U.S. Geological Survey, Austin, Texas
Texas Tech University
University of Houston
Lamar University

SUMMARY OF DIMENSIONLESS TEXAS HYETOGRAPHS AND DISTRIBUTION OF STORM DEPTH DEVELOPED FOR TEXAS DEPARTMENT OF TRANSPORTATION RESEARCH PROJECT 0–4194

Report 0–4194–4

Texas Department of Transportation
Research Project Number 0–4194

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
0–4194–4		

4. Title and Subtitle	5. Report Date
Summary of Dimensionless Texas Hyetographs and Distribution of Storm Depth Developed for Texas Department of Transportation Research Project 0–4194	January 2005
	6. Performing Organization Code
7. Author(s) William H. Asquith, Meghan C. Roussel, David B. Thompson, Theodore G. Cleveland, and Xing Fang	8. Performing Organization Report No.
9. Performing Organization Name and Address U.S. Geological Survey Water Resources Division 8027 Exchange Drive Austin, Texas 78754	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0–4194
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 4000 Jackson Ave., Bldg. 1 P.O. Box 5080 Austin, TX 78731	13. Type of Report and Period Covered Research from 2001 to 2004 14. Sponsoring Agency Code

15. Supplementary Notes

Project conducted in cooperation with the Federal Highway Administration.

16. Abstract

Hyetographs and storm depth distributions are important elements of hydraulic design by Texas Department of Transportation engineers. Design hyetographs are used in conjunction with unit hydrographs to obtain peak discharge and hydrograph shape for hydraulic design. Storm-depth distributions can be used to assess the probability of a total rainfall depth for a storm. A research project from 2000–2004 has been conducted to (1) determine if existing Natural Resources Conservation Service (NRCS) dimensionless hyetographs are representative of storms in Texas, (2) provide new procedures for dimensionless hyetograph estimation if the NRCS hyetographs are not representative, and (3) provide a procedure to estimate the distribution of storm depth for Texas. This report summarizes the research activities and results of the research project. The report documents several functional models of dimensionless hyetographs and provides curves and tabulated ordinates of empirical (nonfunctional) dimensionless hyetographs for a database of runoff-producing storms in Texas. The dimensionless hyetographs are compared to the NRCS dimensionless hyetographs. The distribution of storm depth is documented for seven values of minimum interevent time through dimensionless frequency curves and tables of mean storm depth for each county in Texas. Conclusions regarding application of the research results are included in the report.

17. Key Words	18. Distribution Statement
Precipitation, Rainfall, Rainfall hyetograph, Small watershed, Storm Depth, Texas	No restrictions

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	68	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SUMMARY OF DIMENSIONLESS TEXAS HYETOGRAPHS AND DISTRIBUTION OF STORM DEPTH DEVELOPED FOR TEXAS DEPARTMENT OF TRANSPORTATION RESEARCH PROJECT 0–4194

by

William H. Asquith, Research Hydrologist
Meghan C. Roussel, Civil Engineer
U.S. Geological Survey, Austin, Texas

David B. Thompson, Associate Professor
Department of Civil Engineering, Texas Tech University

Theodore G. Cleveland, Associate Professor
Department of Civil and Environmental Engineering, University of Houston

Xing Fang, Associate Professor
Department of Civil Engineering, Lamar University

Report 0–4194–4

Project Number 0–4194
Research Project Title: "Regional Characteristics of Storm Hyetographs"

Sponsored by the
Texas Department of Transportation

January, 2005

U.S. Geological Survey
Austin, Texas 78754–4733

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The United States government and the State of Texas do not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report. The researcher in charge of this project was Dr. David B. Thompson, Texas Tech University.

No invention or discovery was conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design, or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

ACKNOWLEDGMENTS

The authors recognize the contributions of Amy Ronnfeldt, Design Division (Austin), Project Director 0–4194, and David Stolpa, Design Division (Austin), Program Coordinator for Project 0–4194.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Hyetographs and storm-depth distributions are important elements of hydraulic design performed by Texas Department of Transportation (TxDOT) engineers (Texas Department of Transportation, 2004). Design hyetographs are used in conjunction with unit hydrographs to obtain peak discharge and hydrograph shape for hydraulic design. Storm-depth distributions can be used to assess the probability of total rainfall depth for a storm. Currently (2004), Natural Resources Conservation Service (NRCS) storm hyetographs are used in standard TxDOT procedures to construct synthetic temporal distributions of storm rainfall depths whenever unit hydrographs are required. During 2000–2004, a consortium of researchers at Texas Tech University, Lamar University, the University of Houston, and U.S. Geological Survey (USGS), in cooperation with TxDOT Research Management Committee No. 3, did a study with three major objectives: (1) to determine if NRCS storm hyetographs are representative of storms in Texas, (2) to provide new procedures for hyetograph estimation if NRCS hyetographs are not representative, and (3) to provide a procedure to estimate the distribution of storm depth for Texas.

The time history of rainfall depth on the ground for a specific location or over a specific area is described by a hyetograph. Hyetographs can be expressed as either cumulative mass curves or instantaneous rainfall rates as context dictates. The accumulation of rainfall depth with the duration of the associated storm is a cumulative hyetograph. The instantaneous time history of rainfall rate, also known as an intensity in a length-per-time scale, is an instantaneous hyetograph. A dimensionless hyetograph has the units of time (storm duration) and cumulative rainfall depth (storm depth) expressed in percentages of the respective totals. The dimensionless hyetograph is convenient in many applications. The first derivative of the dimensionless hyetograph is used to compute dimensionless rainfall rates.

Hyetographs are useful for computer-based rainfall-runoff modeling and other applications. Because the shape and timing of the runoff hydrograph primarily is driven by the magnitude and temporal distribution of rainfall, the hyetograph is an important component of the modeling. The modeling is important for cost-effective and risk-mitigated hydrologic design of hydraulic structures. Hyetograph basics and the relation of hyetographs to hydraulic design is discussed in numerous hydrologic engineering textbooks (for example, Chow and others, 1988, p. 75, 136; Haan and others, 1994, p. 44–52).

The expected hyetograph is a synthetic storm that is intended to represent the typical characteristics of a storm when the analyst is given values of potentially influential factors such as geographic location, storm duration, or rainfall magnitude. The expected hyetograph is a hydrostatologic (study of water statistics) model based on the statistical characteristics of observed hyetographs from a database instead of a meteorological model in which a direct coupling of fundamental components of the atmosphere and principles of physics such as humidity, temperature, pressure, and conservation of energy or momentum are represented.

Purpose and Scope

This report describes the research activities and results of the consortium study with specific focus toward definition of design storms for application by TxDOT engineers. The study area included eastern New Mexico, Oklahoma, and Texas. The report is organized in three principle sections. First, previous studies that are highly relevant to the content of this report and contribute to the evaluation of NRCS storm hyetographs are discussed. Second, the dimensionless hyetographs are discussed. Third, the distribution of storm depth for Texas is discussed. These sections are followed by specific conclusions regarding the three major objectives of the study. The research and results summarized in this report have been published previously, except for dimensionless hyetographs and distribution of storm depth derived from a National Weather Service (NWS) database.

Storm Research Sponsored by the Texas Department of Transportation

The TxDOT has conducted a multifaceted research program through several distinct projects on rainfall characteristics in Texas from the mid 1990s to the present (2004). A chronological list and brief description of publications follows:

1. Asquith (1998)—Defines the depth-duration frequency (DDF) of rainfall annual maxima in Texas by providing an atlas of the parameters of probability distributions. DDF values commonly are used in hydrologic engineering design. An example of a DDF value is the depth of rainfall for the 50-year, 6-hour storm.

2. Lanning-Rush and others (1998)—Provides "envelope curves" for extreme storms in Texas showing the relation between areal storm depth and storm extent. The report also provides a bibliography of large and historically important storms in Texas.

3. Asquith (1999)—Defines areal-reduction factors (ARF) for the 1-day design storm in the Austin, Dallas, and Houston areas. ARF are used in conjunction with DDF values to adjust DDF for the influence of watershed area.

4. Asquith and Famiglietti (2000)—Documents the annual-maxima-centered approach used by Asquith (1999) to define ARF.

5. Al-Asaadi (2002)—Provides detailed analysis of dimensionless hyetographs for 204 runoff-producing storms for 12 watersheds in the San Antonio area. The report also provides analysis of the burst characteristics of the storms. The rainfall data considered is summarized by Asquith and others (2004).

6. Asquith (2003)—Provides a comprehensive analysis of the L-moments and other statistics of hyetographs for runoff-producing storms in Texas. The rainfall data considered are summarized in Asquith and others (2004).

7. Asquith and Roussel (2003)—Provides an atlas of mean interoccurrence intervals of daily rainfall for selected thresholds of rainfall in Texas. Interoccurrence intervals can enhance the planning and construction of infrastructure as well as runoff

control structures by providing hydrologic engineers with information on the frequency of rainfall.

8. Asquith and others (2003)—Provides two separate equation pairs based on a triangular model of the expected hyetograph for runoff-producing storms having more than 0.5 inches of rainfall in Texas for two ranges of storm duration (0–24 hour and 24–72 hour). The report augments the research of Asquith (2003).

9. Asquith and Thompson (2003)—Provides an alternative hyetograph model ("L-gamma") to the triangular model (see Asquith, 2003; Asquith and others, 2003). The report provides three distinct hyetograph equations for three storm duration ranges for Texas. These models are more sophisticated than the triangular models and might be preferable to the triangular hyetographs in some applications. The rainfall data considered are summarized in Asquith and others (2004).

10. Asquith and Roussel (2004)—Provides a directly interpretable atlas of DDF in Texas based on research results of Asquith (1998). The atlas contains 96 maps of the depth of rainfall for 12 storm durations and 8 annual nonexceedance probabilities (recurrence intervals). Further context regarding the atlas is available in Strand (2003).

11. Asquith and others (2004)—Provides a synthesis of the rainfall-runoff database used by Al-Asaadi (2002), Asquith (2003), Asquith and others (2003), Asquith and Thompson (2003), and Williams-Sether and others (2004) to develop hyetographs for runoff-producing storms in Texas.

12. Williams-Sether and others (2004)—Provides extensive documentation of the empirical dimensionless hyetographs for selected durations of runoff-producing storms in Texas. The report augments the research of Asquith (2003). The rainfall data is summarized in Asquith and others (2004).

This report summarizes the results from citations 5, 6, 8, 9, and 12 pertaining to hyetographs from runoff-producing storms (Asquith and others, 2004) in Texas.

PREVIOUS STUDIES

Al-Asaadi (2002), Asquith (2003), Asquith and others (2003), and Thompson and others (2002) describe previous studies of hyetographs. Readers are directed to those references for greater detail. The three most important hyetograph studies for TxDOT engineers are described in this section to provide comparative context to the results presented in section “Dimensionless Texas Hyetographs.”

Intensity-Duration Frequency Based Hyetographs

The NRCS developed a hyetograph model (Soil Conservation Service, 1973) related to the intensity-duration frequency (IDF) curve and a “balanced-storm” or “alternating-block method” (Chow and others, 1988). The method provides dimensionless hyetographs classified into four types that depend upon specific regions of the United States. The Type II and III hyetographs (fig. 1) are represented in Texas and elsewhere in the United States. The Type II hyetograph is applicable for most of Texas, is the most intense, and commonly is used by TxDOT engineers (George Herrmann, Texas Department of Transportation, written commun., 2002 and David Stolpa, Texas Department of Transportation, written commun., 2002). The curves are generalizations of the balanced storm techniques (authors’ interpretation of Soil Conservation Service, 1973) based on the now-outdated rainfall DDF values, equivalent to IDF values, of Hershfield (1962). Frederick and others (1977) provide DDF values for very short storm durations (5–60 minutes) and compliment the 30 minutes-to-24-hour storm durations of Hershfield (1962). Updated reports of DDF values for Texas are provided by Asquith (1998), Strand (2003), and Asquith and Roussel (2004).

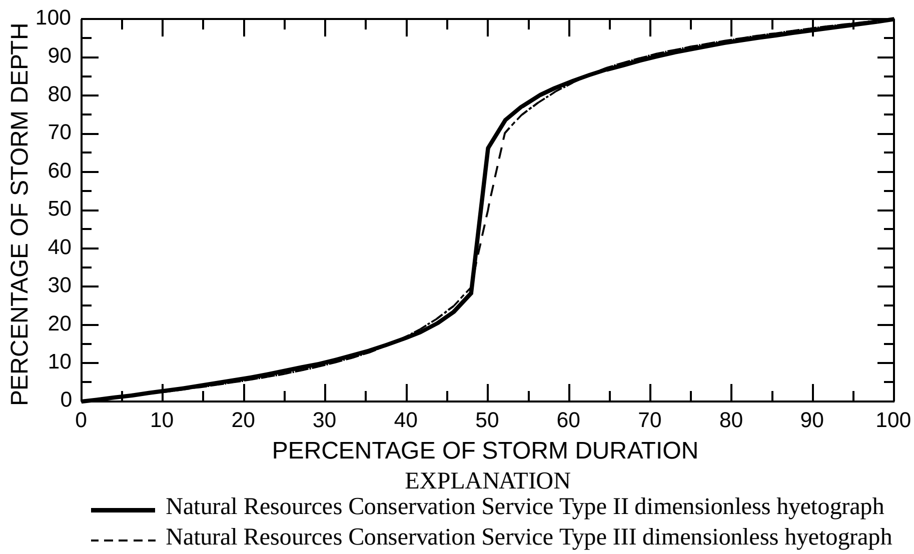

Figure 1. Natural Resources Conservation Service Type II and Type III dimensionless hyetographs.

