT in subsets of PSQ

	N	DLENA (days)	P16 (inch)	TAMTT (inch)	CSAMT (inch)
	PSQA				
T1	72	7.81	4.10	.63	4.53
T2	110	5.67	4.15	1.20	4.51
T3	102	4.66	4.38	2.36	4.64
T4	92	3.93	4.70	3.87	5.01
T5	55	3.05	5.01	6.63	5.15
	PSQB				
T1	45	8.09	6.17	.36	7.40
T2	77	7.25	6.46	1.25	7.51
T3	79	4.63	6.20	2.43	7.20
T4	123	3.30	6.54	3.95	7.50
T5	107	3.17	6.64	7.22	7.45
	PSQC				
T1	14	6.14	7.30	.46	10.89
T2	33	4.52	7.63	1.20	11.39
T3	17	3.71	7.78	2.43	11.32
T4	49	3.65	7.87	3.78	11.06
T5	38	2.74	7.86	6.77	11.30
	PSQD				
T1	3	1.33	7.83	.66	18.85
T2	10	3.20	7.74	1.19	17.44
T3	8	2.63	8.54	2.29	18.67
T4	8	2.38	10.22	3.42	16.23
T5	9	2.22	9.17	6.66	16.37

A detailed depiction of relationships between the antecedent precipitation groups and the four subsets of the primary data set PSQ with respect to the distribution of precipitation in the central wet period (CSAMT), precipitation on the central day (P16), and the duration of the immediate antecedent dry period (DLENA) are shown in Table 12.

Table 12 is stratified using the five groups T1 to T5 and the subsets PSQA to PSQD of the total storm set. For subset PSQA, characterized by moderate central precipitation of 6.00 inches or less, there seems to be a positive association between the central and antecedent precipitation, except for the fluctuation of CSAMT in cell T1. However, for the three subsets PSQB, PSQC and PSQD, all having central precipitation exceeding 6.00 inches, the lack of positive correspondence between the central and antecedent precipitation groups is evident. This is an important revelation. It suggests that the apparent slight correlation between central and antecedent precipitation previously found for the full data set PSQ might be attributed entirely to the presence of sequences with moderate central storms.

Aside from that, the most remarkable feature revealed is the almost universal trend for the immediate antecedent dry period duration (DLENA) to become shorter as the total antecedent precipitation (TAMTT) increases. The only exception is for row T1 at PSQD, where cell sample size is very small. When the whole population is considered, the Pearson's correlation coefficients between TAMTT and DLENA are -.338 and -.346 for data sets PSQ and PSQR, respectively with a significance probability of .0001 in both cases.

The proportions of sequences with total antecedent and subsequent precipitation (TAMTT) greater than 3.00 inches (groups T4 and T5) are 34.1, 53.4, 57.6 and 44.7 percent for subsets PSQA to PSQD, respectively, with PSQC having the highest ratio of 57.6 percent. The proportions of sequences with TAMTT greater than 5.00 inches (group T5) were 12.8, 24.8, 25.2 and 23.7 percent for PSQA to PSQD, respectively. This again indicates that as far as total antecedent and subsequent precipitation are concerned, there is a qualitative disparity between subset PSQA and the other three subsets. Subset PSQA stands out because it has conspicuously less total antecedent and subsequent precipitation than all others. For the other three subsets (PSQB, PSQC and PSQD), the percent differences between the central storm amount and the subsequent and antecedent storm amounts are small. However, it is clear that sequences with large central precipitation do not necessarily also have large total antecedent and subsequent precipitation.

A box plot of total antecedent and subsequent precipitation (TAMTT) for the subsets of data set PSQ is shown in Figure 13 The range of TAMTT is represented by the maximum and minimum values each connected to the box by dashed lines. A box is bounded above by the upper quartile and below by the lower quartile. The interquartile range, represented by the height of the box, is a robust estimator of scale. The horizontal line inside the box represents the median, which is a stable indicator of location. The differences between the quartiles and the median yield information about the skewness of the data. Arranged according to the magnitudes of the medians of total antecedent precipitation in descending order, the sets are: PSQB, PSQC, PSQD and PSQA, the same order as that of the means of the total antecedent precipitation.

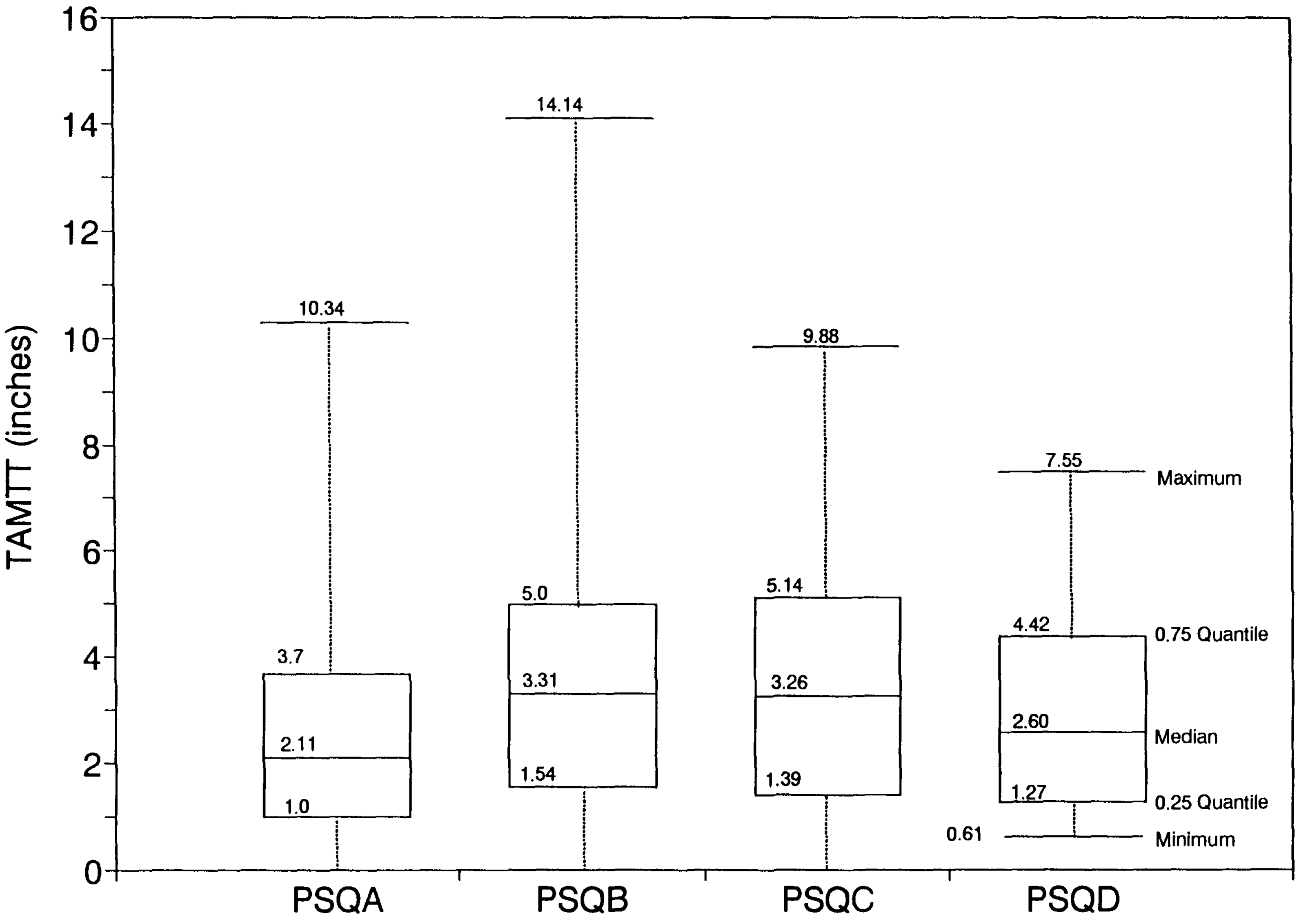

Figure 13.--Box plot to total antecedent and subsequent precipitation, TAMTT, for subsets PSQA, PSQB, PSQC, and PSQD.

4.5 Precipitation Sequences Containing Maximum Amounts

The three sequences containing the maxima of central day precipitation (P16), central wet period precipitation (CSAMT), and total antecedent and subsequent precipitation (TAMTT) are shown in Table 13. By sorting data sets PSQ and PSQR, these same three identical sequences were selected. This is a confirmation that the filtering procedure used to modify the full data set PSQ into the reduced data set PSQR did retain the most significant sequences as intended.

Here, station is identified by a two-digit state number followed by a four-digit station number. Date is expressed in format yyyymmdd. Entries marked with "*" denote actual maxima. For example, the largest central day precipitation for the data sets was 15.68 inches on October 11, 1973 at Enid, Oklahoma (34-2912). The total antecedent amount (TAMTT) in this 31-day sequence was 3.89 inches or 24.8 percent of the central amount (TRTOT). The maximum central wet period precipitation (CSAMT) was 24.95 inches which occurred at Coalgate 1 WNW, Oklahoma (34-1954) in a 7-day period from October 12th to 18th, 1981 with 9.80 inches falling on October 14. The associated total antecedent precipitation was 2.67 inches or 10.7 percent of the central amount. The highest antecedent and subsequent precipitation of the data sets was 14.14 inches recorded at Clayton 11 WNW, Oklahoma (34-1858) in a 31-day sequence centered on October 20, 1984 and was 191.1 percent of the central amount of 7.40 inches. It is observed that the maxima of P16, CSAMT and TAMTT occurred in three distinct sequences. It should also be noted that all three sequences were observed in Oklahoma and had central days in October.

Table 13. Precipitation sequences with maximum amounts.

Station	Date	P16 (inch)	CSAMT (inch)	CSLEN (day)	CDPOS (day)	TAMTT (inch)	TRTOT (%)
34-2912	19731011	15.68*	15.68	1	1	3.89	24.8
34-1954	19811014	9.80	24.95*	7	3	2.67	10.7
34-1858	19841020	7.30	7.40	2	1	14.14*	191.1

*indicates maximum

4.6 Precipitation Sequences with Maximum Central Wet Durations

Three sequences have the maximum observed central wet duration of 10 days. Table 14 lists these sequences in order of magnitude of central precipitation (CSAMT).

The first sequence occurred at Columbus 1 SW, Kansas (14-1740) with central wet period extending from June 20 to June 29, 1948. Of the central precipitation of 13.39 inches, 8.40 inches fell on June 22, and 4.99 inches fell on the other nine days. Total antecedent and subsequent precipitation in a 31-day period from June 7 to July 7, 1948 inclusive was 3.93 inches which was 29.3 percent of the central amount. The second sequence was observed at Ayer Ranch, Colorado (05-0437) with central wet period extending from June 10 to June 19, 1965, and central amount 8.96 inches of which 6.46 inches fell on June 18, the ninth day. Total antecedent and subsequent amount was 2.83 inches or 31.6 percent of the central amount. The third sequence occurred at Hooker, Oklahoma (34-4298), had its central wet period extending from June 4 to June 13, 1960 and central amount 6.44 inches of which 4.74 inches fell on the sixth day or June 9. Total antecedent and subsequent amount was .32 inch, or 5.0 percent of the central amount.

It is interesting to note that all three sequences with the maximum central wet duration of 10 days had their central days in the month of June. Further inquiry revealed that there were 39 sequences having a central wet duration equal to or greater than 7 days. Of these 39, 16 occurred in June, 7 in September, 6 in October, 5 in July, 4 in May, 1 in April and none in other months.

4.7 Regression Analysis.

Regression analysis is often used to detect potential functional relationships between variables in a data set. In practice the true distribution functions of the variable of interest are always unknown. For example, in the context of the

Table 14. Sequences with maximum central wet duration of 10 days (CSLEN).