Actual Rainfall Record Based Hyetographs

Two studies consider the actual rainfall records to develop “complete” storm hyetographs. The research by Huff (1967, 1990) is perhaps the most widely known and cited. Pani and Haragan (1981), cited by Huff (1990), provides dimensionless hyetographs for a small-rain gage network in the southern High Plains of Texas. Because these hyetographs are based on Texas data, the hyetographs are directly comparable to the hyetographs in this report.

Hyetograph Research by Huff

Huff (1990), based largely on Huff (1967), presented dimensionless rainfall hyetographs as families of curves derived from storms that Huff classified as first-, second-, third-, and fourth-quartile. Huff defines a “storm” as a “rain period separated from preceding and succeeding rainfall by 6 hours or more” (Huff, 1967, p. 1,007). Huff does not provide a sensitivity analysis of the presumably arbitrarily chosen 6-hour definition. The quartile designation depends on whether the greatest percentage of total rainfall occurs in the first, second, third, or fourth quarter of the storm duration. Huff’s database comprises 261 storms on a 400-square-mile network of 49 recording rain gages in east-central Illinois sampled between 1955 and 1966. Each storm had an areal mean rainfall of at least 0.5 inches, 3–48 hour storm duration, and at least one rain gage within the area had to record at least 1 inch of rainfall. An inconsistency is that the 1955–1966 period is said by Huff to contain both 11 years of data (Huff, 1967, p. 1,007) and 12 years of data (Huff, 1990, p. 3).

The exact algorithm used by Huff for the storm classification is not provided, although a digital computer was used in the analysis. Huff (1967, p. 1,008) says that the classification depended “on whether the heaviest rainfall occurred in the first, second, third, or fourth quarter of the storm period.” Huff (1967, table 1) determined that the relative frequencies of the quartiles were 30, 36, 19, and 15 percent for the first, second, third, and fourth quartile, respectively. These relative frequencies changed somewhat in Huff (1990) because differences between rainfall at a point and over an area were considered.

Huff concludes that short-duration storms (less than 6 hours) were often associated with first-quartile storms, and moderate-duration storms (6–12 hours) often were associated with second-quartile storms. Third-quartile storms often had durations of 12–24 hours; whereas, fourth-quartile storms had durations greater than 24 hours.

The median (50th percentile) dimensionless hyetograph for each quartile classification based on point rainfall values (rainfall data specifically for the recording device) is presented in figure 2. These curves were generated from a summary data table provided by Huff (1990, table 3). Huff also provides curves representing other percentiles that range from 10 to 90 percent, which envelop the median curve. From figure 2, it is clear that each of the four storm classifications has a considerably different shape. This variation is inherently related to factors such as developmental stage of the storm, size and complexity of the storm system, rainfall type, synoptic storm type, location of the sampling points with respect to the storm center, and the movement of the storm system across the sampling region (Huff, 1967, p. 1,009).

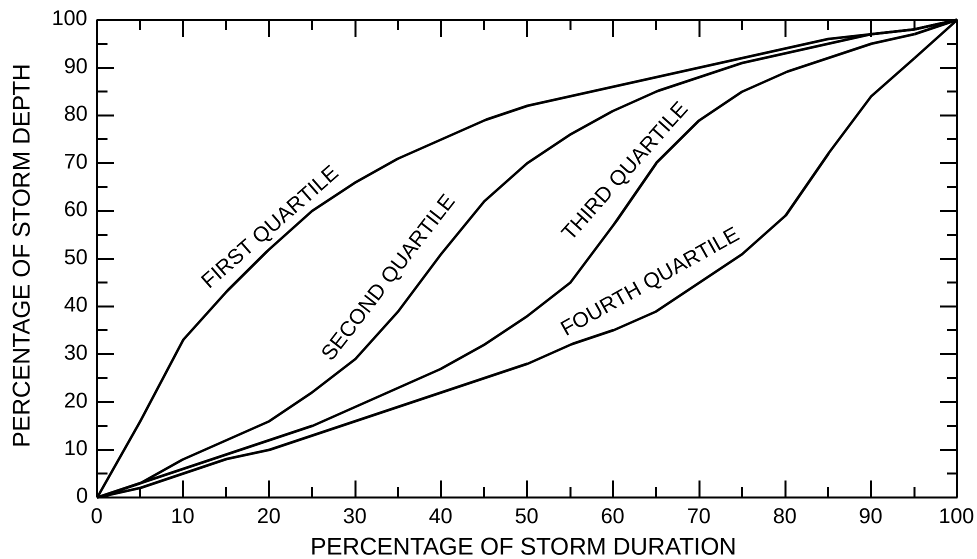

Figure 2. Median dimensionless hyetographs at a point for first-, second-, third-, and fourth-quartile "heavy" (Huff's term) rainfall storms derived from Huff (1990, table 3).

The factors identified and described by Huff result in subtle differences when the dimensionless hyetographs are generated over finite areas instead of at points. Using summary data from Huff (1990, table 4), four median dimensionless hyetographs for areas that range from 10 to 50 square miles are shown in figure 3. Comparison of corresponding curves on figures 2 and 3 shows that the difference between the curves generally is small. Huff concludes that the point hyetographs also are valid for areas but that the validity of the curves diminishes as area increases.

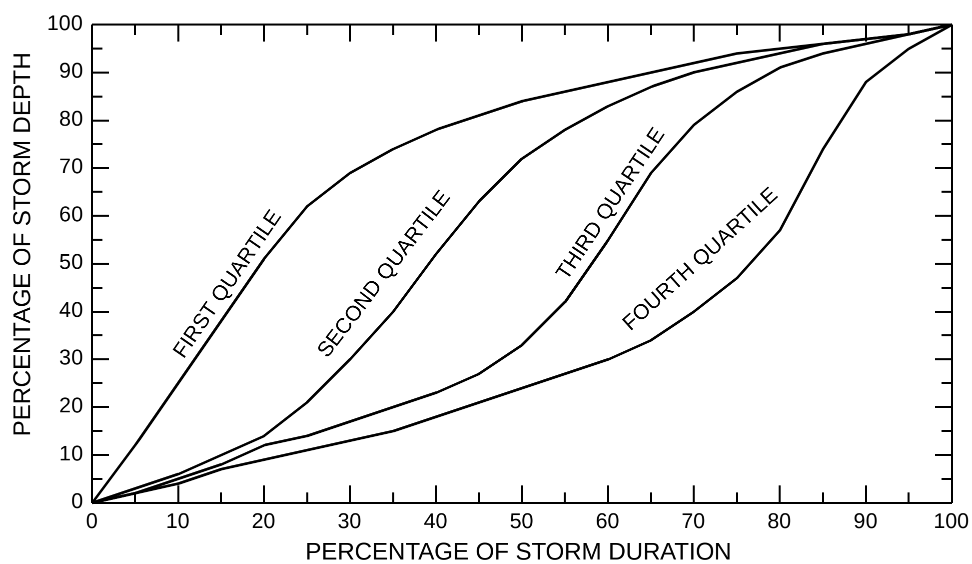

Figure 3. Median dimensionless hyetograph on areas of 10 to 50 square miles for first-, second-, third-, and fourth-quartile "heavy" (Huff's term) rainfall storms derived from Huff (1990, table 4).

Huff (1967) provides considerable discussion of the analysis of rainfall bursts and investigates the relations between rain type, storm type, and storm shape and orientation on the temporal distribution of rainfall.

Huff (1990) concludes that for hydrologic design applications first-quartile hyetographs should be used for design time scales of about 6 hours or less and second-quartile hyetographs should be used for time scales of about 6–12 hours. No direct recommendation for third- or fourth-quartile hyetographs for design applications was made.

Hyetograph Research by Pani and Haragan

The hyetograph research by Pani and Haragan (1981), although not widely known, appears to be the only hyetograph analysis done explicitly on Texas rainfall data prior to the current (2000–2004) TxDOT research project 0–4194. Their analysis followed Huff (1967), and they compare their results favorably to those of Huff. Details of the Huff approach including clarification of terminology used here are provided in the previous section.

Pani and Haragan (1981) classified storms into four quartile categories depending upon which quarter of dimensionless storm time had the greatest change in storm depth. They analyzed 117 storms that occurred during May 15 through July 31 for a 3-year period (1978–80) over the High Plains Cooperative Program (HIPLEX) rain-gage network (Texas Department of Water Resources, 1980). The network was in the southern High Plains of Texas near the town of Big Spring and covered about 2,600 square miles (6,744 square kilometers, reported by Pani and Haragan [1981]). The data consisted of 15-minute rainfall values. The mid-May to July period was selected because the authors were interested in the hyetographs of convective-generated rainfall. The authors defined a storm as a “rain period of at least 0.75-hour duration separated by at least 1 hour” (Pani and Haragan, 1981, p. 77). Pani and Haragan appear to not have identified a minimum storm depth considered for analysis, but Bonta and Rao (1989, table 1) report that Pani and Haragan (1981) used a minimum depth of about 0.75 inch.

Pani and Haragan (1981, table 1) determined that the relative frequencies of the quartiles were 13, 41, 32, and 14 percent for the first, second, third, and fourth quartile, respectively. These frequencies indicate that most storms (73 percent) are characterized as second or third quartile. This observation differs from that of Huff (1967, 1990) who found that most storms (66 percent) are characterized as first or second quartile.

Pani and Haragan (1981, figs. 3, 4) provide median dimensionless hyetographs for only second- and third-quartile storms. First- and fourth-quartile hyetographs are not provided because of small sample sizes (Pani and Haragan, 1981, p. 78). For this report the median hyetographs were graphically extracted from the figures of Pani and Haragan (1981) and are reproduced in figure 4. Unlike Huff (1990), Pani and Haragan (1981) do not provide tables of the coordinate values for their figures. Pani and Haragan (1981) also provide the 10th- and 90th-percentile hyetographs to illustrate uncertainty. Pani and Haragan (1981) used the chi-square test at the 0.1-

percent (.001 significance level) to test whether their hyetographs were similar to Huff's. The test showed no significant differences (Pani and Haragan, 1981, p. 79). Therefore, although the relative frequencies of quartile storm types between Illinois and Texas are statistically different, the resultant hyetographs from each apparently are not.

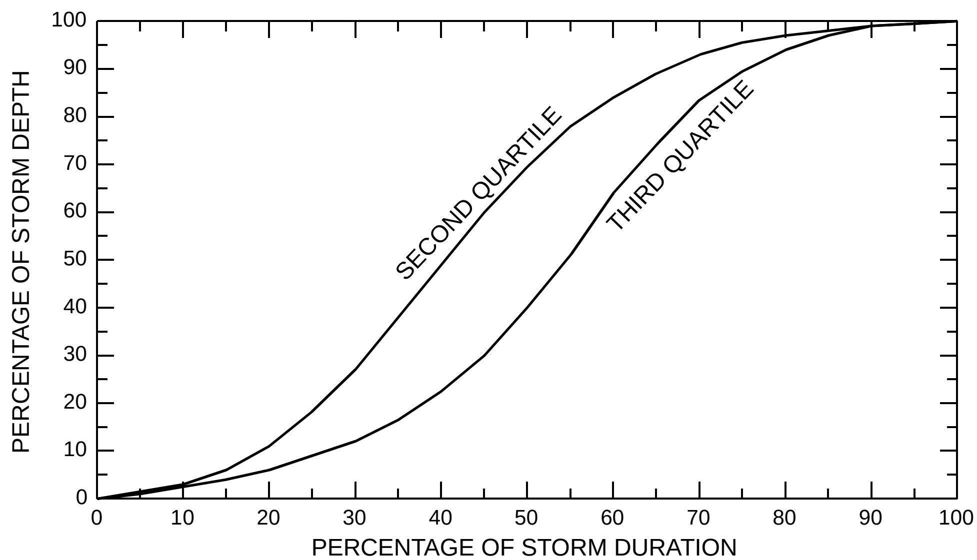

Figure 4. Median dimensionless hyetograph for second- and third-quartile storms for the southern High Plains of Texas derived from Pani and Haragan (1981, figs. 3, 4).

Because the greatest rate of the third-quartile storm is near 55 percent of the duration, Pani and Haragan decided that the third quartile storm was close enough to a second-quartile classification so that, for application purposes, all second- and third-quartile storms should be combined (Pani and Haragan, 1981, fig. 5). The median composite hyetograph along with the 10th- and 90th-percentile curves are shown in figure 5. The hyetograph coordinates again were graphically extracted from the Pani and Haragan figure. The coordinates used to generate figure 5 are listed in table 1 for the benefit of TxDOT engineers.

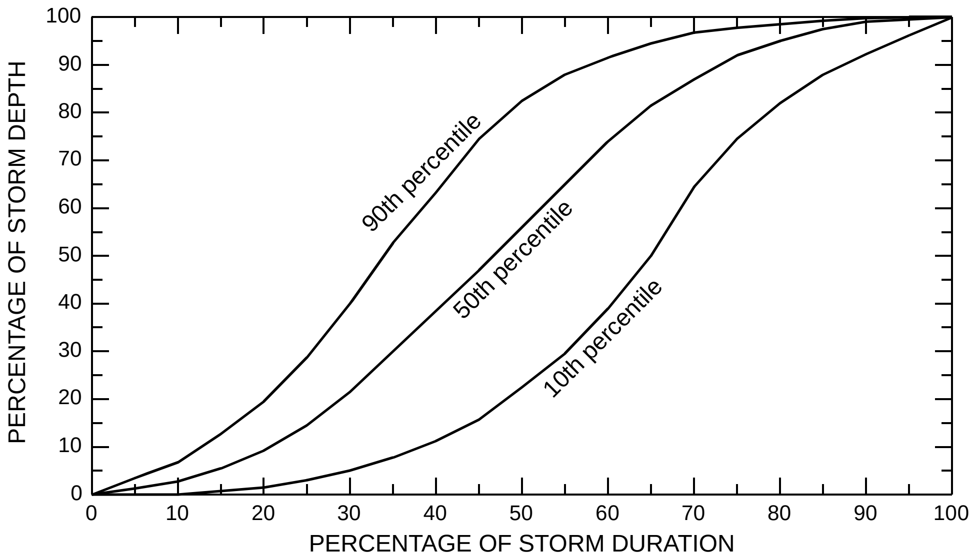

Figure 5. Median, 10th-, and 90th-percentile dimensionless hyetographs for the southern High Plains of Texas derived from Pani and Haragan (1981, fig. 5).

Table 1. Median, 10th-, and 90th-percentile dimensionless hyetograph coordinates for the southern High Plains of Texas derived from Pani and Haragan (1981)

[Table entries manually extracted from figure by Pani and Haragan (1981, fig. 5) and rounded to the nearest quarter interval.]

Storm duration (percent)	10th percentile dimensionless hyetograph (percent)	Median (50th percentile) dimensionless hyetograph (percent)	90th percentile dimensionless hyetograph (percent)
0	0	0	0
5	0	1.25	3.5
10	0	2.75	6.75
15	.75	5.5	12.75
20	1.5	9.25	19.5
25	3	14.5	28.75
30	5	21.5	40
35	7.75	30	52.75
40	11.25	38.5	63.25
45	15.75	47	74.5
50	22.5	56	82.5
55	29.5	65	88
60	39	74	91.5
65	50	81.5	94.5
70	64.5	87	96.75
75	74.5	92	97.75
80	82	95	98.5
85	88	97.5	99.25
90	92.25	99	99.75
95	96.25	99.5	100
100	100	100	100

DIMENSIONLESS TEXAS HYETOGRAPHS

Dimensionless hyetographs synthesized specifically from Texas rainfall data are termed "Texas Hyetographs" in this report. Two separate and distinct databases were used to estimate dimensionless hyetographs. The first database was compiled from rainfall recorded for more than 1,600 storms over mostly small watersheds as part of historical USGS studies; the storms contained in this database are known to have produced runoff. This database is described in Asquith and others (2004). The second database was derived from the NWS hourly rainfall data-collection network in eastern New Mexico, Oklahoma, and Texas (Hydrosphere, 2003).

Al-Asaadi Hyetographs for Runoff-Producing Storms in the San Antonio, Texas Area

Al-Asaadi (2002) provides detailed analysis of dimensionless hyetographs for 204 runoff-producing storms for 12 watersheds in the San Antonio area following the analytical approach of Huff (1967). The storms were classified into five groups depending on storm duration: 0–3 hours, 3–6 hours, 6–12 hours, 12–24 hours, and 24–72 hours. The 72-hour upper limit is approximate. Storms also were classified into four groups depending on storm depth: 0.5–0.99 inches; 1.00–1.49 inches, 1.50–1.99 inches, and 2.00 inches or more. The number of bursts for each storm were recorded; a burst was defined as a complete cessation of rainfall or a change of 100 percent or more in successive 10-minute rainfall amounts provided that the amounts accounted for 5 percent or more of total storm rainfall.

From a summary of storm-quartile frequency (table 2), it is evident that first- and second-quartile storms constitute the bulk of the storm patterns; this finding is consistent with that of Williams-Sether and others (2004) statewide analysis of similar data, which includes the San Antonio area data used by Al-Asaadi (2002). Al-Asaadi (2002) also reports that storms with durations less than 12 hours account for 71 percent of first-quartile storms and 74 percent of second-quartile storms. The author provides tables and figures (not reproduced here) of the 10th-, 50th-, and 90th-percentile empirical hyetograph (unsmoothed and non-monotonic) for each storm quartile and selected storm duration classifications. More comprehensive analyses of empirical hyetographs that are smoothly varying and monotonically increasing are documented in Asquith (2003), Williams-Sether and others (2004), and in section "Empirical Hyetographs by Williams-Sether and others for Runoff-Producing Storms in Texas" of this report.

The burst analysis produced results similar to those of Huff (1967). Huff (1967) results are not reported here. A summary of the burst analysis is listed in table 3. The burst analysis in table 3 constitutes the only burst analysis done by the research consortium for TxDOT research project 0–4194.

Table 2. Frequency of each storm quartile for runoff-producing storms in the San Antonio, Texas, area

[Values derived from chapter 4 of Al-Asaadi (2002).]

Storm quartile	Percent of total number of storms
First	34
Second	27
Third	22
Fourth	17

Table 3. Summary of storm burst analysis for runoff-producing storms in the San Antonio, Texas, area

[Values derived from chapter 4 of Al-Asaadi (2002).]

Storm depth or duration category	Predominant no. of bursts	Percent of total number of cases represented by the predominant burst type
Depth		
0–0.99 inch	1	33
1–1.49 inches	1	30
1.50–1.99 inches	3 to 5	56
> 2.00 inches	3 to 5	53
Duration		
0–3 hours	1	50
3–6 hours	2	36
6–12 hours	2	22
12–24 hours	3 to 6	69
24–72 hours	7 to 8	27

Al-Asaadi (2002) juxtaposes the empirical hyetographs for San Antonio and the NRCS hyetographs. The author reports that the empirical hyetographs offer more “adaptability” in hyetograph choice for the design problem at hand. Empirical hyetographs are computed from actual temporal distributions of storms, unlike the NRCS hyetographs. The use of several curves allows the designer to maximize either peak flow or runoff volume for a given storm depth. The NRCS hyetographs do not share this feature. Multiple empirical hyetographs of a specified nonexceedance probability provide “boundaries of a region of probable storm sequences” (Al-Asaadi, 2002, p. 73).

Furthermore, the NRCS hyetograph is specifically associated with design events of a 24-hour duration. This is a restriction not placed on the empirical hyetographs. Results from the data analysis indicate that approximately three-fourths of the storms have 12 hour or shorter durations. Al-Asaadi (2002, p. 74) concludes that the NRCS hyetographs are “not representative [of] rainfall events in Texas” because of the prevalence of short duration storms, the great variability in hyetographs, and “better” statistical approaches used by Huff (1967) and the author.

Triangular Hyetographs for Runoff-Producing Storms in Texas

Asquith (2003) and Asquith and others (2003) provide background information on triangular hyetograph models for runoff-producing storms in Texas. A triangular hyetograph model based on the rainfall intensity and fractional percentage of elapsed time is shown in figure 6. The equations for a cumulative triangular hyetograph are

$$p_1(0 \le F \le a) = \frac{1}{a}F^2 \text{, and} \tag{1}$$

$$p_2(a < F \le 1) = -\frac{1}{b}F^2 + \left(\frac{2a}{b} + 2\right)F - \left(\frac{a^2}{b} + a\right), \tag{2}$$

where $p(F)$ is the percentage of total rainfall depth for percentage of elapsed time F, and a and b are parameters. The parameters can be expressed in terms of the hyetograph mean, μ:

$$a = 2 - 3\mu \text{, and} \tag{3}$$

$$b = 3\mu - 1. \tag{4}$$

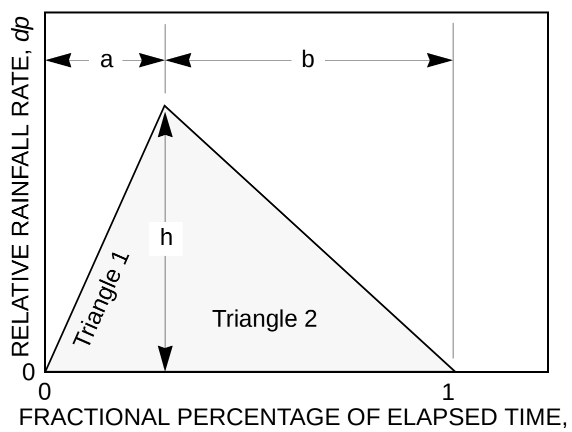

Figure 6. Definition of a triangular hyetograph model.

Estimates of the triangular hyetograph parameters a and b are provided through analysis of the mean values for dimensionless hyetographs. The analysis considers whether the mean ordinate is a function of the storm duration and the total storm depth for a given duration range. In other words, the question is whether a dependency between the temporal characteristics of the storm and the total storm depth exists for small watersheds.

To examine this question, three duration ranges of 0–12 hours, 12–24 hours, and 24–72 hours were considered, and within each duration range, storms with a sequence of depth intervals were analyzed. The upper limit of 72 hours is an approximate upper limit. For each depth interval, the average of the mean of the dimensionless hyetograph for each storm is computed. For example, 290 storms had durations less than 12 hours and a depth range of 0.5–1.5 inches, 290 values for the mean of the dimensionless hyetograph are computed, and the average of the 290 mean values is 0.579 (or 57.9 percent). For purposes of tabulation, the 0.5–1.5-inch range is cataloged as 1 inch, the 1.5–2.5-inch range is cataloged as 2 inches, and so forth. The results of the analysis are provided in table 4. The coefficients of variation and sample sizes (no. of storms) also are listed in table 4.

Table 4. Summary of dimensionless hyetograph averages for 0–12-hour and 12–24-hour storm durations
[CV, coefficient of variation: standard deviation divided by mean; na, not available; --, empty cell]

		0–12-hour storm duration			12–24-hour storm duration		
Storm depth category (inch)	Range of depth represented by category (inch)	Average of the mean for the dimensionless hyetograph (percent)	CV of the mean for the dimensionless hyetograph	Number of storms (sample size)	Average of the mean for the dimensionless hyetograph (percent)	CV of the mean for the dimensionless hyetograph	Number of storms (sample size)
1	0.5–1.5	57.9	0.340	290	56.4	0.444	68
2	1.5–2.5	61.0	.302	253	57.8	.386	180
3	2.5–3.5	58.5	.309	108	58.0	.316	119
4	3.5–4.5	58.8	.279	41	61.2	.292	80
5	4.5–5.5	58.4	.248	11	59.3	.302	30
6	5.5–6.5	49.6	.411	3	70.7	.158	10
7	6.5–7.5	74.0	na	1	57.0	.362	2
8	7.5–8.5	79.8	na	1	38.2	na	1
9	8.5–9.5	22.9	na	1	48.3	na	1
10	9.5–10.5	na	na	0	na	na	na
Rounded weighted average and sample total		59	.317	709	59	.352	491
Parameter *a* of hyetograph		.23	--	--	.23	--	--
Parameter *b* of hyetograph		.77	--	--	.77	--	--

From the results in table 4 for the 0–12-hour duration storm, it is clear that no functional relation between storm depth and the average of the dimensionless hyetograph exists. Therefore, a bulk or weighted average of 59 percent is considered the most representative for the 0–12-hour duration. For the 12–24-hour storm duration, it is possible that a weak relation exists between storm depth and the average of the mean values. The averages monotonically increase from 56.4 percent for a 1-inch depth to 61.2 percent for a 4-inch depth; however, given the large coefficients of variation and fact that the average for greater-than-4-inch depth decreases and then increases, it is concluded that a weighted average of 59 percent also is most representative for the 12–24-hour storm duration.

Because the two weighted averages, when rounded to the nearest two significant figures, are the same, the averages for these two duration ranges can be combined into a single 0–24-hour range. The approximate equality in the weighted averages was unexpected. The weighted average of 59 percent produces a and b parameters of 0.23 and 0.77, respectively. The parameters also are listed in table 4.