Station	Date	P16 (inch)	CSAMT (inch)	CSLEN (day)	CDPOS (day)	TAMTT (inch)	TRTOT (inch)
14-1740	19480622	8.40	13.39	10	3	3.93	29.3
05-0437	19650618	6.46	8.96	10	9	2.83	31.6
34-4298	19600609	4.73	6.44	10	6	.32	.05

present investigation, the antecedent precipitation amount or the central precipitation amount can not be expressed in a ready functional form. The nature of these parameters may be too complicated to be represented by any commonly known mathematical functions. Instead, through regression analysis, we try to approximate the unknown true distribution as a function of other observable meteorological parameters based on limited a priori knowledge.

It is possible that a response variable could be represented by many different combinations of a set of predictors. Since the exact model is unknown, the issue is to identify a best or optimal model among a given set of alternatives. It is intuitively expected that as more and more predictors are incorporated into the analysis, the approximation to reality would become better and better. However, as model complexity increases and degree of freedom reduces, the accuracy of estimation, as measured by the root-mean-square error, may not continue to improve appreciably after substantial initial reductions. Thus, a state of diminishing return is reached. The root-mean-square error may even tend to increase slightly as additional predictors are successively incorporated beyond an optimal set. Some tests in statistical forecasting have indicated that when are attempts were made to apply a prognostic equation on independent data, using more predictors may actually lead to a deterioration of the forecaster's skill.

In the classical Neyman-Pearson theory of hypothesis testing, only the probability of accepting the incorrect or rejecting the correct hypothesis are considered to define the loss caused by the decision. Because the assumed null hypotheses are only approximations to the unknown, and most likely different from reality, the loss defined under such conditions is not an adequate criterion for unambiguous model identification.

Akaike (1974) proposed a statistic, the Akaike Information Criterion (AIC), derived by applying an extension of the maximum likelihood principle to the Kullback-Leibler (1951) mean information for the discrimination between models. In the context of regression analysis:

$$AIC = (n) \ln (SSE/n) + 2k$$

here n is the sample size, SSE the error sum of squares, and k is the number of predictor variables, including intercept, that are used in the regression model. It is seen that AIC consists of two counteracting terms, SSE and K. The first term is a measure of deviation and the second term is related to the sample size's complement of the degree of freedom. As one tries to fit the observed data by regression equations with an increasing number of predictor variables, the deviation term will likely decrease. This reduction is achieved at the price of increasing model complexity and decreasing degree of freedom. There is a trade-off between the accuracy of estimates and the parsimonious use of predictors. The second term, K, represents a graduated penalty for model complexity. The model that minimizes the AIC is the one that represents an optimal balance and is denoted as the minimum AIC estimate or the MAICE model. For more information on model selection based on AIC, one can also refer to Chin (1977).

With the precipitation amount in the central wet period as the response variable and a vector predictor consisting of 15 components plus intercept, an exploratory procedure was first applied to data set PSQ consisting of 1051 precipitation sequences. Among all possible combinations of these predictor variables, one set of seven variables constructs a model that produces the minimum AIC and therefore, was selected as the "optimal" model. These seven predictors in the order of selection are: P16, CSLEN, DLENA, NBRDP, DLENS, TLENS, and WAMTS. Then a linear regression analysis was carried out using these seven predictors to account for the response variable CSAMT. The inclusion of variables following the response variable in the time domain indicates that the objective is a diagnostic study and not a forecast equation.

Because of inherent physical relationships among meteorological variables, the predictors are not strictly independent. There is always some correlation among them and a degree of collinearity will normally be present. When a predictor is nearly a linear combination of some other predictors in the model, the affected estimates are unstable and have high standard errors. In a hypothetical case, if any one of the predictor variables is an exact linear function of one or more other predictors, regression analysis would fail since the coefficients would be indeterminate. For real meteorological data and sample sizes much larger than the number of predictors, this extreme situation seldom arises. To determine if it is a significant factor, a collinearity analysis is also performed. The intercept is adjusted out first. Then the eigenvalues and eigenvectors are computed. Condition numbers are defined as the square roots of the ratio of the largest eigenvalue to each individual eigenvalue. If the maximum condition number is very large, e.g., on the order of 10^2 or greater, the coefficient estimates may have large errors and the regression problem may become ill-conditioned. Under such circumstances, the conventional regression procedure should be replaced by some inverse regression method such as ridge regression in order to mitigate the effect of collinearity. However, these non-conventional procedures produce biased estimates of regression coefficients. A summary of results is shown in Table 15.

The first two predictors, central day precipitation (P16) and duration of central wet period (CSLEN), have perceptible physical relations to the predictand; the precipitation in the central wet period (CSAMT). It is interesting to note that the third predictor, immediate antecedent dry period duration (DLENA) was the first non-obvious predictor parameter selected. The dry period immediately before the central rain event is always selected as a predictor for the central event. The shorter the dry period, the more significant is the magnitude of the central rain event.

Table 15. Summary results of analysis of variance, parameter estimates, and collinearity diagnostics

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General Framework:

1. Data set: PSQ consisting of 1051 precipitation sequences of 31 days each
2. Predictand: CSAMT
3. Predictors: Intercept, P16, NBRDP, TLENT, TLENA, TLENS, DLENA, DLENS, CSLEN, WAMTA, WAMTS, RAMTA, RAMTS, WLENA, WLENS, CDPOS
4. Units: All amount variables are in inches, all duration variables are in day units, counting variables NBRDP and CDPOS are integers.

Results:

1. Analysis of Variance:

Source	DF	Sum Squares	Mean Square	F value	Prob>F
Model	7	7655.85867	1093.69410	468.969	.0001
Error	1043	2432.40612	2.33212		
Total	1050	10088.26479			

Root MSE	1.52713	R-Square	.7589
CSAMT Mean	7.22131	Adj R-Sq	.7

2. Parameter Estimates:

Variable	Parameter Estimate	Standard Error	t for H0: Parameter=0	Prob>|t|
Intercept	-1.81906	.60999	-2.982	.0029
P16	1.24513	.02821	44.141	.0001
CSLEN	.73891	.03416	21.632	.0001
DLENA	-.05776	.01481	-3.900	.0001
NBRDP	-.13489	.04783	-2.820	.0049
TLENS	.07573	.03261	2.322	.0204
DLENS	-.03698	.01561	-2.368	.0180
WAMTS	.08224	.05321	1.546	.1225

Table 15. (continued) Summary results of analysis of variance, parameter estimates, and collinearity diagnostics

	Standardized Estimate	Tolerance	Variance Inflation
P16	.69645	.92861	1.07687
CSLEN	.40342	.66470	1.50444
DLENA	-.07466	.63063	1.58573
NBRDP	-.06719	.40734	2.45497
TLENS	.05484	.41441	2.41308
DLENS	-.05305	.46077	2.17026
WAMTS	.02549	.84990	1.17661

3. Collinearity Diagnostics (with Intercept adjusted out):

Number	Eigenvalue	Condition Number
1	2.42655	1.00000
2	1.21742	1.41181
3	1.09805	1.48656
4	1.04617	1.52298
5	.69648	1.86655
6	.28433	2.92137
7	.23100	3.24107

An explanation of the 'Results' section in Table 15 follows:

Source:	Source of the variation; Model for fitted regression, Error for residual error.
D.F.:	Degree of freedom.
Sum Squares:	Sum of squares.
Mean Square:	Mean Square is computed by dividing Sum Squares by D.F.
F Value:	The F statistic for testing the hypothesis that all parameters are zero except for the intercept.
Prob>F:	Significance probability. Here a value of .0001 indicates that the relationship described by the regression equation is statistically significant.

R-Square:	The portion of the total variance attributed to the fit, about 76 percent.
Adj R-Sq:	A version of R-Square adjusted for degree of freedom for error. The adjustment makes little difference in this case.
Variables:	The predictor variables including intercept that constitute a model characterized by the minimum AIC among all possible models. The selected variables are: Intercept, P16, CSLEN, DLENA, NBRDP, TLENS, DLENS, and WAMTS.
Parameter Estimate:	Estimated regression coefficients.
Standard Error:	Estimate of the standard deviation of the coefficients.
t for H0 Parameter=0:	The t test that the parameter is zero.
Prob>|t|:	The probability that a t test would get a greater absolute value than that observed given that the true parameter is zero.
Standardized Estimate:	Standardized regression coefficient.
Tolerance:	$(1-R^2)$ for a variable with respect to all other regressor variables in the model.
Variance Inflation:	The reciprocal of tolerance.
Eigenvalue:	Eigenvalues of the product matrix **X'X**. Here **X** is the 1051 by 7 matrix containing the sample values of 7 predictor variables at each of 1051 data sequences and **X'** is the transpose of **X**. The 7 by 7 matrix **X'X** is scaled to have 1s on the diagonal and then eigenvalues are computed.
Condition Number:	The square root of the ratio of the largest eigenvalue to each individual eigenvalue. The fact that the largest condition number is 3.24 and does not have a magnitude of 10^2 or 10^3 or greater suggests that collinearity is not a major factor and, therefore, the parameter estimates are stable.

5. ALTERNATE PRECIPITATION SEQUENCES.

5.1 Data Sets Selected by Higher Threshold Criteria

The primary data set PSQ consisting of 1051 31-day precipitation sequences was selected on the basis that the central day amount be greater than or equal to the 10-year 24-hour rain. This threshold was successively raised to 25-, 50- and 100-year 24-hour rainfalls and 31-day precipitation sequences were extracted to create data sets PSQ25Y, PSQ50Y, and PSQ100Y, respectively.

As the threshold increases, the sample size decreases from the original 1051 to 529, 253 and 131, successively. Comparisons of selected parameters among these four data sets are shown in Table 16.

These four data sets are not mutually exclusive. They are related in the notation of set algebra:

$$\text{PSQ} \supset \text{PSQ25Y} \supset \text{PSQ50Y} \supset \text{PSQ100Y}$$

Set PSQ contains PSQ25Y which contains PSQ50Y which contains PSQ100Y. In other words, PSQ100Y is a subset of PSQ50Y which is a subset of PSQ25Y which in turn is a subset of PSQ. A sequence in PSQ100Y belongs to all four data sets, and a sequence in PSQ50Y may or may not belong to PSQ100Y, but it belongs to all other three sets and so on. Because the data overlap, Table 16 should be interpreted with due caution. The procedures leading to the formation of these three additional data sets are quite different from the criteria used to partition PSQ into four distinctive and mutually exclusive subsets PSQA to PSQD. PSQA to PSQD used an arbitrary central amount, while these data sets used return periods for each station.

Table 16. Comparisons among PSQ, PSQ25Y, PSQ50Y and PSQ100Y; units are inches for P16, CSAMT, WAMTA, WAMTS, WAMTT, and TAMTT; days for CSLEN and percent for CRTOT and TRTOT.

	PSQ	PSQ25Y	PSQ50Y	PSQ100Y
N	1051	529	253	131
P16	5.89	6.76	7.58	8.26
CSAMT	7.22	8.36	9.41	10.17
CSLEN	2.75	2.92	3.00	3.08
WAMTA	.80	.82	.91	.84
WAMTS	.67	.76	.79	.67
WAMTT	1.47	1.58	1.69	1.51
TAMTT	3.17	3.28	3.51	3.34
CRTOT	21.86	20.10	17.99	14.86
TRTOT	47.88	42.21	37.31	32.84

It is interesting to note that the largest total precipitation in the first antecedent and first subsequent wet period (WAMTT) and the largest total antecedent and subsequent precipitation (TAMTT) are both associated with PSQ50Y and not PSQ100Y. However, both the ratio of the total precipitation in the first antecedent and subsequent wet periods to the central amount (CRTOT) and the ratio of total antecedent and subsequent precipitation to central amount (TRTOT) do show a steady decline as the central day precipitation threshold was successively raised from 10, 25, 50 to 100-year 24-hour amounts.

5.1.1 Distributions of Sequences According to CSLEN and Month

Table 17 depicts the distributions of sequences in the three data sets with raised selection-threshold criteria with respect to the duration of central wet period CSLEN. For comparison such distribution for PSQ is also listed.

As the selection-threshold increases from 10- up to 100-year 24-hour amounts there is a tendency for the longer durations of central wet periods (CSLEN) to become better represented. For example, the proportions of a central wet period duration of four days or longer from Table 17 increases from 24.4 to 28.9, 31.6, and 33.6 percent from data sets PSQ, to PSQ25, PSQ50, and PSQ100, respectively.