A similar analysis was done for the 24–72-hour storm duration (table 5). Based on the average of the mean (column 3 in table 5), the mean of the hyetograph distribution generally decreases with increasing storm depth. This trend might be expected because the duration range is unbounded (duration can increase indefinitely). It is possible that longer duration storms (multiple days) are more likely to produce larger depths and have multiple bursts, which would increase the potential for substantial rainfall to occur in later parts of the duration. The variation is large and the sample size is relatively small for the 0.5–1.5-inch and greater-than-5-inch ranges. Therefore for purposes of design applications, it is reasonable that a single weighted average should be used to represent the 24–72-hour dimensionless hyetograph. The weighted average of 55 percent is preferred and produces a and b parameters of 0.35 and 0.65, respectively. The parameters also are listed in table 5.

Table 5. Summary of dimensionless hyetograph averages for 24–72-hour storm duration

[CV, coefficient of variation: standard deviation divided by mean]

		24–72-hour storm duration		
Storm depth category (inch)	Range of depth represented by category (inch)	Average of the mean for the dimensionless hyetograph (percent)	CV of the mean for the dimensionless hyetograph	Number of storms (sample size)
1	0.5–1.5	65.0	0.369	23
2	1.5–2.5	56.8	.364	123
3	2.5–3.5	55.7	.380	131
4	3.5–4.5	55.8	.296	72
5	4.5–5.5	53.7	.355	43
6	5.5–6.5	50.6	.317	41
7	6.5–7.5	51.6	.362	12
8	7.5–8.5	50.2	.422	11
9	8.5–9.5	42.2	.527	4
10	9.5–10.5	57.0	.0368	2
Rounded average and total sample size		55	.355	462
Parameter *a* of hyetograph		.35	--	--
Parameter *b* of hyetograph		.65	--	--

The ordinates of both the 0–24-hour and the 24–72-hour duration dimensionless hyetographs are listed in table 6. The hyetographs in the table were computed by the triangular hyetograph models. This table facilitates application of the hyetographs. The equation pairs used to compute each hyetograph are listed below. The pairs are derived by parameter substitution into equations 1 and 2.

Storm durations between 0 and 24 hours

$$p_1(0 \le F \le 0.23) = 4.35F^2\text{, and} \quad (5)$$

$$p_2(0.23 < F \le 1) = -1.30F^2 + 2.60F - 0.299\,. \quad (6)$$

Storm durations between 24 and 72 hours

$$p_1(0 \le F \le 0.35) = 2.86F^2 \text{, and} \tag{7}$$

$$p_2(0.35 < F \le 1) = -1.54F^2 + 3.08F - 0.538 \,. \tag{8}$$

Table 6. Triangular model dimensionless hyetographs for 0–24-hour and 24–72-hour durations for runoff-producing storms in Texas with at least 1 inch of rainfall

Storm duration (percent)	Dimensionless hyetograph for 0–24-hour storm duration (percent)	Dimensionless hyetograph for 24–72-hour storm duration (percent)
0	0	0
5	1.09	.71
10	4.35	2.86
15	9.78	6.43
20	17.4	11.4
25	27.0	17.9
30	36.4	25.7
35	45.1	35.0
40	53.3	44.6
45	60.7	53.5
50	67.5	61.5
55	73.7	68.9
60	79.2	75.4
65	84.1	81.2
70	88.3	86.2
75	91.9	90.4
80	94.8	93.9
85	97.1	96.5
90	98.7	98.5
95	99.7	99.6
100	100	100

The dimensionless hyetographs for the 0–24-hour and 24–72-hour storm durations are illustrated in figure 7. The median composite hyetograph by Pani and Haragan (1981) is shown for comparison. By inspection of the figure, it is clear that the triangular model produces dimensionless cumulative hyetographs that are consistent in shape and acceptably close to the empirically determined ordinates of the Pani and Haragan hyetograph. However, the 0–24-hour and 24–72-hour hyetographs peak slightly earlier and are more front-loaded[1] than the Pani and Haragan hyetograph, and each is a second-quartile storm. The triangular model hyetographs are inconsistent with the NRCS Type II and Type III dimensionless hyetographs. See example 1 in the appendix for an application and solution of dimensionless hyetographs.

[1]Loadedness refers to the fraction of the storm duration containing the bulk of the rainfall. For example, a front-loaded storm releases most of the rainfall in the first one-half of the storm.

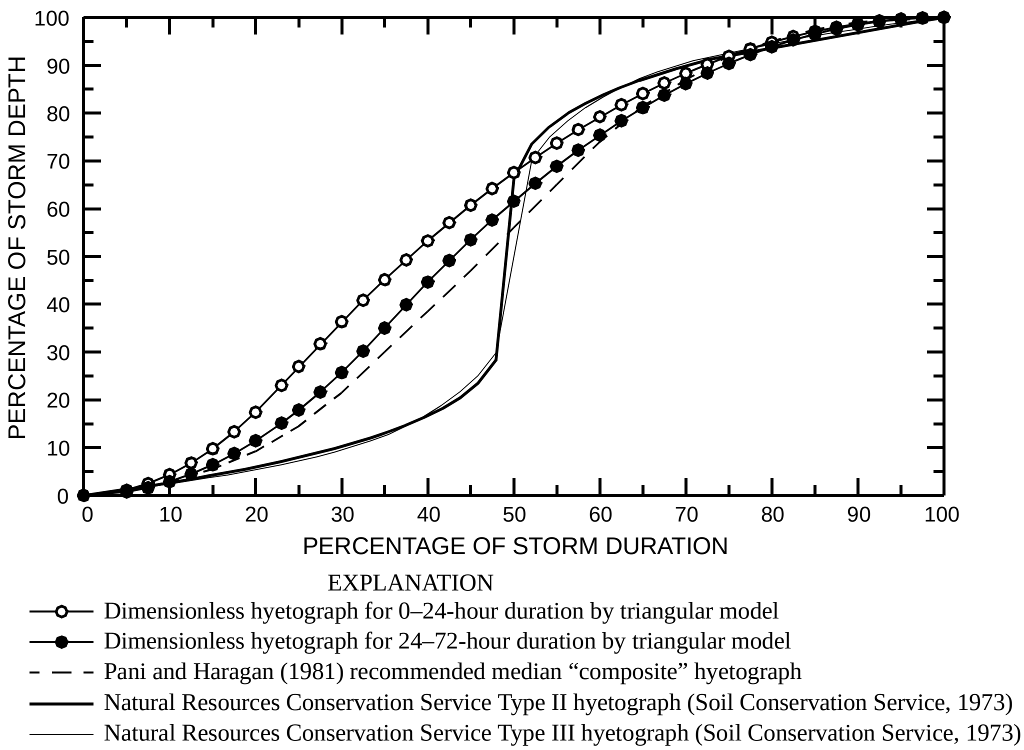

Figure 7. Dimensionless hyetographs for runoff-producing storms having 0–24-hour and 24–72-hour durations computed by triangular hyetograph model for Texas, composite dimensionless hyetograph by Pani and Haragan (1981), and Natural Resources Conservation Service Type II and Type III dimensionless hyetographs.

Triangular and Wakeby Hyetographs from National Weather Service Hourly Rainfall Stations

A large database recorded by the NWS hourly rainfall stations for eastern New Mexico (approximately east of the Rio Grande), Oklahoma, and Texas was derived from National Climatic Data Center data (Hydrosphere, 2003). The data for the period of record (through calendar year 2002) for all stations with a number, name, latitude, and longitude were included in the study. Latitude and longitude are reported to the nearest minute. The database contains more than 155 million values of hourly rainfall (including zero values) from 774 stations. For perspective, an 8-hour minimum interevent time identifies 584,159 storms in Texas. (Minimum interevent time is discussed in detail in section “Distribution of Storm Depth for Texas.”)

The sequence of incremental rainfall for each storm and station in the database was extracted using a minimum interevent time of 8 hours. Subsequently, for each storm and station in the database, the hourly rainfall values of the storm were cumulated and each cumulative value was divided by the total storm depth. Also, the hourly time increments were divided by the total storm duration. The hyetographs expressed in dimensionless depth and duration are dimensionless hyetographs.

The L-moments (Hosking, 1990) of each dimensionless hyetograph for each station subsequently were computed. The computed L-moments were the mean, L-scale, L-skew, L-kurtosis, and Tau5). The mean values for these L-moments (mean of the mean, mean of L-scale, and so forth) were then computed for each station. However, only those storms with depths of at least 1 inch and durations of at least 5 hours were included in the computations. Five hours was chosen as the lower limit because the storm data have a 1-hour resolution; all five L-moments of the hyetograph can be computed. Substantial sampling variability exists for the shortest duration storms because of small sample size in the L-moments of observed hyetographs. The analysis was restricted to storms having at least 1 inch of rainfall to make the hyetograph statistics more applicable to synthetic storms often considered by hydrologic designers. Prior to computation of mean L-moments, the storms were classified further into three groups according to total storm duration: storms with duration ranges of 5–12 hours, 13–24 hours, and 25–72 hours.

According to the minimum storm depth and duration range criteria, the statewide mean and median values for each mean L-moment were computed. The statewide L-moment values for Texas are listed in tables 7–9. Several observations regarding the statistical values in the tables are made:

1. The mean or median of the mean values of the observed hyetographs decrease with duration range. An interpretation is that as storm duration increases, storms become progressively less front-loaded.
2. L-scale measures the variability or steepness of the distribution. The L-scale values generally decrease with increasing duration. An interpretation is that the hyetograph becomes less steep as duration increases because rainfall becomes relatively less intense. This interpretation is consistent with findings of Asquith (2003) and Asquith and others (2003).
3. L-skew measures the symmetry of the distribution. The L-skew values approach zero as duration increases. An interpretation is that the rainfall rates become more symmetrical, hence, relatively more uniform in time as storm duration increases.
4. The mean and median of the L-moment statistics generally are similar. Thus, each statistic should be a reasonable estimate of the central tendency of the L-moment value.

Table 7. Mean and median statistics of L-moments of observed dimensionless hyetographs for storms in Texas with at least 1 inch of rainfall and durations of 5–12 hours

[Total sample size is 31,794 storms; statistics and parameters are dimensionless.]

Statistics	Mean	Median	Triangular model parameters (equations 1 and 2)		Wakeby model parameters (equation 9)	
Mean	0.66895	0.66588	a =	0.02197	ξ =	-0.70196
L-scale	.19102	.19151	b =	.97803	α =	20.140
L-skew	-.14918	-.17052			β =	21.034
L-kurtosis	.15414	.13177			γ =	.90258
Tau5	-.08110	-.09082			δ =	-.98893

Table 8. Mean and median statistics of L-moments of observed dimensionless hyetographs for storms in Texas with at least 1 inch of rainfall and durations of 13–24 hours

[Total sample size is 27,659 storms; statistics and parameters are dimensionless.]

Statistics	Mean	Median	Triangular model parameters (equations 1 and 2)		Wakeby model parameters (equation 9)	
Mean	0.58222	0.57570	a =	0.28936	ξ =	-0.25713
L-scale	.18389	.18487	b =	.71064	α =	7.3210
L-skew	-.03426	-.03598			β =	19.762
L-kurtosis	.06849	.06263			γ =	.88698
Tau5	-.03200	-.03338			δ =	-.84708

Table 9. Mean and median statistics of L-moments of observed dimensionless hyetographs for storms in Texas with at least 1 inch of rainfall and durations of 25–72 hours

[Total sample size is 12,776 storms; statistics and parameters are dimensionless.]

Statistics	Mean	Median	Triangular model parameters (equations 1 and 2)		Wakeby model parameters (equation 9)	
Mean	0.54055	0.53631	a =	0.38959	ξ =	-0.083256
L-scale	0.17982	.18075	b =	.61041	α =	1.6611
L-skew	-.01063	-.01255			β =	14.320
L-kurtosis	.02594	.02240			γ =	.98944
Tau5	-.00927	-.00996			δ =	-.93577

A simple triangular hyetograph model was used as in Asquith and others (2003). A complex Wakeby hyetograph model also was used; the Wakeby model uses the Wakeby distribution equation (Hosking and Wallis, 1997, p. 204–208). The use of two models provides comparison and contrast between simple and complex models of hyetograph shape.

The triangular model is a one-parameter model. The Wakeby model has five parameters. The parameters can be estimated by the method of L-moments (Hosking, 1990). The triangular model is fit only to the mean of the hyetograph distribution. The Wakeby model is fit to all five L-moments (mean, L-scale, L-skew, L-kurtosis, and Tau5).

Triangular Hyetograph Model

Equations 1 and 2 (p. 12) describe the triangular hyetograph model, and the parameters of a triangular model corresponding to the median of the L-moment means are listed in tables 7–9. The authors prefer to use the median L-moment values for parameter estimation. The triangular hyetograph models for Texas are shown in figure 8, and parameters are shown in tables 7–9. To illustrate spatial variation in hyetograph shape, figure 8 also includes triangular hyetographs for storms derived from the NWS hourly rainfall database for eastern New Mexico and Oklahoma. The dimensionless triangular hyetographs for the three states show little spatial variation. Therefore, a single triangular hyetograph for the entire State of Texas and for a specified duration range is suitable.

The triangular model is constrained to pass through the origin and unity (0 and 1) for both fractional percentage of storm depth and duration (fig. 8). These are requirements for a physically meaningful dimensionless hyetograph. As previously mentioned, the triangular model is fit only to the hyetograph mean. Although the mean statistic contains the most information pertaining to a distribution, a substantial amount of information, as represented by the higher L-moments, is not included in the model. The triangular model is discontinuous at the p_1 to p_2 transition (the peak of the triangle). This transition corresponds to the point of greatest relative rainfall intensity. Hence, a more complex hyetograph model might be preferable.

Wakeby Hyetograph Model

The Wakeby distribution is

$$p(F) = \xi + \frac{\alpha}{\beta}[1 - (1 - F)^{\beta}] - \frac{\gamma}{\delta}[1 - (1 - F)^{-\delta}], \qquad (9)$$

where p is the fraction of storm depth, F is the fraction of storm duration, ξ is a location parameter, α and γ are scale parameters, and β and δ are shape parameters. Each parameter is dimensionless.

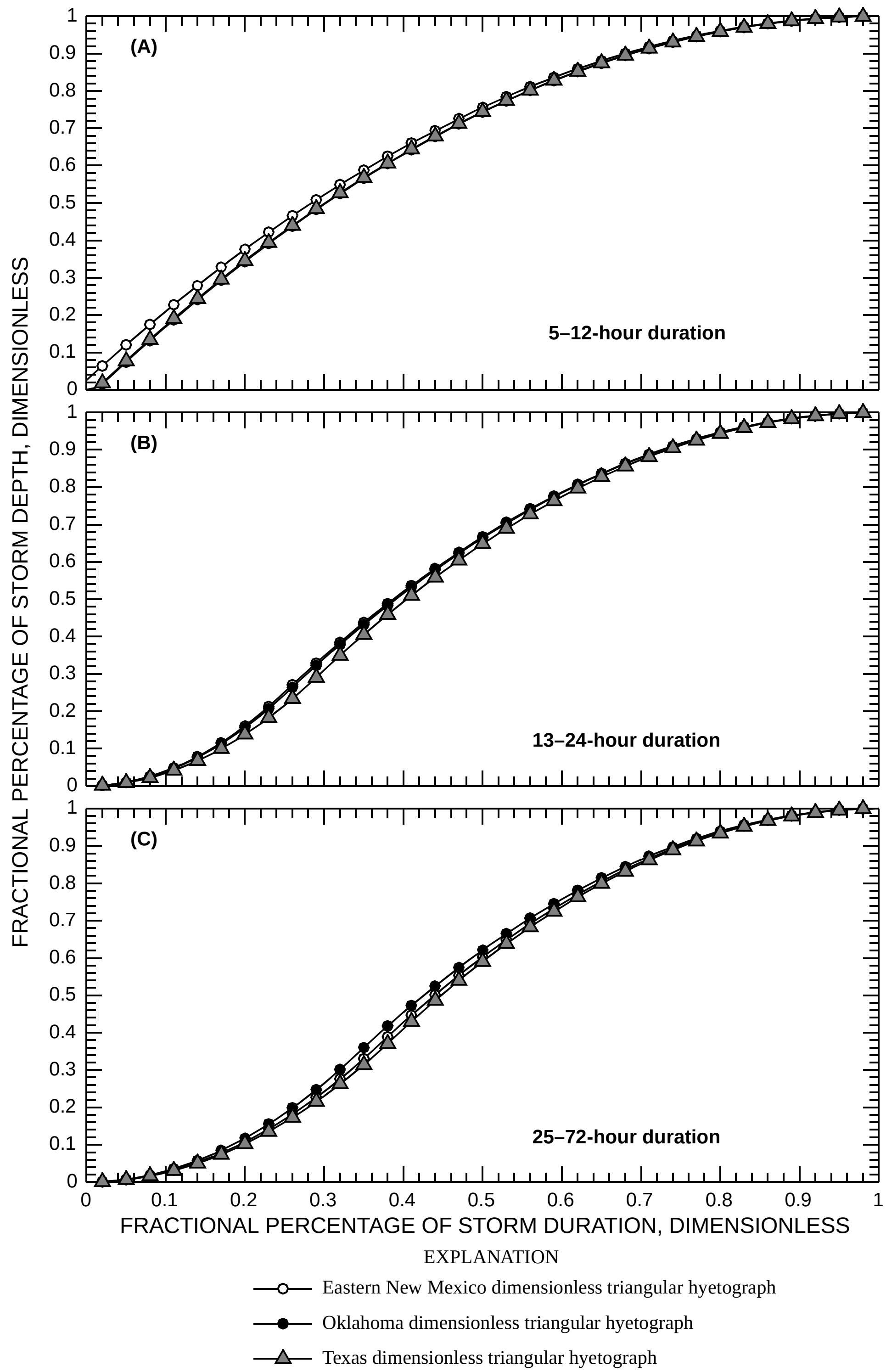

Figure 8. Comparison of triangular dimensionless hyetograph models for 5–12-hour, 13–24-hour, and 25–72-hour durations for eastern New Mexico, Oklahoma, and Texas for storms with at least 1 inch of rainfall.

There are no manually solvable expressions for the parameters of the Wakeby distribution in terms of the L-moments, unlike the parameters for the triangular model. Hosking and Wallis (1997) describe parameter estimation and algorithms for the Wakeby distribution. The parameters of a Wakeby model corresponding to the median of the L-moment mean, L-scale, L-skew, L-kurtosis, and Tau5 have been calculated and are listed in tables 7–9.

A demonstration of the Wakeby model through parameter substitution is useful. The Wakeby model of the medians of the hyetograph L-moments for storms in Texas with at least 1 inch of rainfall and a 5–12 hour duration is

$$Q(F) = -0.70196 + \frac{20.140}{21.034}[1 - (1-F)^{21.034}] - \quad (10.1)$$

$$\frac{0.90258}{-0.98893}[1 - (1-F)^{0.98893}] . \quad (10.2)$$

The five parameters are listed in table 7 and have been substituted into equation 9 to yield equation 10. Thus, the ordinate of the hyetograph at 25 percent of storm duration (F=0.25), is $p(0.25) = 0.479$ or 47.9 percent of storm depth.

Unlike the triangular model, by formulation, the Wakeby model is not constrained to pass through the origin and unity (0 and 1) for both fractional percentage of storm depth and duration. Parameter estimation for an origin-and-unity constrained Wakeby distribution proved to be difficult. The Wakeby model, as fitted to the five L-moments, produces some ordinates that are less than zero and some that are greater than one. These are physically impossible conditions for a dimensionless hyetograph. The authors suggest that the Wakeby model be truncated at zero when the ordinates are negative and truncated at one when the ordinates are greater than one. The Wakeby hyetograph models represented in tables 7–9 are shown in figure 9. The curves are truncated as indicated by the annotation on figure 9A.

To illustrate spatial variation in hyetograph shape, figure 9 also includes Wakeby hyetographs for storms from eastern New Mexico and Oklahoma. As with the triangular hyetographs, little spatial variation in the dimensionless Wakeby hyetographs exists. Therefore, a single Wakeby hyetograph for the entire State of Texas for a specified duration range is suitable.

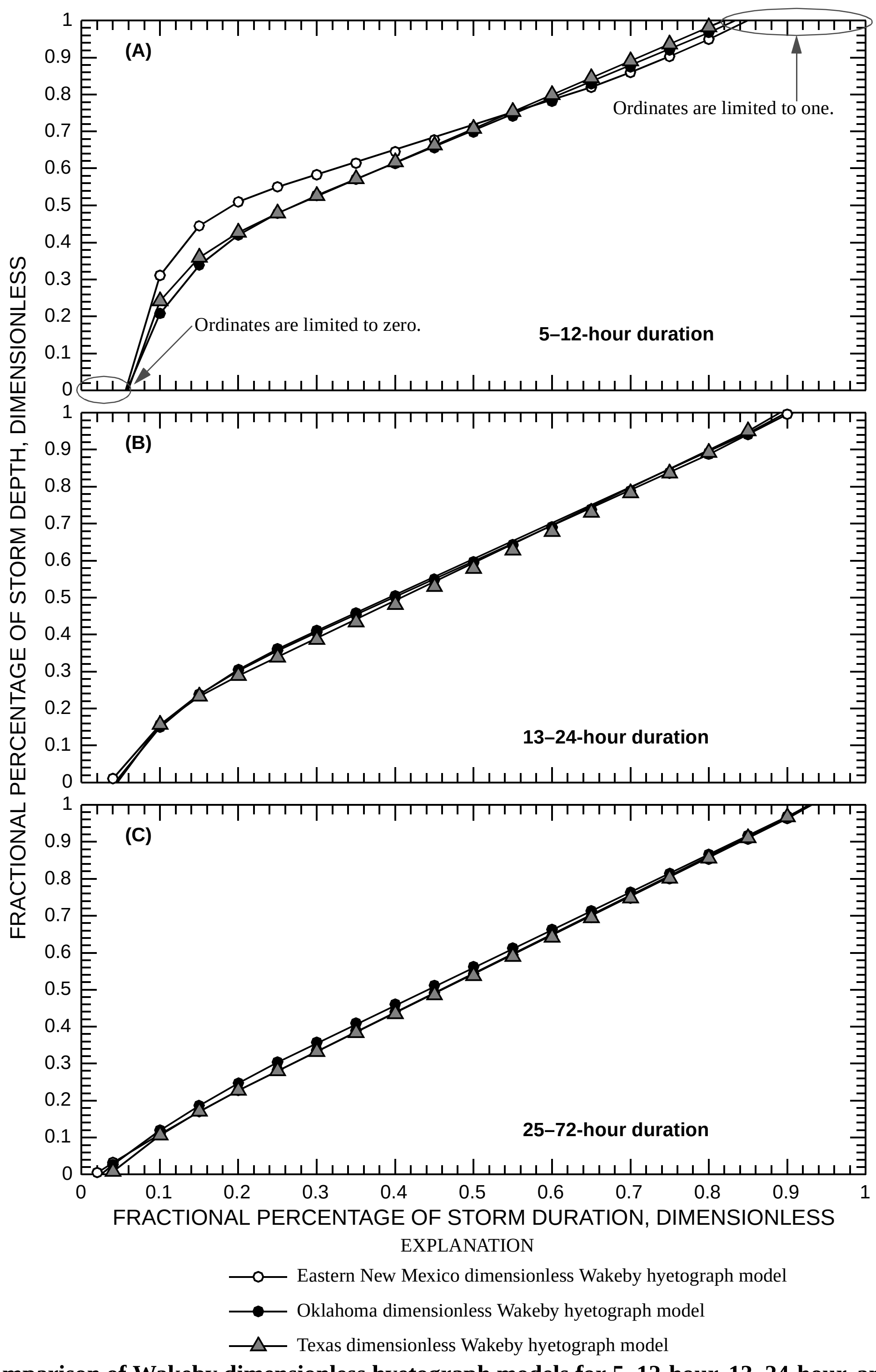

Figure 9. Comparison of Wakeby dimensionless hyetograph models for 5–12-hour, 13–24-hour, and 25–72-hour durations for eastern New Mexico, Oklahoma, and Texas for storms with at least 1 inch of rainfall.

L-gamma Hyetographs for Runoff-Producing Storms in Texas

Asquith (2003) and Asquith and Thompson (2003) provide hyetographs for runoff-producing storms in Texas based on what those reports refer to as the “L-gamma” distribution. The L-gamma distribution is

$$p(F) = F^b e^{c(1-F)}, \tag{11}$$

where $p(F)$ is the fractional percentage of rainfall depth for fractional percentage of storm duration F and $0 \le F \le 1$. The variables b and c are shape parameters that require estimation. Asquith (2003, ch. 6) provides further explanation and properties of the L-gamma distribution and provides a method to estimate the parameters of the distribution using L-moments.

The sample L-moments of 1,659 dimensionless hyetographs for runoff-producing storms in Texas were computed. Asquith and others (2004) describe the database; Asquith (2003) provides extensive discussion on how the computations were done. The L-moments for storms with at least 1 inch of rainfall are considered. To estimate the most likely or most suitable values of the mean and L-scale from the database, a graphical modal analysis was done for storms in each of three classifications for storm duration: 0–12 hours, 12–24 hours, and 24–72 hours. The analysis for the hyetograph means is summarized in figure 10, and the analysis for the L-scale statistics is summarized in figure 11. The most likely value (mode) for the hyetograph means and the L-scale values are each indicated by the labeled thin vertical line. The “Dallas” data were not used for the 24–72-hour duration (Asquith, 2003; Asquith and others, 2004). Asquith (2003) provides further explanation, ancillary figures, and justification for the selected graphically estimated modes.

The L-gamma distribution is fit to each pair of mean and L-scale statistics shown in figures 10 and 11. The estimated parameters (b, c) of the L-gamma distribution for the corresponding favorable statistic sets and duration are as follows: For the 0–12-hour duration the parameters (1.262, 1.227) result from mean and L-scale values of 67 and 17 percent, respectively. For the 12–24-hour duration the parameters (0.7830, 0.4368) result from mean and L-scale values of 66 and 15 percent, respectively. For the 24–72-hour duration the parameters (0.3388, -0.8152) result from the mean and L-scale values of 54 and 14 percent, respectively. See example 2 in the appendix for an application and solution for dimensionless L-gamma hyetographs.