Table 17. Distributions of central wet period duration CSLEN on precipitation sequences with selection thresholds of 10, 25, 50 and 100-year 24-hour rain

CSLEN (days)	PSQ	PSQ25	PSQ50	PSQ100
1	241	103	51	25
2	359	175	81	37
3	195	98	41	25
4	97	55	30	17
5	69	42	19	13
6	51	37	20	7
≥7	39	19	11	7

Table 18. Distributions of key parameters on CSLEN.

	PSQ25			PSQ50			PSQ100		
	CSAMT (inch)	TAMTT (inch)	DLENA (day)	CSAMT (inch)	TAMTT (inch)	DLENA (day)	CSAMT (inch)	TAMTT (inch)	DLENA (day)
CSLEN (day)									
1	6.25	3.15	5.72	6.92	3.20	5.71	7.35	2.68	6.20
2	7.52	3.66	4.55	8.53	3.92	4.42	9.46	3.78	3.84
3	8.62	3.14	4.15	9.69	3.19	4.22	10.69	2.86	4.24
4	9.02	2.94	4.67	9.59	3.09	4.53	11.02	3.32	4.47
5	10.28	3.40	3.79	11.39	4.83	3.68	11.25	5.11	4.38
6	13.07	2.71	3.16	14.75	3.06	2.95	15.71	2.10	3.86
≥7	11.00	3.18	2.79	12.70	2.77	2.36	12.46	3.10	2.57

As the durations of central wet periods increase successively from 1 to 6 days, mean precipitation in the central wet period (CSAMT) also increases unequivocally, but then decreases as the central wet periods extend beyond 6 days (Table 18). This phenomenon is present for all three data sets. The contiguous antecedent dry period durations (DLENA) fluctuate, but generally decrease with increasing duration of the central wet period (CSLEN). The pattern of changes of total antecedent precipitation (TAMTT) is also not clear-cut. It can be observed that the three maxima of TAMTTs are associated with central wet period durations of 2, 5 and 5 days for data sets PSQ25Y, PSQ50Y and PSQ100Y, respectively. It should also be noted that for CSLEN longer than 6 days, the mean CSAMT for data set PSQ100Y becomes less than that for data set PSQ50Y. This indicates that reductions in CSAMX overpowered the increases in P16 in data set PSQ100Y and implies that in the 18 sequences with P16 equal to, or greater than, 50-year 24-hour rain and with duration of central wet period exceeding 6 days, a larger P16 does not necessarily lead to a larger central amount because of potential reduction of precipitation in the days surrounding day 16.

The monthly distribution of the three data sets, plus the primary data set PSQ, are shown in Table 19. Here we have four data sets PSQ, PSQ25Y, PSQ50Y, and PSQ100Y which were selected based on whether the central day precipitation was equal to, or greater than, 10, 25, 50, or 100-year 24-hour amounts.

Table 19. Monthly distribution of sequences

	PSQ	PSQ25Y	PSQ50Y	PSQ100Y
January	4	3	3	1
February	3	1	0	0
March	4	2	1	1
April	26	15	6	4
May	161	81	37	18
June	173	82	43	25
July	191	91	43	21
August	122	56	19	8
September	203	99	47	19
October	125	72	42	24
November	27	15	6	5
December	12	12	6	5
Total	1051	529	253	131

The months with the maximum number of occurrences are September for data sets PSQ, PSQ25Y, and PSQ50Y; and June for data set PSQ100Y. The months with the second most frequent occurrences are July for PSQ and PSQ50Y; June and July for PSQ50Y; and October for PSQ100Y.

It is interesting to compare the co-distribution of subset PSQD consisting of sequences with central precipitation equal to, or greater than, 14.50 inches with those of PSQ100Y. Of the 38 members of subset PSQD of the primary data set PSQ, 17 also belong to data set PSQ100Y. This indicates that for the other 21 sequences in subset PSQD, precipitation on central days were smaller than the 100-year 24-hour precipitation at their respective stations. However, when precipitation in the days surrounding day 16 were added to P16, the total central amounts became equal to, or greater than, 14.50 inches and led to these 21 sequences being classified into PSQD.

5.2 Precipitation Sequences of 21- and 13-day Periods

The data screening procedure applied to the climatological precipitation records of the region was modified so that if for any day found with daily precipitation equal to, or exceeding, the 10-year 24-hour amount for that station, a 21-day and a 13-day sequence were extracted centered on that central day. These two new data sets of 1051 21-day and 13-day sequences with the central day specified as day 11 and 7, in turn, are designated as PSQ21 and PSQ13, respectively. As in data set PSQ, the central

Table 20. Comparisons of means of selected parameters among PSQ, PSQ21, and PSQ13, units are inches for P16/11/7 to PSUMT, days for CSLEN to TLENT, and percent for ratio parameters from CRTOA to TRTOT.

	PSQ	PSQ21	PSQ13
P16/11/7	5.89	5.89	5.89
CSAMT	7.22	7.22	7.20
WAMTA	.80	.71	.44
RAMTA	.92	.34	.05
WAMTS	.67	.57	.37
RAMTS	.79	.32	.06
TAMTA	1.71	1.04	.49
TAMTS	1.46	.88	.43
TAMTT	3.17	1.93	.92
PSUMT	10.39	9.15	8.14
CSLEN	2.75	2.75	2.69
DLENA	4.66	4.18	3.22
DLENS	5.52	4.73	3.46
WLENA	1.51	1.33	.90
WLENS	1.42	1.21	.75
TLENT	21.97	14.38	8.39
CRTOA	11.8	10.4	6.5
CRTOS	10.1	8.6	5.8
CRTOT	21.9	19.0	12.2
TRTOA	25.5	15.4	7.3
TRTOS	22.4	13.8	6.7
TRTOT	47.9	29.2	14.0

days were selected applying exactly the same precipitation thresholds, but the span of sequence lengths was shortened from 31 days to 21 or 13 days. Comparisons between some parameters in data sets PSQ, PSQ21 and PSQ13 are shown in Table 20.

Table 20 shows that the procedure for creating data sets PSQ21 and PSQ13 did not affect the central day amount which remains 5.89 inches. This is to be expected since by definition, P16, P11 and P7 of data sets PSQ, PSQ21 and PSQ13, respectively, are identical. Because the longest central wet period in the original full data set happened to be 10 days, the parameters CSAMT and CSLEN were fortuitously not altered in data set PSQ21. However, in data set PSQ13, the effect of truncation began to show. Depending on its placement, a central wet period longer than 7 days might become shortened while central precipitation (CSAMT) undergoes a simultaneous decrease. Parameters such as WAMTA, WAMTS, and associated WLENA, WLENS all experienced progressive reduction as length of data sequences contracted from 31 days to 21 and then to 13 days. The substantial decreases in

RAMTA and RAMTS are not surprising. These are the rainfall totals of the antecedent and subsequent rainfall, excluding the first antecedent or subsequent wet periods. Considerable portions of these amounts were located at the extreme ends of the original 31-day sequences. The much larger reduction in RAMTA compared with that in RAMTS might be partially explained by the fact that more rain fell in days 1-5 than in days 27-31, and more rain fell in days 1-9 than in days 23-31 in the original 31-day sequences. All such decreases led to corresponding reductions in antecedent precipitation (TAMTA), subsequent precipitation (TAMTS), and their sum (TAMTT); and all ratio parameters, such as CRTOA, CRTOS, CRTOT, TRTOA, TRTOS, and TRTOT in PSQ21 and PSQ13 as compared with corresponding parameters in PSQ. However, the parameter that experienced the greatest changes, as could be expected, happened to be total number of dry days (TLENT), as it plunged from about 22 days in PSQ to about 14.4 and 8.4 in PSQ21 and PSQ13, respectively.

Recall that PSUMT is defined as the total sum of all precipitation in a sequence. A shortening of sequence length from 31 to 21 and then to 13 days reduced the mean total sequence precipitation from 10.39 to 9.15 and then to 8.14 inches, respectively. In other words, a shortening of PSQ sequence length by 32 and 58 percent reduced PSUMT by approximately 12 and 22 percent, respectively. This suggests that in the original PSQ set, 88 percent of the precipitation was distributed in days 6 to 26 and preserved by PSQ21 while the remaining 12 percent was contained in the two 5-day periods of days 1 to 5 and 27 to 31. Similarly, it also indicates that in the PSQ set, 78 percent of the precipitation occurred in the 13 day period from day 10 to day 22 and preserved by PSQ13, while 22 percent was in two 9-day periods of days 1 to 9 and 23 to 31.

The immediate antecedent dry period (DLENA) and the immediate subsequent dry period (DLENS) also became smaller due to truncation, with larger (smaller) reductions taking place in DLENS (DLENA). In view of the unequal decreases, it is possible that the hypothesis which is valid for the PSQ set; i.e., that DLENA is significantly smaller than DLENS, may no longer be valid for PSQ21 and PSQ13. To resolve whether this is actually the case, a paired Student t-test was applied successively to data sets PSQ21 and PSQ13 to test the null hypothesis that there is essentially no difference between expected values of DLENA and DLENS in each data set. The appropriate test variable is the expected difference DDLEN between these two contiguous dry periods. The test results are summarized in Table 21.

Table 21. Results for the test for the null hypothesis: there is no difference in durations between immediate antecedent and immediate subsequent dry periods or DDLEN=0.

mean	s.d.	sum	s.e.m.	c.v.	skew	t	s.p.
		Data set PSQ21 (N=1051)					
-.5442	4.132	-572	.1275	-759.210	.1287	-4.27	.0001
		Data set PSQ13 (N=1051)					
-.2483	2.465	-261	.0760	-932.623	.1435	-3.27	.0011

The fact that the means and sums of DDLEN are considerably different from zero suggests that DLENA and DLENS may not have the same magnitude. Under the null hypothesis that DDLEN is zero, the probability of getting a Student t-statistic with absolute value larger than 4.27 is .0001 for data set PSQ21; while the probability of getting one with absolute value larger than 3.27 is .0011 for data set PSQ13. Therefore, the null hypothesis should be rejected. The alternate hypothesis that the expected duration of the contiguous antecedent dry period is significantly shorter than that of the contiguous subsequent dry period is accepted. This conclusion is valid for both data sets PSQ21 and PSQ13. Even though the precipitation sequence lengths were reduced from 31 to 21 and then to 13 days, the significant differences between the antecedent and subsequent contiguous dry period durations were preserved.

A typical sequence of five events centered around the central rainy stretch consists of an antecedent wet period, followed in succession by a contiguous antecedent dry period, the central wet period, a contiguous subsequent dry period and a subsequent wet period. Such a typical scenario would extend over approximately 16 days on the average for the region under study. These events do not distribute symmetrically with respect to the day with maximum precipitation or central day. To properly investigate the relations between the antecedent and the main events, it is imperative to examine what is going on over a duration considerably longer than 16 days. The original sequences of 31 days meet this requirement. A sampling length less than 24 days or one-and-a-half times the average time span for the evolution of the five events is inadequate to capture the full essence of relations among these events. If the sequence length were further reduced to less than the average time span of 16 days, for example to 11 or 9 days, any findings regarding the relations between events would most likely be seriously biased because the short sampling lengths are not able to provide sufficient time resolutions.

5.3 Characteristics of PSQT and PSQRT

Examination of the full data set PSQ reveals that the precipitation in the central wet period extends over a very wide range. Since in many applications one is primarily concerned with storms with heavy rainfalls, it is appropriate to determine the consequence of eliminating those storms with only moderate rains from the data sample. For convenience, the central precipitation observations are classified into two groups. A main storm with precipitation greater than 6.00 inches is defined as a substantial storm, otherwise it is defined as a moderate storm. This criterion is not completely arbitrary. The results shown in section 4.4 do point out that there is a qualitative difference between these storms in their respective relationships with antecedent precipitation. Once all storms in data sets PSQ and PSQR with central precipitations less than or equal to 6.00 inches were deleted, two new truncated data sets PSQT and PSQRT containing 620 and 304 sequences respectively were created. In the case of PSQT, this procedure is equivalent to the elimination of subset PSQA from the full data set PSQ.

5.3.1 Correlation Analysis

The Pearson correlation coefficients between central precipitation (CSAMT) and other parameters for data sets PSQT and PSQRT are shown in Table 22, while those between central wet duration (CSLEN) and the same parameters are shown in Table 23. For comparison, one should consult Tables 8 and 9 for the corresponding correlation coefficients for the untruncated data sets PSQ and PSQR.

Again a more stringent significance probability of .01 is chosen as the criterion of significance. Cases with significance probabilities greater than .01 are considered to be not significant. Furthermore a parameter is considered significantly correlated with central precipitation only if this is true for both data set PSQT and PSQRT.

Recall that data sets PSQT and PSQRT are derived from PSQ and PSQR respectively, by eliminating all sequences with moderate central precipitation. In other words, data sets PSQT and PSQRT contain only sequences with substantial central precipitation.

Table 22. Correlations between central period precipitation CSAMT and selected parameters in two data sets with CSAMT > 6.00 inches.

	PSQT (N = 620)		PSQRT (N = 304)	
	Correlation Coefficient	Significant Probability	Correlation Coefficient	Significant Probability
P16	.552	.0001	.595	.0001
CSAMX	.872	.0001	.821	.0001
WAMTA	-.007	.8558	.104	.0702
WAMTS	.020	.6110	.011	.8458
WAMTT	.007	.8566	.072	.2109
RAMTA	-.0001	.9975	.030	.6065
RAMTS	-.090	.0250	-.035	.5437
TAMTA	-.005	.8941	.084	.1443
TAMTS	-.051	.2050	-.017	.7621
TAMTT	-.037	.3547	.043	.4549
NBRDP	-.091	.0232	-.041	.4756
CSLEN	.465	.0001	.430	.0001
CDPOS	.399	.0001	.299	.0001
DLENA	-.187	.0001	-.147	.0102
DLENS	-.041	.3101	-.068	.2370
WLENA	.071	.0769	.116	.0437
WLENS	.056	.1607	.053	.3579
TLENA	-.222	.0001	-.175	.0022
TLENS	-.101	.0122	-.171	.0029
TLENT	-.214	.0001	-.216	.0001
CRTOA	-.163	.0001	-.098	.0867
CRTOS	-.149	.0002	-.125	.0292
CRTOT	-.214	.0001	-.150	.0088
TRTOA	-.230	.0001	-.155	.0069
TRTOS	-.234	.0001	-.178	.0019
TRTOT	-.313	.0001	-.220	.0001

The correlation results in Table 22 are for data sets PSQT and PSQRT and should be compared with that of Table 8 for data sets PSQ and PSQR. Comparing Table 22 with Table 8, the following conclusions can be made regarding correlations between central precipitation (CSAMT) and other parameters:

The high to medium correlations with parameters that are component parts of CSAMT such as P16 and CSAMX are preserved as expected.

The modest positive or negative correlations with duration parameters that are obviously physically related to CSAMT are also maintained. These include duration of central wet period (CSLEN), position of day 16 in the central wet period (CDPOS), number of antecedent dry days (TLENA), number of subsequent dry days (TLENS), and their sum (TLENT).The slightly negative correlations with the ratio parameters are generally retained. These include the ratio of precipitation in the two contiguous wet periods to central precipitation (CRTOT), ratio of antecedent to central precipitation (TRTOA), ratio of subsequent to central precipitation (TRTOS), ratio of total antecedent and subsequent precipitation to central precipitation (TRTOT).

The most drastic change is that there is no longer any linear correlation between central precipitation (CSAMT) and any and all parameters representing antecedent precipitation starting from row 3 up to row 8 of Table 22. Of particular consequence is the fact that the total antecedent precipitation (TAMTT) is no longer statistically related to the central precipitation when only sequences with substantial storms are concerned. Therefore, it can be concluded that the slight, but significant, correlations between antecedent precipitation and central precipitation in the full data set PSQ shown in Table 8 previously are entirely due to the presence of sequences with moderate storms. Once these sequences are removed as in data set PSQT, no significant correlation can be detected between central amount (CSAMT) and the total antecedent and subsequent precipitation (TAMTT). Previous results in Table 8 also indicated a large negative correlation between the central amount (CSAMT) and the ratio of total antecedent and subsequent precipitation to central amount (TRTOT), in addition to a slight positive correlation between CSAMT and TAMTT and for both data sets PSQ and PSQR. However, if only storms with central precipitation depth greater than 6.00 inches are considered, then the previous duality vanishes and only an unambiguously significant negative correlation between CSAMT and TRTOT remains as shown in Table 23.

The most crucial fact is that for sequences with substantial central storms, total antecedent precipitation is no longer in any sense statistically related to central precipitation. This is one of the key findings of the investigation.

Comparing the correlation results for data set PSQ in Table 9, with Table 23 the large to moderate positive correlation between CSLEN and the following parameters are preserved in data sets PSQT and PSQRT: CSAMX, CSAMT, and CDPOS. There is no longer any correlations with P16, DLENA, CRTOT and TRTOS. The significant negative correlation with these parameters remain unaltered: DLENS, TLENA, TLENS, TLENT, TRTOA, and TRTOT.

Table 23. Correlations between central wet duration CSLEN and selected parameters in two data sets with CSAMT > 6.00 inches.

	PSQT (N = 620)		PSQRT (N = 304)	
	Correlation Coefficient	Significant Probability	Correlation Coefficient	Significant Probability
P16	-.078	.0535	-.069	.2286
CSAMX	.601	.0001	.585	.0001
CSAMT	.465	.0001	.430	.0001
WAMTA	-.094	.0195	.015	.7970
WAMTS	-.105	.0087	-.042	.4654
WAMTT	-.137	.0006	-.022	.7063
RAMTA	-.058	.1479	-.071	.2163
RAMTS	-.061	.1324	-.050	.3875
TAMTA	-.113	.0048	-.053	.3616
TAMTS	-.113	.0047	-.062	.2813
TAMTT	-.157	.0001	-.077	.1807
NBRDP	-.070	.0811	-.028	.6263
CDPOS	.689	.0001	.592	.0001
DLENA	-.139	.0005	-.138	.0160
DLENS	-.152	.0001	-.196	.0006
WLENA	.058	.1483	.101	.0783
WLENS	.036	.3699	.097	.0921
TLENA	-.318	.0001	-.265	.0001
TLENS	-.421	.0001	-.521	.0001
TLENT	-.492	.0001	-.497	.0001
CRTOA	-.168	.0001	-.087	.1287
CRTOS	-.171	.0001	-.102	.0755
CRTOT	-.231	.0001	-.127	.0273
TRTOA	-.215	.0001	-.149	.0094
TRTOS	-.197	.0001	-.141	.0141
TRTOT	-.280	.0001	-.191	.0008

5.3.2 Monthly Distributions

The monthly distributions of sequences in data sets PSQT and PSQRT are shown in Table 24. Such distribution for the primary data set PSQ is also included as a frame of reference. PSQT and PSQRT both have central storm amounts of 6 inches or less. However, PSQT is developed from all storm sequences (PSQ), and PSQRT is developed from the storm set PSQR which only allows no more than one sequence to represent a storm.

Comparing the number of cases between data sets PSQT and PSQRT, the largest proportional reductions occurred in October, December, November and September in descending order. These months are characterized by lowered frequency of convective

Table 24. Monthly distribution of sequences

	PSQ	PSQT	PSQRT
January	4	4	4
February	3	2	2
March	4	4	3
April	26	9	7
May	161	76	45
June	173	99	52
July	191	104	55
August	122	44	32
September	203	145	62
October	125	96	28
November	27	25	10
December	12	12	4
Total	1051	620	304

activity. This observation indicates that these are the favored months for large scale storms to occur over the region of interest. For the 96 storm sequences in October in data set PSQT, many were associated with extratropical cyclones covering large areas (Table 24). When they were screened by a procedure that any storm could only be represented by one sequence on any one day, N decreased from 96 to 28.

5.3.3 Total Antecedent Precipitation (TAMTT)

Besides the two key parameters mentioned previously, the parameter TAMTT representing total antecedent and subsequent precipitation is also of particular interest. Its correlation with selected parameters are shown in Table 25.

The same conservative approach used in previous correlation analysis is adopted, that correlation between TAMTT and a parameter exists only if their correlation coefficients are not greater than .01 in both data sets PSQT and PSQRT.

By this stringent criterion, the total antecedent and subsequent precipitation (TAMTT) is:

- positively correlated with the number of dry periods in a sequence (NBRDP) and as expected with its ratio to the central precipitation (TRTOT);

Table 25. Correlations between total antecedent and subsequent precipitation TAMTT and selected parameters in two data sets with CSAMT > 6.00 inches.

	PSQT (N = 620)		PSQRT (N = 304)	
	Correlation Coefficient	Significant Probability	Correlation Coefficient	Significant Probability
P16	.109	.0064	.131	.0225
CSAMX	-.109	.0067	.040	.4915
CSAMT	-.037	.3547	.043	.4549
NBRDP	.450	.0001	.512	.0001
CSLEN	-.157	.0001	-.077	.1807
CDPOS	-.116	.0039	.042	.4619
DLENA	-.339	.0001	-.382	.0001
DLENS	-.255	.0001	-.329	.0001
TLENT	-.478	.0001	-.566	.0001
TRTOT	.929	.0001	.940	.0001

- negatively correlated with the duration of immediate antecedent dry period (DLENA), the duration of immediate subsequent dry period (DLENS) and the total number of dry days in a sequence (TLENT);

- not statistically correlated to precipitation on central day (P16), precipitation on days in the central wet period other than day 16 (CSAMX), total precipitation in central wet period (CSAMT), duration of central wet period (CSLEN), and position of day 16 in central wet period (CDPOS).

These results have plausible physical explanations. For example, the parameter NBRDP, denoting number of dry periods in a sequence, is also an approximate measure of the number of wet periods in a sequence. Because dry and wet periods alternate, the number of wet periods is either equal to NBRDP or differs by one. The more numerous the wet periods are, the larger the total antecedent precipitation (TAMTT) would likely be. Similar explanation for other parameters will not be presented here for the sake of brevity.

The most crucial finding is the fact that for data sets composed of sequences with precipitation exceeding 6.00 inches in the central storm, there is a complete lack of a statistical relationship between precipitation in the central wet period and the total antecedent and subsequent precipitation.

5.3.4 Distribution of Parameters on CSLEN

For data sets PSQT and PSQRT, the distributions of amount parameters P16, CSAMX, CSAMT and duration parameter DLENA with respect to CSLEN are summarized in Tables 26 and 27, respectively, which should be compared with Table 5, (page 27).

In both truncated data sets (PSQRT, Tables 26 and 27) as the duration of central wet period increases there is a corresponding steady increase in the sum of the central wet precipitation excluding the central day (CSAMX). This compensates for the slight fluctuations in P16 and enables the central amount (CSAMT) to maintain a positive trend up to at least a central wet duration of 6 days. The distribution of the mean total antecedent precipitation (TAMTT) shows a local maximum when the central wet period is two days. The immediate antecedent dry period duration (DLENA) shows irregular fluctuations amid a general tendency to decline as the duration of central wet period increases. These observed patterns in data sets PSQT and PSQRT are quite similar to those depicted in Table 5 for the full data set PSQ.

Table 26. Distributions of selected parameters with CSLEN in data set PSQT.

CSLEN	N	P16 (day)	CSAMX (inch)	CSAMT (inch)	TAMTT (inch)	DLENA (day)
1	76	7.05	0	7.05	3.28	5.76
2	196	6.99	0.98	7.98	4.25	4.58
3	137	6.79	1.91	8.69	3.45	4.13
4	68	6.99	2.57	9.56	3.48	4.24
5	59	7.01	3.51	10.52	3.39	3.93
6	47	6.91	5.67	12.58	2.71	3.34
≥7	37	6.30	4.45	10.75	2.50	3.57

Table 27. Distributions of selected parameters with CSLEN in data set PSQRT.