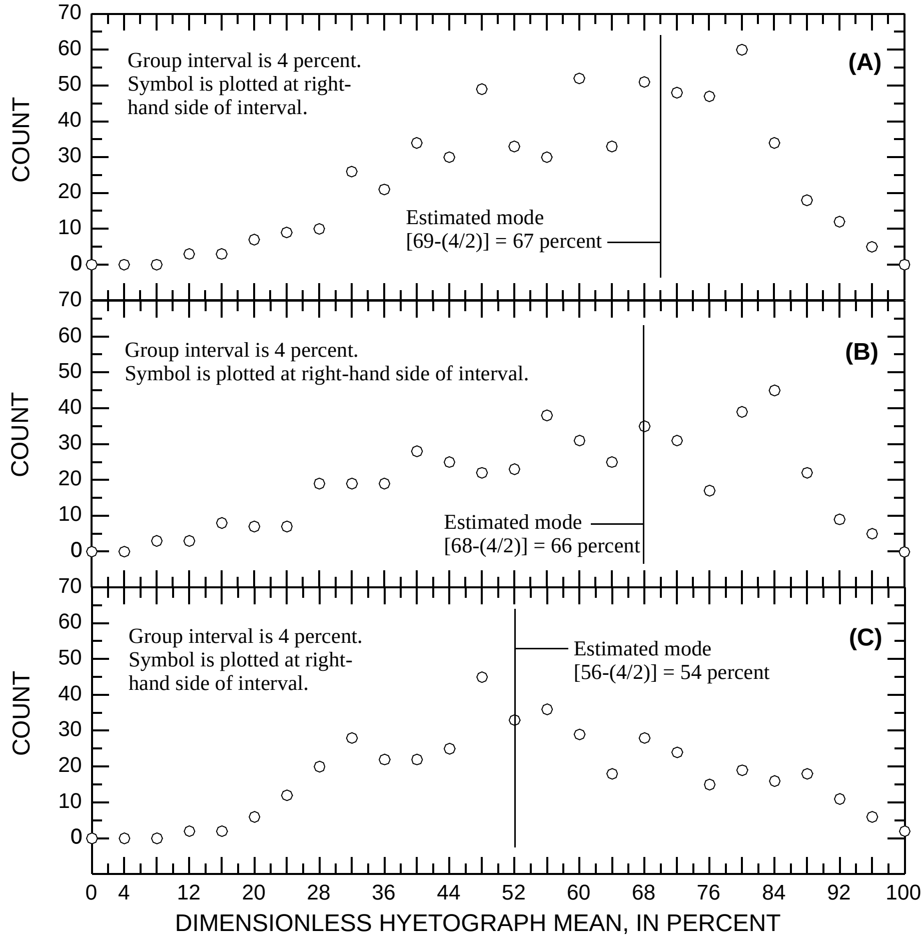

Figure 10. Modal analysis of mean statistics of dimensionless hyetographs for storms with at least 1 inch of rainfall. Graphs A, B, and C represent storm durations of 0–12 hours, 12–24 hours, and 24–72 hours, respectively.

The L-gamma distribution models of the expected hyetograph for the three durations based on the graphically estimated modes of the mean and L-scale statistics are shown in figure 12. The authors judge that the parameter values estimated from graphically estimated modes of the mean and L-scale provide reliable values for the expected hyetographs. Asquith (2003) elaborates on alternative values. From figure 12 it is apparent that the peak rainfall rates—steepest part of each curve—for all three L-gamma hyetographs are either at the beginning of the storm (12–24-hour and 24–72-hour duration) or at about 12 percent (0–12-hour duration). The general shapes of the hyetographs in figure 12 are great departures from the NRCS Type II or Type III hyetograph shapes shown in figure 1.

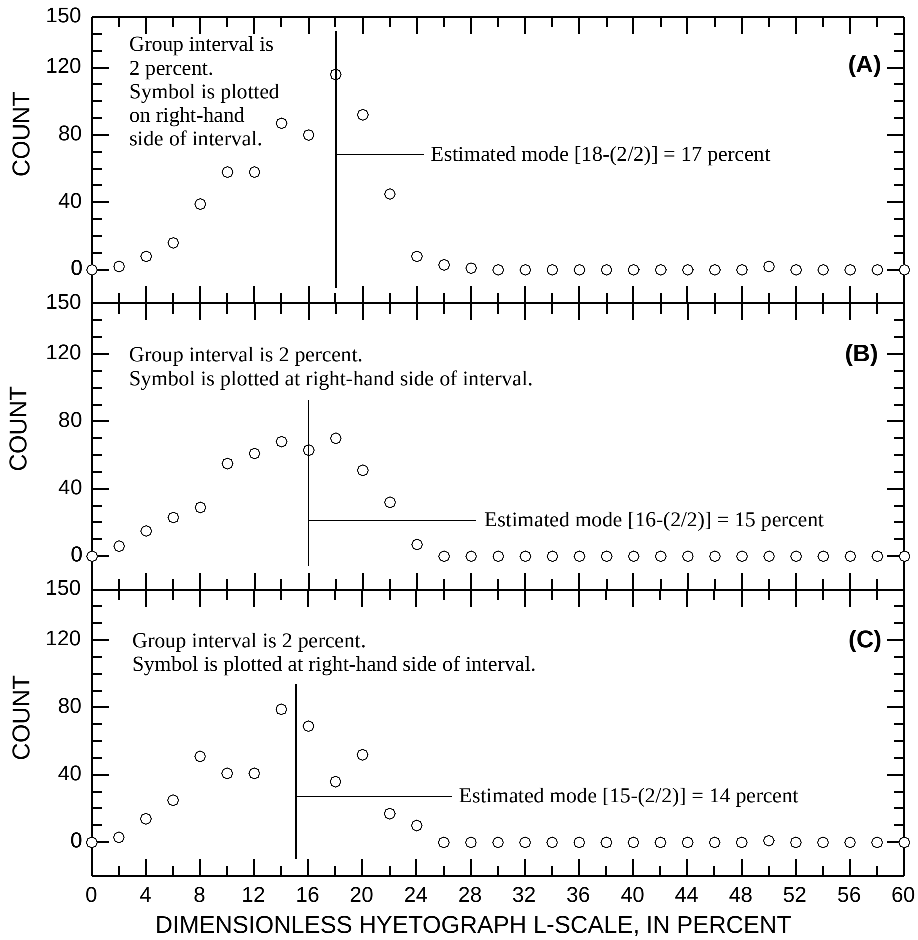

Figure 11. Modal analysis of L-scale statistics of dimensionless hyetographs for storms with at least 1 inch of rainfall. Graphs A, B, and C represent storm durations of 0–12 hours, 12–24 hours, and 24–72 hours, respectively.

Asquith (2003, p. 183) concludes that geography has little or no influence on the L-moments of hyetographs for the area represented by the database. This conclusion is consistent with the spatial characteristics of the triangular hyetograph models in the previous section. Asquith (2003, p. 183, fig. 47) also concludes that dimensionless hyetographs appear affected by the month or season of occurrence. Although the relations between the monthly mean of the mean, median, and L-scale statistics and the month of the calendar are vague, it appears that storms occurring in April through June and again in October and November are the most front-loaded. For purposes of design application, Asquith (2003) concludes that seasonal hyetograph variations are minor and are not a critical factor for expected hyetograph estimation.

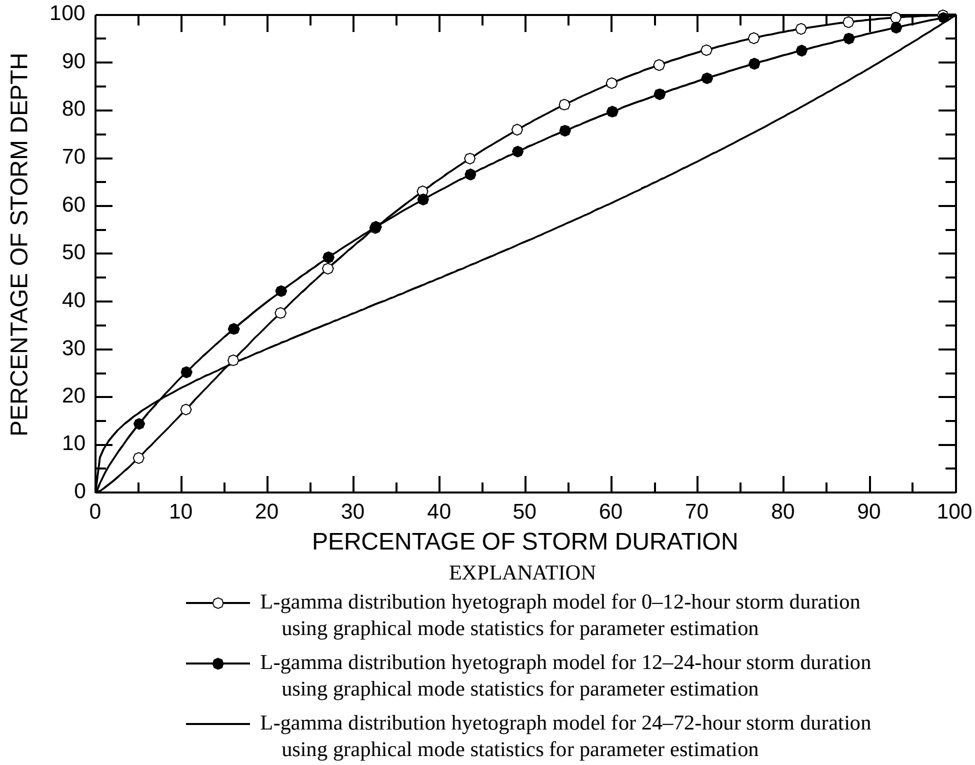

Figure 12. Comparison of L-gamma distribution hyetograph model for 0–12-hour, 12–24-hour, and 24–72-hour durations and at least 1 inch of rainfall.

Empirical Hyetographs by Asquith for Runoff-Producing Storms in Texas

Asquith (2003) provides empirical hyetographs from the runoff-producing storm database of Asquith and others (2004). Empirical hyetographs are produced from statistical analysis of the distribution of dimensionless hyetograph ordinates (percentage storm depth) for evenly spaced intervals of storm duration. An *n* th percentile of each interval defines the *n* th-percentile empirical hyetograph. Empirical hyetographs are constructed by decomposing each observed hyetograph (with dimension removed) into 2.5-percent wide intervals of percentage storm duration. For the hyetograph ordinates within each interval, percentiles and other statistics are computed. The distribution of hyetograph ordinates is investigated using these interval statistics. Empirical hyetographs provide graphics of the expected hyetograph without the need for interpretation of overall statistics (such as figs. 10 and 11) and a parametric model (L-gamma). Empirical hyetographs are straightforward to interpret. For example, the median of the distribution of hyetograph ordinates within each 2.5-percent interval of percentage storm duration defines the 50th-percentile empirical hyetograph. Empirical hyetograph analysis also documents the uncertainties in the expected hyetograph—a feature not provided by the L-gamma (and triangular and Wakeby models) hyetograph models.

The empirical hyetographs (10th, 25th, median, 75th, and 90th percentile) for the 0–12-hour duration are shown in figure 13. Also shown in the figure is the 0–12-hour expected hyetograph estimated by applying the L-gamma model. It is apparent that both the median empirical hyetograph and the L-gamma expected hyetograph are similar in shape and magnitude for most of the storm duration. Because the L-gamma model is estimated in a fundamentally different way than the median empirical hyetograph, the L-gamma curve is not expected to represent a best fit or even a fit specifically to the median empirical hyetograph. This statement also applies for the other two durations (figs. 14 and 15) presented next.

The empirical hyetographs (10th, 25th, median, 75th, and 90th percentile) and L-gamma model for the 12–24-hour duration are shown in figure 14. It is apparent that both the median empirical hyetograph and the L-gamma hyetograph are similar in shape and magnitude for most of the storm duration. The slopes of the median empirical hyetograph and the L-gamma hyetograph are similar except in approximately the first 15 percent of the storm duration. The L-gamma hyetograph model shape mimics the median empirical hyetograph through the first one-half of the storm. For the second one-half smaller rainfall rates are predicted.