CSLEN	N	P16 (day)	CSAMX (inch)	CSAMT (inch)	TAMTT (inch)	DLENA (day)
1	47	7.08	0	7.08	2.77	5.77
2	109	7.08	1.10	8.17	4.10	4.42
3	62	6.80	1.91	8.71	3.04	4.98
4	37	6.89	2.43	9.32	3.49	4.35
5	21	7.21	3.52	10.73	3.90	3.19
6	12	6.48	5.02	11.50	3.34	4.08
≥7	16	6.73	5.15	11.88	2.07	3.19

5.3.5 Differences Between Antecedent and Subsequent Events

The presence in the full data set PSQ of many storms with moderate precipitation might dilute, or even mask potentially important features possessed by the stronger storms. Regarding data set PSQT (CSAMT> 6.00 inches), this concern is no longer a factor and more intensive probing is carried out. For this purpose, a set of difference parameters are defined as follows:

DWAMT = WAMTA - WAMTS
DRAMT = RAMTA - RAMTS
DTAMT = TAMTA - TAMTS
DTLEN = TLENA - TLENS.

Together with DDLEN (DLENA - DLENS) defined previously, they constitute a set of five derived parameters representing the differences in distributions between the antecedent and subsequent cases.

Using these five parameters computed from data sets PSQT and PSQRT as inputs, a series of paired Student t-Test were run and the results are shown in Tables 28 and 29.

Even by adhering to a more stringent significance probability of.02 instead of the conventional .05 for t tests, the following conclusions can be drawn from Table 28 for data set PSQT which contains 620 precipitation sequences with central amounts greater than 6.00 inches:

1. The expected value of WAMTA is significantly larger than that of WAMTS. Here WAMTA (WAMTS) is the precipitation in the wet period separated from the main storm by one antecedent (subsequent) dry period.

2. The expected value of RAMTA is significantly larger than that of RAMTS. Here RAMTA (RAMTS) is the antecedent (subsequent) precipitation of a sequence excluding precipitation in the immediate antecedent (subsequent) wet period.

Table 28. Paired t-Test results for five null hypotheses: DWAMT=0, DRAMT=0, DTAMT=0, DTLEN=0, and DDLEN=0 for data set PSQT (N=620) composed of PSQ sequences with central period precipitation exceeding 6.00 inches only.

	mean	s.d.	sum	s.e.m.	c.v.	skew	t	s.p.
DWAMT	.1656	1.6731	102.66	.0672	1010.4	.7510	2.46	.0140
DRAMT	.2392	1.8011	148.30	.0723	753.0	.6426	3.31	.0010
DTAMT	.4048	2.3964	250.96	.0962	592.0	.1618	4.21	.0001
DTLEN	-.2387	2.9472	-148.00	.1184	-1234.6	.1818	-2.02	.0442
DDLEN	-1.1048	5.3180	-685.00	.2136	-481.3	.1314	-5.17	.0001

Table 29. Paired t-Test results for five null hypotheses: DWAMT=0, DRAMT=0, DTAMT=0, DTLEN=0 and DDLEN=0 for data set PSQRT (n=304) composed of PSQR sequences with central wet period precipitation exceeding 6.00 inches only.

	mean	s.d.	sum	s.e.m.	c.v.	skew	t	s.p.
DWAMT	-.0501	1.4116	15.24	.0810	-2815.7	-.4768	-.62	.5362
DRAMT	.1073	1.8251	32.62	.1047	1700.9	.9689	1.03	.3061
DTAMT	.5717	2.3133	17.38	.1327	4046.4	.0863	.43	.6668
DTLEN	-.0296	2.8207	-9.00	.1618	-9527.6	.4185	-.18	.8549
DDLEN	-.8980	5.2173	-273.0	.2992	-580.9	-.0725	-3.00	.0029

3. The expected value of TAMTA is significantly larger than that of TAMTS. Here TAMTA (TAMTS) is the total antecedent (subsequent) precipitation of a sequence.

4. The expected magnitude of DLENA is significantly shorter than that of DLENS. Here DLENA (DLENS) is the duration of the immediate antecedent (subsequent) dry period.

These are key characteristics of data set PSQT. The first three features are not evident in the full set PSQ because of the masking effect by lesser storms. Once those storms are excluded, these three features come sharply into focus in data set PSQT, composed of sequences with central precipitation greater than 6.00 inches. Feature 4 represents a reaffirmation of a recurring theme, that the antecedent dry period is principally shorter than the subsequent dry period. Thus far, this remains valid for all data sets that have been tested.

For data set PSQRT, the paired sample Student t-test results shown in Table 29 are quite different from those for data set PSQT shown in Table 28. The only valid finding is that the expected duration of the contiguous antecedent dry period is significantly shorter than that of the contiguous subsequent dry period. Other than that, there is no significant difference in magnitudes between WAMTA and WAMTS, between RAMTA and RAMTS, and between TAMTA and TAMTS in data set PSQRT. However, if the paired sample Student t-Test were applied to data set PSQR before truncation, one would arrive at the same conclusion. Thus, the removal of storms with central precipitation ≤ 6.00 inches does not affect the test result.

Therefore, it appears that the significant differences in the expected values of antecedent versus subsequent parameters shown in Table 28 are due to the weighting of large-storm contributions. In PSQ, the weighting is caused by representing a large storm by multiple sequences over a wide area. Once storms with moderate rainfalls are removed to form data set PSQT, the large-storm phenomena become dominant. Significant differences in the expected values between WAMTA and WAMTS, between RAMTA and RAMTS, and between TAMTA and TAMTS become prominent. In data set PSQR, the weighting had been eliminated because only one sequence on a particular day was permitted to represent a storm no matter how large its areal extent. After storms with moderate rainfalls were eliminated to form data set PSQRT, no change in test results occurred because large-storm weighting was absent in the beginning.

It should be pointed out that the significant difference between the expected durations of DLENA and DLENS is again unmistakably present in both data sets PSQT and PSQRT.

5.4 Experiment with Modified Sequences

In all work so far, the conventional meteorological definition of rain with a threshold value of .01 inch was applied. Any day with observed amount equal to, or greater than, .01 inc considered as a wet day, otherwise it is a dry day. Since daily amounts of .01 or .02 inch etc., hardly constitute a major contribution in a significant storm event, an experiment was conducted to raise the demarcation threshold for a wet day to a considerably higher level, i.e., .21 inch to see how the precipitation sequences would be affected. The characteristics of the 31-day sequences became altered and the resulting data set is defined as PSQM set, here "M" stands for modified. Comparisons of selected amount and duration parameters between data sets PSQ and PSQM are shown in Table 30. Here PSQM represents the modified data set with the raised rain-threshold of .21 inch.

With this newly defined higher threshold of appreciable rain, some tangible changes in the distribution of parameters can be observed. The average number of dry days in a 31-day sequence (TLENT) increased from 21.97 to 25.44, for a gain of 3.47 dry days. At the same time, the immediate antecedent dry period duration (DLENA) increased from 4.66 to 6.94 days, while the corresponding subsequent dry duration (DLENS) increased from 5.52 to 7.61 days. These added up to a combined increase in contiguous dry periods of 4.37 days which exceeded the total increases of 3.47 dry days in a sequence. This seeming inconsistency can be explained by the fact that changes in the durations of contiguous dry periods are primarily caused by the realignment of the dry days and are only marginally affected by the increases in their total numbers. There is no one-to-one correspondence between these two features. Setting a day with precipitation less than .21 inches to zero adds to the number of dry days in the sequence by one. Depending on the relative position of that particular day with respect to the central wet period, the immediate antecedent or subsequent dry period could either increase or decrease by one day or by several days, or remain the same.

Table 30. Comparisons of means of selected parameters between data sets PSQ and PSQM. Units are inches for ten parameters from P16 to PSUMT, and days for nine parameters from TLENA to DDLEN.

	PSQ	PSQM
P16	5.89	5.89
CSAMT	7.22	6.94
WAMTA	.80	1.02
RAMTA	.92	.69
WAMTS	.67	.86
RAMTS	.79	.58
TAMTA	1.71	1.71
TAMTS	1.46	1.44
TAMTT	3.17	3.15
PSUMT	10.39	10.09
TLENA	10.89	12.65
TLENS	11.08	12.79
TLENT	21.97	25.44
DLENA	4.66	6.94
DLENS	5.52	7.61
WLENA	1.51	1.08
WLENS	1.42	1.02
CSLEN	2.75	1.91
DDLEN	-.86	-.67

The precipitation in the central wet period (CSAMT) decreased from 7.22 to 6.94 inches; while the contiguous antecedent and subsequent amounts WAMTA and WAMTS increased from .80 to 1.02 and from .67 to .86 inches, respectively. Because of the required higher threshold of .21 inches, some central precipitation events were either truncated, broken up, or both, and rains were redistributed into WAMTA and/or WAMTS categories as the central wet duration decreased from 2.75 to 1.91 days. The sum total of precipitation amounts, or PSUMT, for the 31-day sequences decreased from a mean of 10.39 to 10.09 inches; a reduction of less than 3 percent. In other words, over 97 percent of the average total rainfall of a sequence is contributed by precipitation greater than .20 inches. Raising the threshold of appreciable rain to .21 inches led to some regrouping of precipitation events, but only a slight reduction of the total precipitation in a sequence. Comparisons between the distributions of the duration of the central wet period (CSLEN), for the two data sets PSQ and PSQM are shown in Table 31.

Ratio in Table 31 is defined as [(N for PSQM)/(N for PSQ)]. Raising the threshold for appreciable rain from .01 to .21 inches caused a 92-percent increase in the number of cases where the central wet period lasts for only one day. At the same time, proportionally more substantial decreases occurred in the number of cases as CSLEN becomes longer. This is the result of breaking up the central wet periods in the original sequences into wet periods of shorter durations in the PSQM data set. For the case where central wet duration is two days, there is only a reduction of less than two percent. Because even as the break up of the original two-day wet periods occurred, some new two-day cases are generated due to the fragmentation of wet periods of 3 days or longer. This process went on and, as CSLEN increased, the attrition became progressively more pronounced. When one reached the category of longer duration of seven or more days, where no new member could be added, a 95-percent reduction in frequency resulted.

Table 31. Distribution of N on CSLEN (days)

CSLEN	PSQ	PSQM	PSQM/PSQ
1	241	463	1.921
2	359	353	.983
3	195	149	.764
4	97	47	.485
5	69	29	.420
6	51	8	.157
≥7	39	2	.051

Table 32. Result of paired t-Test for null hypothesis DDLEN=0 for modified data set PSQM (N=1051)

mean	s.d.	sum	s.e.m.	c.v.	skew	t	s.p.
-.6746	6.6231	-709	.2043	-981.79	.2069	-3.30	.0010

Parameter DDLEN for the data set PSQM is calculated and again the question: "Are the expected values of the parameters DLENA and DLENS equal?" is raised. A paired-sample Student t-test is applied and results are shown in Table 32.

Under the null hypothesis that DDLEN is zero, the probability of getting a Student t-statistic with absolute value larger than 3.30 is .001 for data set PSQM. Therefore, the null hypothesis should be rejected. The alternate hypothesis that the expected duration of the contiguous antecedent dry period is significantly shorter than that of the contiguous subsequent dry period is accepted. It is important to note that this conclusion applies to all five data sets consisting of 31-day sequences; PSQ, PSQR, PSQT, PSQRT and PSQM, as well as data sets consisting of shorter sequences PSQ21 and PSQ13.

Additional experimentations to raise the wet-day threshold to .31 inch, .41 inch, and so on, were carried out. The results generally follow the trend set by PSQM and, therefore, are not presented here.

6. PRECIPITATION RATIOS AND PROFILE OF EVENTS

6.1 Distribution of Ratios of Antecedent to Central Precipitation

Recall that a set of ratio parameters is defined as follows:

CRTOA = WAMTA/CSAMT
CRTOS = WAMTS/CSAMT
CRTOT = WAMTT/CSAMT

TRTOA = TAMTA/CSAMT
TRTOS = TAMTS/CSAMT
TRTOT = TAMTT/CSAMT.

The mean (Table 33) and 0.75 quantile (Table 34) values of these ratio parameters in percent are shown for data sets PSQ, PSQR and the four subsets of PSQ, i.e., PSQA to PSQD. The general tendency for these ratios to decrease from PSQA to PSQD as the sample central precipitation increase is conspicuous. The distributions of the mean and 0.75 quartiles of CRTOT and TRTOT with the four subsets of PSQ and with PSQ and PSQR are shown in Figures 14 and 15, respectively.

The most conspicuous and important characteristic revealed in Tables 33 and 34 are the steady decreases of the ratio of total antecedent precipitation to that in the central wet period (TRTOT), as central precipitation of the subsets increases. The mean ratio decreases from 54.6, successively to 49.4, 31.6 and 18.9 percent from subsets PSQA through PSQD, respectively, while the 0.75 quartile value reduced from 75.2 successively to 69.3, 44.5 and 27.6 percent from subsets PSQA through PSQD. This feature represents a fundamental relationship between the central precipitation and its antecedent precipitation.

Table 33. Distributions of the mean of precipitation ratio parameters in percent.

	PSQA	PSQB	PSQC	PSQD	PSQ	PSQR
CRTOA	12.2	13.3	7.8	6.4	11.8	10.1
CRTOS	11.0	10.7	7.2	4.3	10.0	10.4
CRTOT	23.2	24.0	15.0	10.7	21.9	20.5
TRTOA	27.7	27.3	17.3	12.2	25.5	22.3
TRTOS	26.9	22.1	14.3	6.7	22.4	23.2
TRTOT	54.6	49.4	31.6	18.9	47.9	45.5

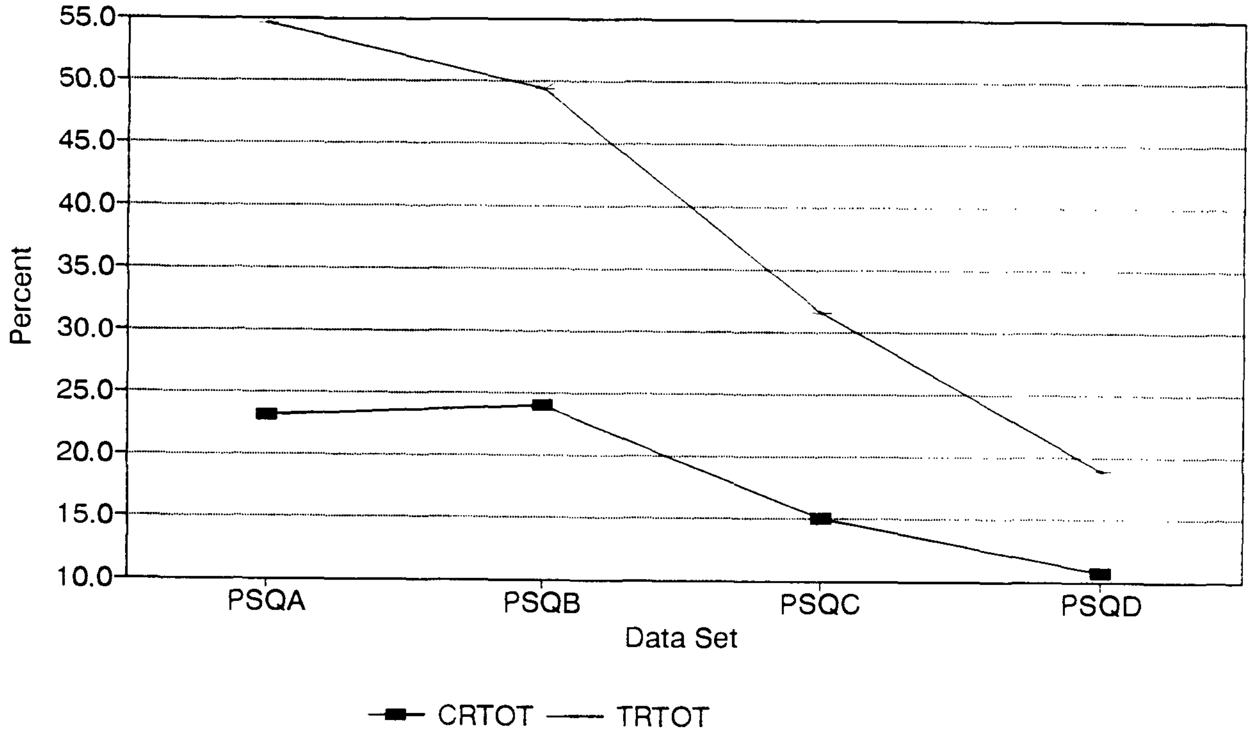

Figure 14.--Distribution of the means of the ratio parameters CRTOT and TRTOT for subsets PSQA, PSQB, PSQC, and PSQD.

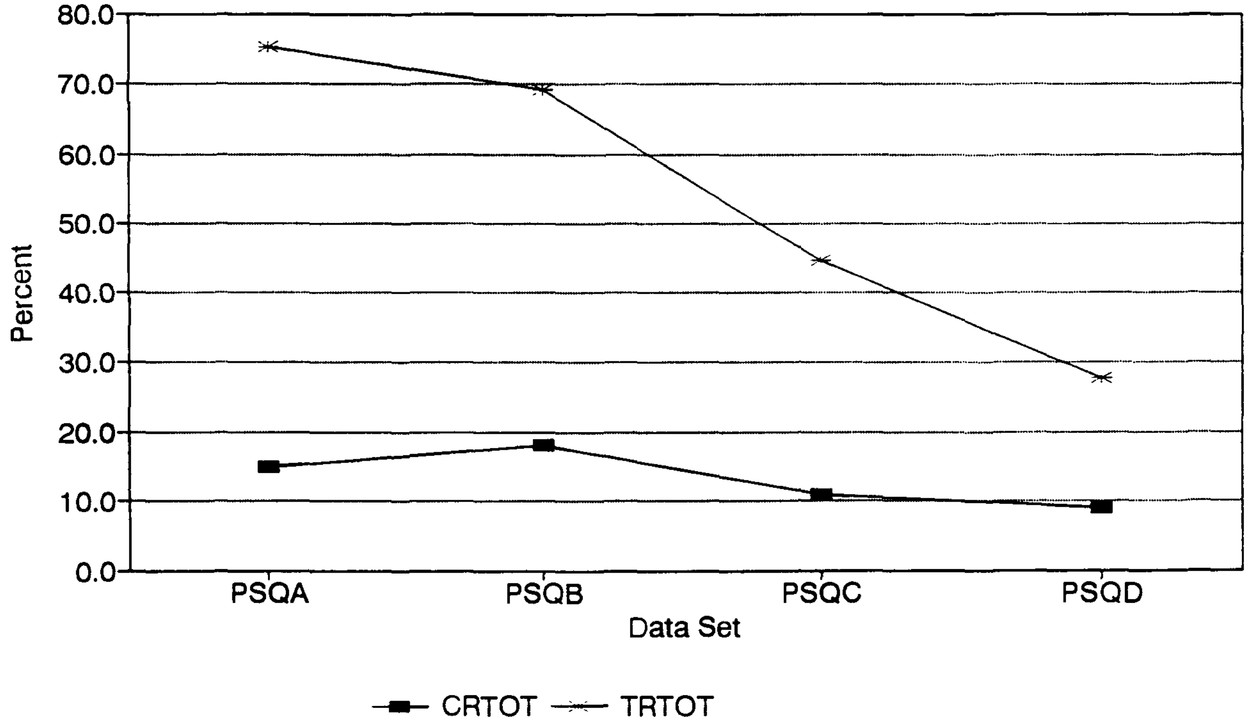

Figure 15.--Distribution of the 0.75 quartiles of the ratio parameters CRTOT and TRTOT for the subsets PSQA, PSQB, PSQC, and PSQD.

Table 34. Distributions of the 0.75 quantiles of precipitation ratio parameters in percent.

	PSQA P≤6.0	PSQB 6.0<P<9.5	PSQC 9.5≤P<14.5	PSQD P≥14.5	PSQ	PSQR
CRTOA	15.2	17.6	11.3	9.0	14.7	13.5
CRTOS	14.2	14.5	8.6	4.9	13.3	14.0
CRTOT	31.9	31.2	22.2	10.9	29.5	27.9
TRTOA	40.3	39.7	26.3	18.9	36.5	31.4
TRTOS	38.6	32.2	23.0	6.6	32.3	34.3
TRTOT	75.2	69.3	44.5	27.6	64.6	62.7

By comparing the magnitudes of TRTOA with those of TRTOS in Table 33 for each data set and forming the ratio (TRTOA/TRTOS), one obtains 1.03, 1.24, 1.21 and 1.82 for subsets PSQA to PSQD, respectively. This can be interpreted that for subset PSQA (≤ 6.00 inches). Little difference exists between the mean antecedent and subsequent precipitation. However for subset PSQD (≥ 14.5 inches), the mean antecedent precipitation is 82 percent greater than the mean subsequent precipitation. The mean precipitation exceeds the subsequent precipitation by 24 and 21 percent for PSQB and PSQC, respectively. This points out that for the central precipitation amounts ≥ 6.00 inches the antecedent precipitation is greater than the subsequent precipitation. Little or no difference was found in the antecedent and subsequent precipitation for central rain amounts less than 6.00 inches. However, as the central amount of precipitation increases the ratios between the antecedent precipitation and subsequent precipitation increases substantially. Thus, there is a substantial difference in rainfall amounts for central storm amounts greater than, or equal to, 14.5 inches.

By comparing the magnitudes of CRTOA versus those of TRTOT within each subset, one can conclude that for PSQD, more than half, or 56.6 percent of the total antecedent precipitation, is contained in the two contiguous wet periods. For data sets PSQA to PSQC the two contiguous wet periods contribute 42.5, 48.6 and 47.5 percent, respectively.

6.2 Profile of Events Surrounding the Central Wet Period

An attempt was made to define a typical sequence of events preceding, including, and following the central event. If one were to quantify these events both by duration and amount (when applicable) concurrently, the data decomposition would cause so much fragmentation that a 'typical' sequence could not be meaningfully defined. To overcome this difficulty, the duration and amount for each event are quantified separately. The means and medians of relevant events surrounding the central precipitation are then concatenated with those of the central event in a time-series fashion to form a "profile of the means" and a "profile of the medians," respectively. It should be emphasized however, that the "profile of the means" represents a best estimate for the mean profile and is not a mean profile per se. No claim is made that such a profile provides a rigorous measure of exact central location. The same cautionary remarks also apply to the interpretation of the "profile of medians." These profiles are presented in Figures 16 and 17.

Schematic profiles for the means and medians of selected key parameters of the precipitation sequence are shown in Figures 16 and 17, respectively. The lengths of the segments of the horizontal lines are proportional to various durations (in days) which are denoted beneath, while the corresponding rainfall (in inches) lie above the line. Sketches at the bottoms of Figures 16 and 17 indicate the included parameters for the PSQ precipitation sequence. They are intended also as a reference in interpreting other data sets in the figures. The fractions of days in Figure 16 are the results of averaging process. For example, in Figure 16, the data set PSQD has an average central wet period (CSLEN) of five days, with average central rainfall amount (CSAMT) of 17.30 inches. The central wet period is preceded by an antecedent dry period (DLENA) of 2.53 days and followed by a subsequent dry period (DLENS) of 4.87 days with no rain. Preceding the antecedent dry period is an antecedent wet period (WLENA) of 1.84 days when 1.07 inches of rain (WAMTA) falls. Similarly following the subsequent dry period is a subsequent wet period (WLENS) of 1.68 days with rainfall (WAMTS) of 0.75 inches. It should be noted that these rainfalls are not evenly distributed over their corresponding wet periods. Of the central amount of 17.30 inches (for data set PSQD) 8.78 inch or more than half falls on the central day. The average central day rainfalls (P16) for data sets PSQA, PSQB, PSQC and PSQ are 4.42, 6.45, 7.75 and 5.89 inches, respectively. Similarly, Figure 17 shows that for data set PSQD, the central wet period (CSLEN) has a median of six days, while the central rainfall amount (CSAMT has a median of 16.40 inches. Not shown is the rainfall on the central day (P16) which has a median of 8.48 inches. The median central day rainfalls (P16) for data sets PSQA, PSQB, PSQC and PSQ are 4.40, 6.45, 7.65 and 5.76 inches, respectively.