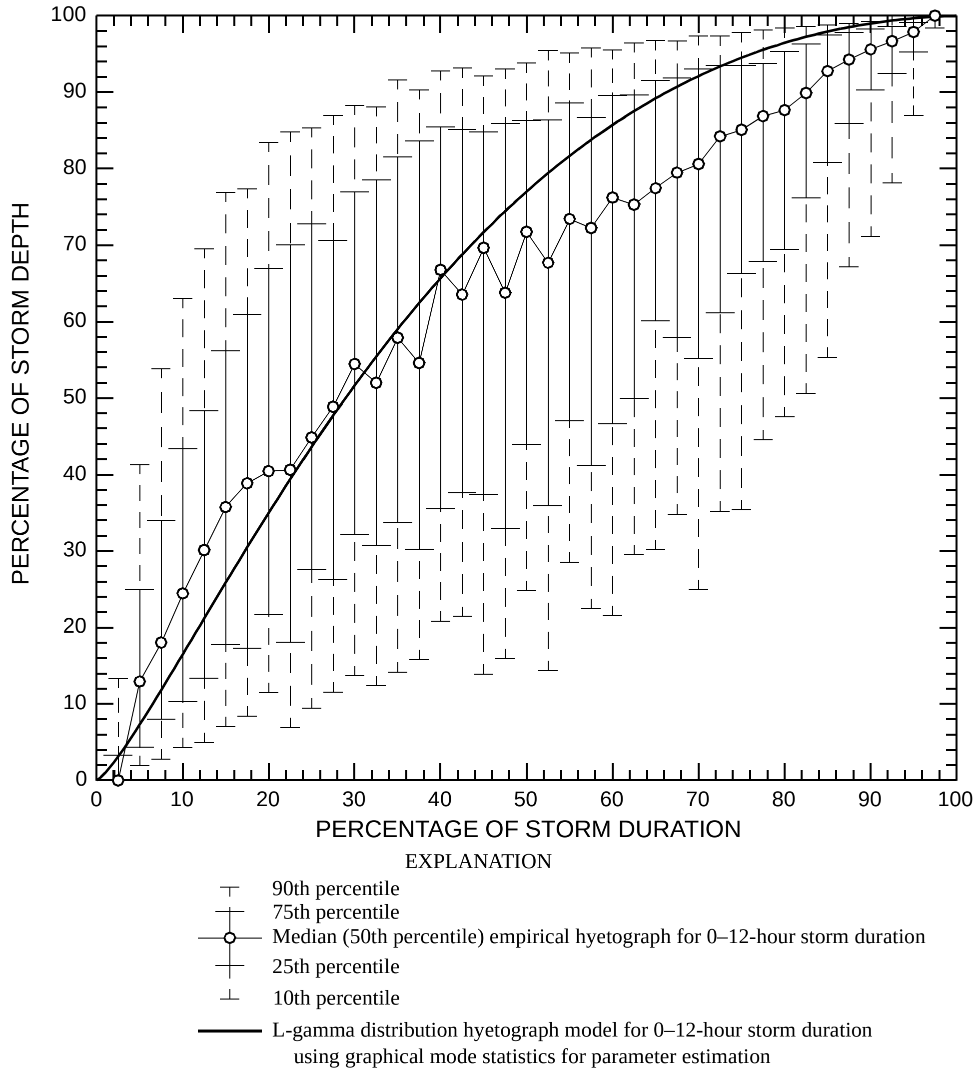

Figure 13. Empirical hyetographs and the L-gamma distribution hyetograph model for 0–12-hour duration and at least 1 inch of rainfall.

The empirical hyetographs (10th, 25th, median, 75th, and 90th percentile) and L-gamma model for the 24–72-hour duration are shown in figure 15. It is apparent that both the median empirical hyetograph and the L-gamma hyetograph are similar in shape and magnitude for most of the storm duration. The general slope of the median empirical hyetograph and the L-gamma hyetograph are similar throughout most of the storm duration. The fact that both the median empirical hyetograph and the L-gamma hyetograph bend upward as they approach the end of the storm duration enhances the credibility of the oddly shaped L-gamma model for the 24–72-hour duration compared with the general shapes of the other two durations.

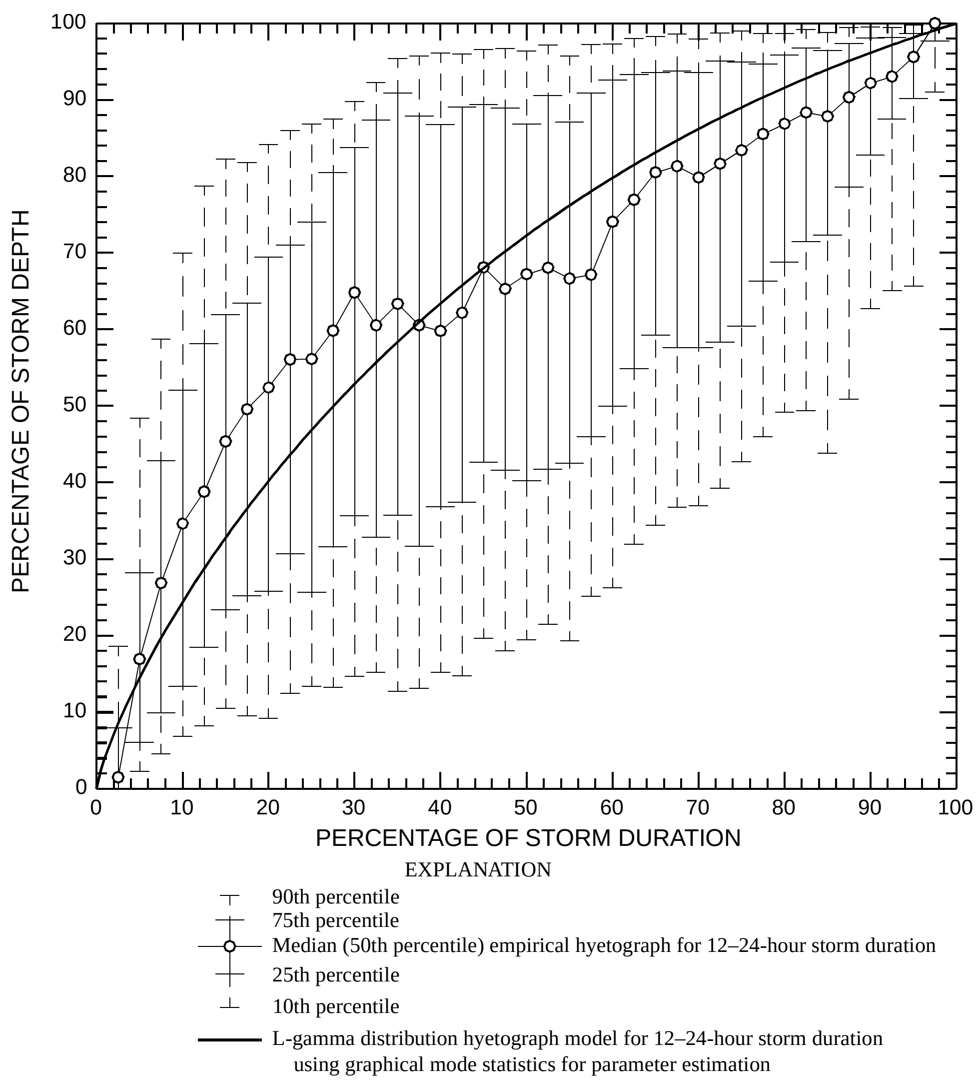

Figure 14. Empirical hyetographs and the L-gamma distribution hyetograph model for 12–24-hour duration and at least 1 inch of rainfall.

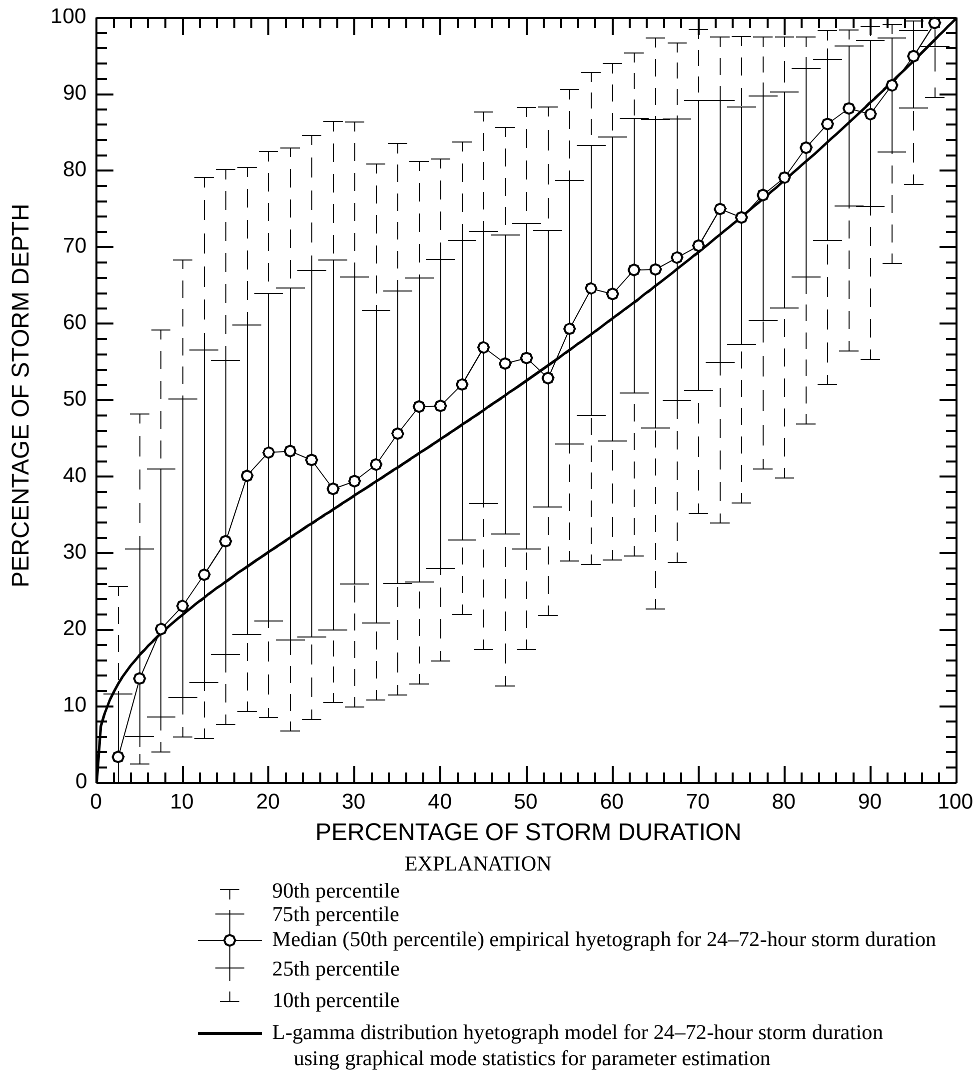

Figure 15. Empirical hyetographs and the L-gamma distribution hyetograph model for 24–72-hour duration and at least 1 inch of rainfall.

Tables 10–12 (modified from Asquith, 2003, tables F7–9) list the graphically smoothed values of the 10th, 25th, 50th, 75th, and 90th percentiles shown in figures 13–15 and listed in Asquith (2003, tables F1, F3, and F5) for the 0–12-hour, 12–24-hour, and 24–72-hour storm durations. The smoothed values are not represented in figures 13–15. The smoothed values are provided in tabular form to increase the applicability of the percentiles in hydrologic design applications because the smoothed percentiles monotonically increase with percentage of storm duration. A sophisticated curvilinear smooth algorithm was not used. However, the analysis by Williams-Sether and others (2004) provides preferable documentation of empirical hyetographs from the runoff-producing storm data base.