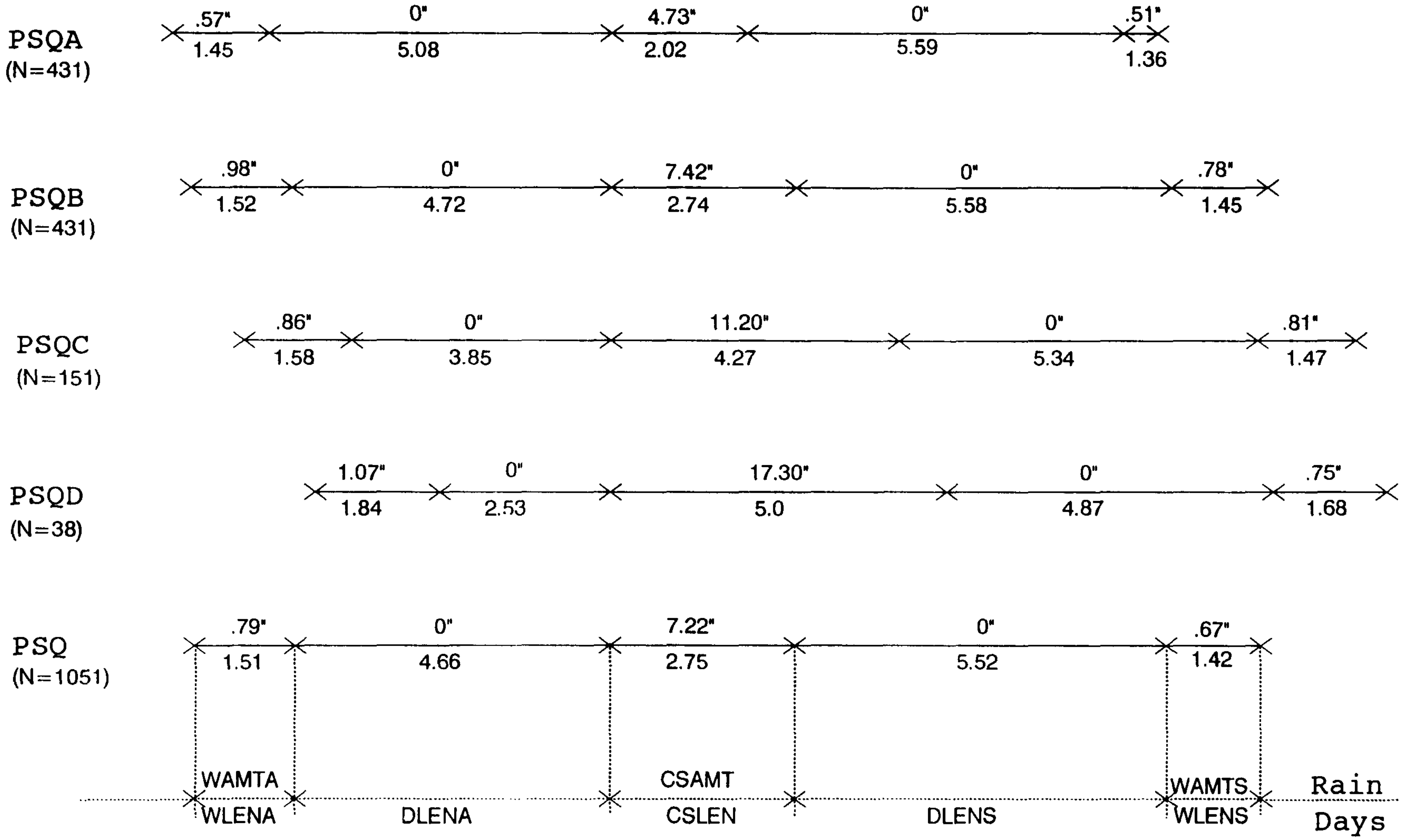

Figure 16.--Schematic profile of the means of selected precipitation events.

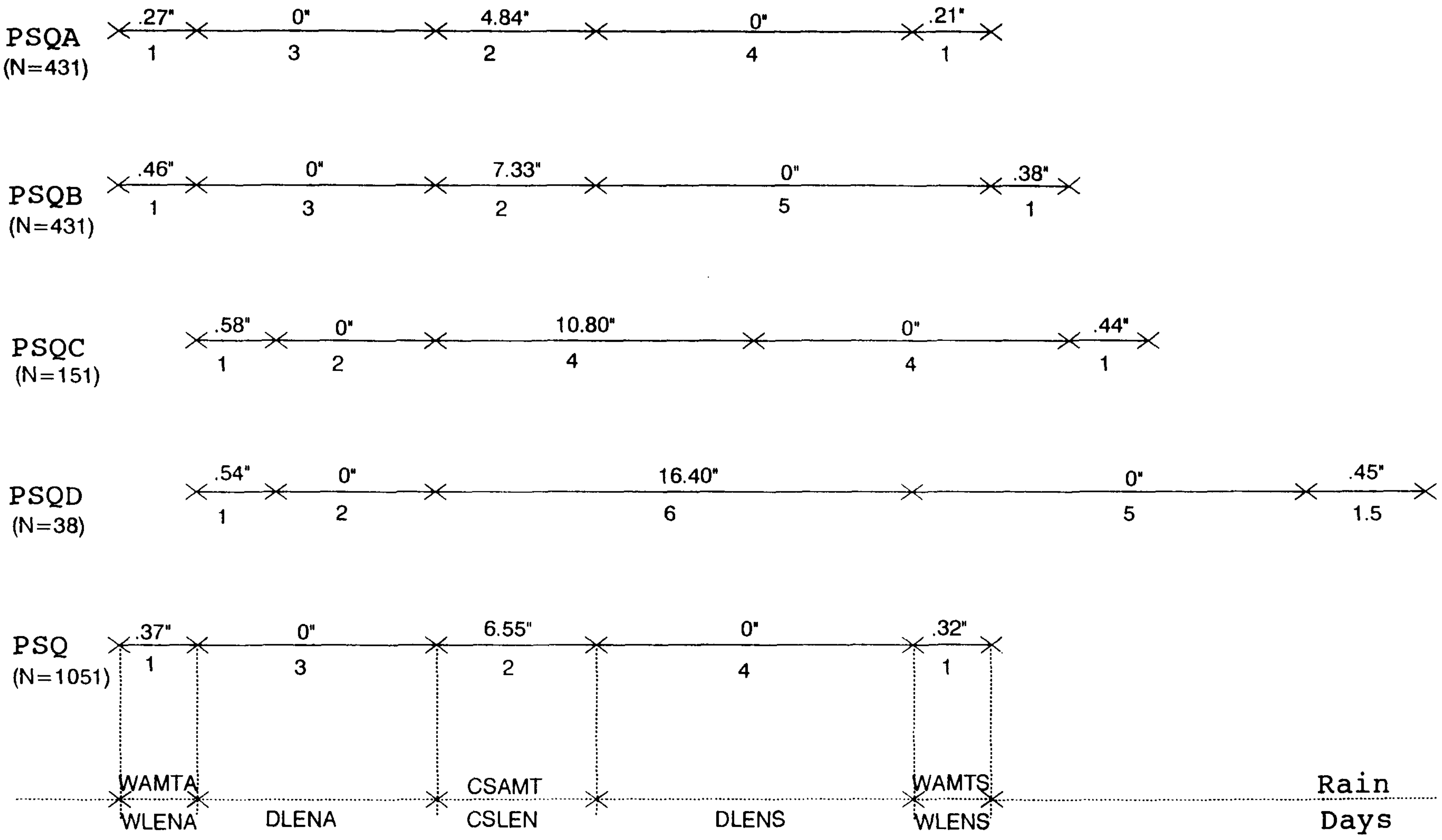

Figure 17.--Schematic profile of the medians of selected precipitation events.

7. CONCLUDING REMARKS

A total of 26,610 station-years of precipitation data covering Kansas, Oklahoma, and eastern Colorado were processed to study the relations between a main storm and its antecedent precipitation. From the base data a variety of data sets were created to address the requirements of the inquiry. The primary data set consists of a total of 1051 31-day precipitation sequences centered on a day with station precipitation equal to, or greater than, the 10-year 24-hour amount. Other data sets were extracted from the source data using higher threshold criteria such as 25-, 50-, and 100-year, 24-hour amounts. From the primary data set, other data sets with different characteristics were also derived to meet specific needs of the investigation. For example, the precipitation sequence lengths were shortened to 21 and 13 days to ascertain the impact of shorter sampling intervals on relationships between events. Among the derived sets, there was a reduced data set with potential data redundancy removed. Most operations were carried out in parallel on both the full and reduced data sets. A modified data set was created by deleting any precipitation less than .21 inch to simulate the effect of ignoring small amounts. Finally, precipitation sequences with central precipitation depths less than, or equal to, 6.00 inches were removed from the primary and the reduced data sets to construct two truncated data sets composed of sequences possessing substantial central precipitation.

All data used in this investigation are observed data. Neither data maximization nor data modification to fit some model were permitted. These analyses used various data sets, which are presented throughout this report. However, the more significant results are summarized into the following conclusions. The proper domain of application of these findings are for small river basins. Areal analysis over a domain of the order of 10^2 square miles was beyond the scope of this investigation. However, this should not preclude the possibility that some of these findings might also have relevance for larger areas.

1. There is no indication that the distributions of the antecedent and subsequent precipitation and dry period separations are in any way symmetric with respect to the central precipitation event. In particular, the distributions of the immediate dry period durations are highly asymmetrical.

2. The average cycle of a storm preceded by an immediate dry period and an antecedent precipitation event, and followed by an immediate dry period and a subsequent precipitation event is about 16 days in the region of interest. In any investigation on the relationships between the main storm and

its antecedent and subsequent precipitation, it is of the utmost importance that one employs a data structure that contains nearly twice the length of the average cycle, such as the 31-day sequence adopted in the current study. This length is required by the asymmetry of events with respect to the central day. For example, if a 10-day sequence was adopted as the basic data structure, then any conclusion reached regarding the relations between the main storm and the antecedent precipitation would be distorted due to the effect of truncations imposed by the short sampling interval.

3. There is no evidence that the larger the central precipitation is, the longer the immediate dry period separations are. As depicted by the profile of mean events (Figure 16), as central precipitation depths increase, the duration of the immediate antecedent dry periods undergo significant and progressive decreases, while the duration of the subsequent dry periods remain about the same or undergo moderate decreases. Much larger central precipitation amounts tends to be associated with much shorter than average immediate antecedent dry periods.

4. It was found that the expected duration of the immediate antecedent dry period is significantly shorter than that of the corresponding subsequent dry period. This phenomenon is particularly pronounced in cases with large central precipitation.

5. For precipitation sequences with central storm amounts greater than 6.00 inches, significant negative correlations exist between the total antecedent precipitation and both the immediate antecedent and the immediate subsequent dry period durations. The percent of the total antecedent and subsequent precipitation decreases as the central storm amount increases.

6. Precipitation in the central wet period consists of the precipitation on the central day (P16), and on those wet days immediately surrounding the central wet day (CSAMX). When the central amount is less than 6.00 inches, P16 dominates and constitutes more than 90 percent of the central amount (CSAMX). This is mainly due to the initial data selection criteria; but as the central amounts increase, the relative contribution of P16 decreases, while that of CSAMX increases. For sequences with precipitation in the central wet period equal to or greater than 14.50 inches, the average precipitation on surrounding days other than the central day rises to approximately 50 percent.

7. There is no evidence that large storms with substantial precipitation tend to be associated with large antecedent precipitation amounts.

8. However, when the full data set which includes many sequences with moderate central storm amount ($\leq$ 6.00 inches) is considered, very weak positive correlations can be found between the central amounts and the antecedent amounts. These apparent marginal correlations are caused by the contributions of the moderate storms. Once storms with precipitation of 6.00 inches or less are removed, such apparent relationships vanish.

9. For storms having large areal extent and with central precipitation greater than 6.00 inches, both the immediate and total antecedent precipitation are significantly greater than their respective subsequent counterparts.

10. The distribution of storms with intense central precipitation is seasonal. For the region of this study, the months of September and October are the most likely months for the occurrence of storms with large central precipitation. Over 60 percent of storms with central precipitation greater than 14.50 inches occurred in October.

11. For storms with substantial central precipitation (CSAMT > 6.00 inches), there is a significant negative correlation between the storm precipitation and the duration of the immediate antecedent dry interval. Thus, the duration of the dry period is shorter for storms greater than 6.0 inches, than for storms less than 6 inches.

12. For storms with substantial central precipitation, there are significant negative correlations between the durations of the central storm and the durations of both the immediate antecedent and immediate subsequent dry intervals.

13. For storms with substantial central precipitation, significant positive correlation exists between total antecedent and precipitation (TAMTT) and the number of dry periods in the sequence. Significant negative correlations exist between total antecedent and subsequent precipitation (TAMTT) and durations of both the immediate antecedent and immediate subsequent dry intervals.

14. For storms having substantial central precipitation (> 6.00 inches), there is **NO** statistical relationship between the central and antecedent precipitation. This is a conclusive finding.

15. The mean ratios of total antecedent and subsequent precipitation to the central amount show progressive decreases as central precipitation increases. For the subsets stratified by the magnitude of central precipitation this ratio decreased from 55 percent for PSQA (≤ 6.00 inches) to 49, 32, and 19 percent PSQB (>6.00 but less than 9.5 inches), PSQC (≥ 9.5 but less than 14.5 inches), and PSQD (≥ 14.5 inches), respectively. The 0.75 quartiles of these ratios declined similarly from 75 percent for PSQA steadily to 69, 45, and 28 percent for PSQB, PSQC and PSQD, respectively. By logical deduction and extension, the conclusion is that a reasonable and prudent antecedent precipitation associated with a 3- to 5-day PMP event in the region of study would be 10 to 20 percent of the PMP within a 31-day period centered on the day of maximum precipitation in the PMP storm for the region of study.

Schematic profiles of means and medians for precipitation events preceding, including, and following the central storm have been constructed. These profiles could serve as a frame of reference for future applications.

The above conclusions are based results from statistical analyses of over 26,000 years of daily precipitation data. Much of the information, especially for the heavier storms, was based upon storms that covered an area greater than 100 square miles. This is evident by the mean length of the central wet period (CSLEN), which for precipitation events in excess of 6 inches is between 3 to 5 days, and the statistical results are physically consistent with wide-spread precipitation events.

However, short-term events called mesoscale convective complexes (MCCs) can occur, especially in the Midwest (Maddox 1983). These events are short-duration, intense rainfalls over a relatively small area. The most intense rains from these storms are usually on the order of several thousand square miles or less. It is possible that such storms could occur in close proximity to each other with only a few days between occurrences. For example, in July 1987 two MCCs occurred over Minneapolis, Minnesota. During the first storm over 8 inches of rain fell on July 20 and 21. Only 72 hours later over 11 more inches of rain fell within 10 miles of the first center.

These mesoscale events are most prevalent in the Midwest and the Great Plains states, and such a short-duration, intense event is possible throughout the central part of the Untied States. Thus, it is possible that two such events could occur within 48 hours of one another. This points to the physical possibility that it is conceivable that two MCCs could occur over the same basin within 48 hours of one another. These mesoscale events should be separated from the statistical results presented above. It is believed that the statistical results point more toward the general storms rather than short-duration, intense precipitation events, such as MCCs. It is also possible that an intense MCC could occur only a few days before the advent of a major general rain. Such scenarios though obviously infrequent are nevertheless possible.

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APPENDIX A

This appendix provides a list of the various abbreviations and their definitions used in this report. This includes various parameters used to describe the antecedent and subsequent data, and the data sets used.

Precipitation Parameters

CDPOS	Position of day 16 in the central wet period counting from the beginning of that period. If there are m wet days immediately preceding day 16, then, CDPOS = m + 1.
CRTOA	Ratio of precipitation in the first antecedent wet period to the central amount. CRTOA = WAMTA/CSAMT.
CRTOS	Ratio of precipitation in the first subsequent wet period to the central amount. CRTOS = WAMTS/CSAMT.
CRTOT	Ratio of the total precipitation in the first antecedent and subsequent wet periods to the central amount. CRTOT = WAMTT/CSAMT.
CSAMT	Sum of precipitation in central wet period. CSAMT = P16 + CSAMX.
CSAMX	Sum of precipitation in central wet period excluding precipitation on day 16. CSAMX = CSAMT - P16.
CSLEN	Duration of central wet period.
DDLEN	Difference in lengths between the dry period immediately preceding and immediately following the central wet period. DDLEN = DLENA - DLENS.
DLENA	Duration of the dry period immediately preceding the central wet period.
DLENS	Duration of the dry period immediately following the central wet period.
DRAMT	Difference between the antecedent and subsequent precipitation excluding the precipitation in the first antecedent and subsequent periods. DRAMT = RAMTA - RAMTS.
DTAMT	Difference between the total antecedent and subsequent precipitation. DTAMT = TAMTA - TAMTS.
DTLEN	Difference of the total number of antecedent and subsequent dry days. DTLEN = TLENA - TLENS.

DWAMT	Differences in precipitation between the first antecedent wet period and the first subsequent wet period. DWAMT = WAMTA - WAMTS.
NBRDP	Number of dry periods in a sequence.
P16	Precipitation on day 16, the central day.
PSUMT	Sum of all precipitation in a sequence. PSUMT = CSAMT + TAMTT.
RAMTA	Sum of antecedent precipitation excluding precipitation in the first antecedent wet period or WAMTA.
RAMTS	Sum of subsequent precipitation excluding precipitation in the first subsequent wet period or WAMTS.
TAMTA	Total antecedent precipitation. TAMTA = WAMTA + RAMTA.
TAMTS	Total subsequent precipitation. TAMTS = WAMTS + RAMTS.
TAMTT	Total antecedent and subsequent precipitation. TAMTT = TAMTA + TAMTS.
TLENA	Total number of antecedent dry days.
TLENS	Total number of subsequent dry days.
TLENT	Total number of dry days in a sequence. TLENT = TLENA + TLENS.
TRTOA	Ratio of total antecedent precipitation to central amount. TRTOA = TAMTA/CSAMT.
TRTOS	Ratio of total subsequent precipitation to central amount. TRTOS = TAMTS/CSAMT.
TRTOT	Ratio of total antecedent and subsequent precipitation to central amount. TRTOT = TAMTT/CSAMT.
WAMTA	Precipitation in the wet period separated from the central wet period by one antecedent dry period.
WAMTS	Precipitation in the wet period separated from the central wet period by one subsequent dry period.

WAMTT	Total precipitation in the first antecedent and first subsequent wet period. WAMTT = WAMTA + WAMTS.
WLENA	Duration of the wet period separated from the central wet period by one antecedent dry period.
WLENS	Duration of the wet period separated from the central wet period by one subsequent dry period.

Data Sets

N	Number of elements in a data set or any specified group.
PSQ	Primary data set consists of 31-day precipitation sequences centered on day 16 which has precipitation equal to or greater than the station 10-year 24-hour rain. N = 1051.
PSQA	A subset of PSQ with precipitation in the central wet period less than or equal to 6.00 inches: CSAMT $\leq$ 6.00 inches. N = 431.
PSQB	A subset of PSQ with precipitation in the central wet period greater than 6.00 inches, but less than 9.50 inches: 6.00 inches $<$ CSAMT $<$ 9.50 inches. N = 431.
PSQC	A subset of PSQ with precipitation in the central wet period equal to or greater than 9.50 inches, but less than 14.50 inches: 9.50 inches $\leq$ CSAMT $<$ 14.50 inches. N = 151.
PSQD	A subset of PSQ with precipitation in the central wet period equal to or greater than 14.50 inches: CSAMT $\geq$ 14.50 inches. N = 38.
PSQM	Modified data set of 31-day precipitation sequences derived from PSQ. Threshold for appreciable rain is raised from the conventional .01 inches to .21 inches. All daily precipitation less than .21 inches is set to 0. N = 1051.
PSQR	Reduced data set of 31-day precipitation sequences derived from PSQ by a filtering procedure that basically permits no more than one sequence to represent a storm on any given day. N = 558.
PSQRT	Truncated data set of 31-day precipitation sequences derived from PSQR by a truncation procedure that eliminates all sequences with CSAMT $\leq$ 6.00 inches. N = 304.

PSQT	Truncated data set of 31-day precipitation sequences derived from PSQ by a truncation procedure that eliminates all sequences with CSAMT ≤ 6.00 inches. N = 620.
PSQ21	Data set of 21-day precipitation sequences centered on day 11 which has precipitation equal to, or greater than, the station 10-year 24-hour rain. N = 1051.
PSQ13	Data set of 13-day precipitation sequences centered on day 7 which has precipitation equal to or greater than the station 10-year 24-hour rain. N = 1051.
PSQ25Y	Data set of 31-day precipitation sequences created by using 25-year 24-hour rainfall from TP-40 as selection threshold. N = 529.
PSQ50Y	Data set of 31-day precipitation sequences created by using 50-year 24-hour rainfall from TP-40 as selection threshold. N = 253.
PSQ100Y	Data set of 31-day precipitation sequences created by using 100-year 24-hour rainfall from TP-40 as selection threshold. N = 131.

Any general mention of precipitation data set in this report will mean the primary data set, PSQ, consisting of 1051 precipitation sequence unless specified otherwise.

(Continued from inside front cover)

NWS HYDRO	18	Numerical Properties of Implicit Four-Point Finite Difference Equations of Unsteady Flow. D. L. Fread, March 1974, 38 pp. (COM-74-011691)
NWS HYDRO	19	Storm Tide Frequency Analysis for the Coast of Georgia. Francis P. Ho, September 1974, 28 pp. (COM-74-11746/AS)
NWS HYDRO	20	Storm Tide Frequency Analysis for the Gulf Coast of Florida from Cap San Blas to St. Petersburg Beach. Francis P. Ho and Robert J. Tracey, April 1975, 34 pp. (COM-75-10901/AS)
NWS HYDRO	21	Storm Tide Frequency Analysis for the Cost of North Carolina, South of Cape Lookout. Francis P. Ho and Robert J. Tracey, May 1975, 44 pp. (COM-75-11000/AS)
NWS HYDRO	22	Annotated Bibliography of NOAA Publications of Hydrometeorological Interest. John F. Miller, May 1975, 50 pp. (Superseded by NWS HYDRO 34)
NWS HYDRO	23	Storm Tide Frequency Analysis for the Coast of Puerto Rico. Francis P. Ho, May 1975, 43 pp. (COM-11001/AS)
NWS HYDRO	24	The Flood of April 1974 in Southern Mississippi and Southeastern Louisiana. Edwin H. Chin, August 1975, 45 pp. (COM-75-11387/AS)
NWS HYDRO	25	The Use of Multizone Hydrologic Model with Distributed Rainfall and Distributed Parameters in the National Weather Service River Forecast System. David G. Morris, August 1975, 15 pp. (COM-75-11361/AS)
NWS HYDRO	26	Moisture Source for Three Extreme Local Rainfalls in the Southern Intermountain Region. E. Marshall Hansen, November 1975, 57 pp. (PB-248-433)
NWS HYDRO	27	Storm Tide Frequency Analysis for the Coast of North Carolina, North of Cape Lookout. Francis P. Ho and Robert J. Tracey, November 1975, 46 pp. (PB-247-900)
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NWS HYDRO	44	Modernized Areal Flash Flood Guidance. Timothy L. Sweeney, October 1992, 38 pp.
NWS HYDRO	45	Relationship between Storm and Antecedent Precipitation over Kansas, Oklahoma, and Eastern Colorado. Edwin H. Chin and John L. Vogel, March 1994, 81 pp.

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