Table 10. Graphically smoothed percentile (of percentage of storm depth) statistics for empirical hyetographs for runoff-producing storms in Texas with 0–12-hour duration and at least 1 inch of rainfall (modified from Asquith, 2003, table F7)

Center of percentage of storm duration interval (percent)	Median 50th percentile (percent)	Lower quartile 25th percentile (percent)	Upper quartile 75th percentile (percent)	Lower decile 10th percentile (percent)	Upper decile 90th percentile (percent)
2.5	3.00	2.00	6.00	1.00	9.00
5.0	11.00	4.42	25.00	2.00	41.30
7.5	18.04	8.05	34.00	2.80	53.83
10.0	24.45	10.36	43.37	4.33	63.02
12.5	30.13	13.40	48.36	4.94	69.53
15.0	35.75	15.00	56.21	7.04	76.93
17.5	38.87	17.34	61.00	8.00	80.00
20.0	40.46	20.00	67.50	8.00	83.45
22.5	42.00	22.00	70.04	8.50	84.78
25.0	44.84	24.00	72.82	9.47	85.37
27.5	48.86	26.50	74.00	11.56	87.02
30.0	51.50	30.00	76.95	13.00	88.10
32.5	54.00	30.75	78.56	14.00	88.33
35.0	56.50	32.00	81.57	14.21	89.00
37.5	59.50	33.00	83.61	15.82	90.31
40.0	62.00	34.00	84.50	16.50	91.00
42.5	63.54	36.00	85.00	17.50	91.50
45.0	66.00	36.50	85.11	18.00	92.12
47.5	68.00	37.50	85.91	19.50	93.03
50.0	70.00	39.50	86.28	20.00	93.84
52.5	71.00	40.50	86.38	21.00	95.00
55.0	72.50	42.00	87.00	22.00	95.13
57.5	73.50	44.00	88.00	22.47	95.55
60.0	75.00	46.65	89.59	25.00	95.82
62.5	76.50	50.00	89.70	27.50	96.44
65.0	77.45	53.00	91.57	30.16	96.71
67.5	79.49	56.00	91.90	32.00	96.76
70.0	81.50	58.00	93.06	33.50	97.32
72.5	83.50	61.14	93.47	35.21	97.38
75.0	85.07	65.00	93.50	38.50	97.80
77.5	86.88	67.89	93.77	43.50	98.17
80.0	87.66	72.00	95.32	47.56	98.38
82.5	89.90	76.21	96.32	50.63	98.62
85.0	92.76	80.81	97.50	55.34	98.80
87.5	94.27	85.91	97.82	64.00	99.00
90.0	95.60	90.30	98.30	71.15	99.26
92.5	96.67	92.48	98.65	78.16	100.0
95.0	97.86	95.22	99.14	86.99	100.0
97.5	99.40	98.90	99.90	98.42	100.0

Table 11. Graphically smoothed percentile (of percentage of storm depth) statistics for empirical hyetographs for runoff-producing storms in Texas with 12–24-hour duration and at least 1 inch of rainfall (modified from Asquith, 2003, table F8)

Center of percentage of storm duration interval (percent)	Median 50th percentile (percent)	Lower quartile 25th percentile (percent)	Upper quartile 75th percentile (percent)	Lower decile 10th percentile (percent)	Upper decile 90th percentile (percent)
2.5	3.00	1.50	7.97	1.00	18.61
5.0	16.94	6.07	28.21	2.27	48.43
7.5	26.87	9.90	42.88	4.61	58.75
10.0	34.64	13.41	52.06	6.85	69.96
12.5	38.81	18.53	58.18	8.22	78.73
15.0	45.37	23.00	61.99	9.00	81.50
17.5	49.58	25.19	63.42	9.55	83.50
20.0	52.42	25.82	68.50	10.50	84.20
22.5	55.50	27.50	71.06	12.00	86.03
25.0	57.50	29.50	74.01	13.00	86.85
27.5	59.84	31.00	80.50	13.26	87.49
30.0	60.50	32.00	83.74	14.00	89.79
32.5	61.50	32.87	86.50	14.50	92.29
35.0	62.00	34.50	87.50	14.76	94.50
37.5	63.00	35.50	87.87	15.00	95.75
40.0	63.50	36.87	88.50	15.50	95.98
42.5	64.00	37.43	89.07	15.50	96.10
45.0	65.30	39.00	89.43	17.00	96.59
47.5	65.50	39.50	88.50	18.04	96.39
50.0	67.22	40.27	89.50	19.47	96.70
52.5	68.06	41.78	90.58	21.49	97.00
55.0	70.00	42.58	90.87	22.50	97.00
57.5	71.00	46.01	91.00	24.00	97.22
60.0	73.00	49.50	92.61	27.50	97.28
62.5	76.00	54.90	93.30	32.00	98.04
65.0	77.50	57.00	93.59	34.42	98.26
67.5	80.00	57.62	93.82	36.80	98.50
70.0	81.00	57.63	94.00	38.00	98.62
72.5	81.65	58.37	94.50	39.25	98.70
75.0	83.41	60.43	94.94	42.75	98.73
77.5	85.53	66.34	95.50	45.50	98.76
80.0	86.88	68.84	95.88	48.00	98.80
82.5	88.35	71.49	96.82	49.44	99.10
85.0	90.00	72.34	96.46	50.50	99.20
87.5	90.50	78.62	97.35	53.00	99.45
90.0	92.19	82.80	98.11	60.50	99.47
92.5	93.04	87.48	98.17	65.05	99.53
95.0	95.59	90.20	98.70	67.00	99.77
97.5	98.00	97.00	99.50	91.05	100.0

Table 12. Graphically smoothed percentile (of percentage of storm depth) statistics for empirical hyetographs for runoff-producing storms in Texas with 24–72-hour duration and at least 1 inch of rainfall (modified from Asquith, 2003, table F9)

Center of percentage of storm duration interval (percent)	Median 50th percentile (percent)	Lower quartile 25th percentile (percent)	Upper quartile 75th percentile (percent)	Lower decile 10th percentile (percent)	Upper decile 90th percentile (percent)
2.5	5.00	2.50	11.63	0.50	25.68
5.0	13.64	6.06	30.58	2.44	48.26
7.5	20.11	8.59	41.01	4.06	59.20
10.0	24.00	11.12	50.16	5.99	68.39
12.5	27.20	13.14	54.00	7.00	78.00
15.0	31.58	16.74	57.00	7.65	80.18
17.5	35.50	18.00	59.85	8.50	81.50
20.0	37.50	19.00	63.97	8.54	82.51
22.5	39.50	19.50	64.71	9.00	83.03
25.0	40.00	20.00	66.00	9.50	84.00
27.5	41.00	20.02	66.13	9.96	84.50
30.0	42.00	21.00	66.50	10.00	84.50
32.5	43.00	21.50	66.70	10.83	84.50
35.0	45.64	23.00	67.00	11.48	84.50
37.5	47.50	25.00	67.50	12.91	84.50
40.0	49.27	28.02	68.39	15.50	85.00
42.5	52.07	30.00	70.00	17.00	85.00
45.0	54.00	31.00	72.08	17.49	85.50
47.5	56.00	31.50	72.50	18.00	87.00
50.0	57.00	33.00	73.11	19.50	88.29
52.5	58.00	36.09	74.00	21.91	88.37
55.0	59.35	41.00	77.50	26.00	90.62
57.5	61.00	44.00	81.00	28.54	92.00
60.0	63.50	44.71	84.44	29.14	93.99
62.5	66.00	45.50	85.50	29.65	95.44
65.0	67.10	46.42	86.73	30.00	96.00
67.5	68.66	49.00	86.79	31.00	96.73
70.0	70.21	51.32	88.00	32.50	97.00
72.5	72.50	54.95	89.00	33.97	97.47
75.0	73.90	57.27	89.00	36.60	97.58
77.5	76.82	60.45	89.78	40.00	97.70
80.0	79.11	62.07	90.28	43.00	98.00
82.5	83.01	66.16	92.50	46.92	98.20
85.0	85.00	70.94	94.57	52.04	98.32
87.5	88.00	74.00	96.34	55.50	98.41
90.0	89.00	75.35	97.04	60.00	98.86
92.5	91.16	82.46	97.40	67.88	99.15
95.0	94.96	88.20	98.32	78.19	99.55
97.5	98.50	96.22	99.50	89.63	100.0

Empirical Hyetographs by Williams-Sether and Others for Runoff-Producing Storms in Texas

Williams-Sether and others (2004) provide comprehensive analysis of empirical hyetographs for runoff-producing storms in Texas using the database of Asquith and others (2004). Their analysis is substantially independent of the empirical hyetograph analysis of Asquith (2003).

Williams-Sether and others (2004), following the analytical approach of Huff (1967), provide statistics for empirical dimensionless hyetographs. These are presented along with hyetograph curves and tables. The curves and tables do not present exact mathematical relations but can be used to estimate distributions of rainfall with time for small drainage areas. Williams-Sether and others (2004) provide extensive supplemental tables. This section summarizes and graphically illustrates the research by Williams-Sether and others (2004).

Storm-quartile classifications are determined from the rainfall values, which were divided into data groups on the basis of storm-quartile classification (first, second, third, fourth, and first through fourth combined), storm duration (0–6, 6–12, 12–24, 24–72, and 0–72 hours), and rainfall amount (1 inch or more). The storm-quartile classification depends upon when the greatest rate of rainfall occurred during the storm duration. Because of both long leading and trailing hyetograph tails, two data groups, untrimmed and trimmed, were used for analysis. (Asquith, 2003 also discussed tail trimming in the context of the same database.) The analysis of the trimmed data is judged most reliable and applicable to hydrologic design.

Averages and ranges for the rainfall amounts for the untrimmed and trimmed data groups are listed in table 13. The distribution of storm occurrences by quartile for both groups is listed in table 14. Removing the leading tails increased the number of first-quartile occurrences for all storm durations in the trimmed data group. The number of second- and third-quartile occurrences increased for storm durations of 0–6 hours and 6–12 hours, and the fourth-quartile occurrences increased slightly for a storm duration of 0–6 hours. Between 47 and 51 percent of the 1,507 storms used were classified as first quartile in the trimmed data group if the storm duration was 12 hours or less. If the storm duration was 12–24 hours or 24–72 hours, 47 and 38 percent of the storms were classified as first quartile in the trimmed data group. These results are slightly different from those given by Pani and Haragan (1981) who classified most storms in their Texas rainfall database as second and third quartile. For a storm duration of 0–72 hours, the first-, second-, third-, and fourth-quartile storms in the trimmed data group accounted for 46, 21, 20, and 13 percent of all storms, respectively.

Probability percentiles of the dimensionless hyetograph allow the selection of a temporal rainfall distribution that is most appropriate (or critical) for a particular application. In some cases, a median (50th-percentile) distribution of rainfall with time might be most useful, and in other cases, either the 10th- to 90th-percentile hyetographs might be most useful. The median dimensionless hyetograph curves for first- through fourth-quartile storms and for a combination of the first- through fourth-quartile storms are shown in figure 16 for a storm duration of 0–72 hours. The 10th- to 90th-percentile curves are shown in figure 17. The curves shown in both figures are for the trimmed data group. See example 3 in the appendix for estimation of a first-quartile 90th-percentile hyetograph.

Table 13. Averages and ranges of rainfall amounts for selected ranges of storm duration for runoff-producing storms in Texas

Storm duration (hours)	Untrimmed data group		Trimmed data group	
	Average rainfall amount (inches)	Range of rainfall amount (inches)	Average rainfall amount (inches)	Range of rainfall amount (inches)
	First-quartile storms, untrimmed data group		First-quartile storms, trimmed data group	
0–6	1.99	1–5.76	1.97	1–5.76
6–12	2.56	1–10.95	2.51	1–10.95
12–24	3.02	1.07–9.35	2.98	1.07–9.35
24–72	3.25	1–8.44	3.25	1–8.44
0–72	2.68	1–10.95	2.67	1–10.95
	Second-quartile storms, untrimmed data group		Second-quartile storms, trimmed data group	
0–6	1.83	1–3.55	1.82	1–3.55
6–12	2.60	1.01–4.36	2.61	1.01–5.04
12–24	3.17	1.17–6.99	3.23	1.07–7.26
24–72	3.68	1.34–8.45	3.82	1.41–8.45
0–72	2.86	1–8.45	2.83	1–8.45
	Third-quartile storms, untrimmed data group		Third-quartile storms, trimmed data group	
0–6	1.77	1–3.68	1.80	1–3.68
6–12	2.27	1–5.47	2.32	1–5.47
12–24	2.47	1.07–4.90	2.66	1.18–4.90
24–72	3.68	1.05–8.89	3.95	1.39–8.89
0–72	2.79	1–8.89	2.84	1–8.89
	Fourth-quartile storms, untrimmed data group		Fourth-quartile storms, trimmed data group	
0–6	1.71	1.03–2.93	1.68	1.03–2.93
6–12	1.97	1.02–3.97	2.02	1.02–3.97
12–24	2.31	1.06–5.42	2.34	1.06–5.42
24–72	3.88	1.02–19.26	4.57	1.56–19.26
0–72	2.75	1.02–19.26	2.82	1.02–19.26

Williams-Sether and others (2004) specifically conclude that the hyetograph curves and tables can be used to estimate distributions of rainfall with time for small drainage areas (less than about 160 square miles) in urban and small rural watersheds in Texas. However, for purposes of design the authors of this report recognize that 160 square miles could be considered too large to expect a single dimensionless hyetograph to properly represent the temporal distribution of design storms.

Table 14. Distribution of storm occurrences by quartile for runoff-producing storms in Texas
[Number in parenthesis is percent of total.]

Storm-quartile classification	Storm duration (hours)									
	0 to 6		6 to 12		12 to 24		24 to 72		0 to 72	
	Untrimmed data group	Trimmed data group	Untrimmed data group	Trimmed data group	Untrimmed data group	Trimmed data group	Untrimmed data group	Trimmed data group	Untrimmed data group	Trimmed data group
First	157 (57)	173 (51)	136 (44)	161 (47)	187 (39)	220 (47)	102 (25)	135 (38)	582 (39)	689 (46)
Second	90 (29)	96 (29)	50 (16)	62 (18)	106 (22)	91 (19)	90 (22)	75 (21)	336 (22)	324 (21)
Third	47 (15)	50 (15)	70 (23)	74 (21)	102 (21)	78 (17)	133 (33)	95 (26)	352 (23)	297 (20)
Fourth	15 (5)	17 (5)	53 (17)	47 (14)	85 (18)	79 (17)	84 (20)	54 (15)	237 (16)	197 (13)
All	309 (100)	336 (100)	309 (100)	344 (100)	480 (100)	468 (100)	409 (100)	359 (100)	1,507 (100)	1,507 (100)

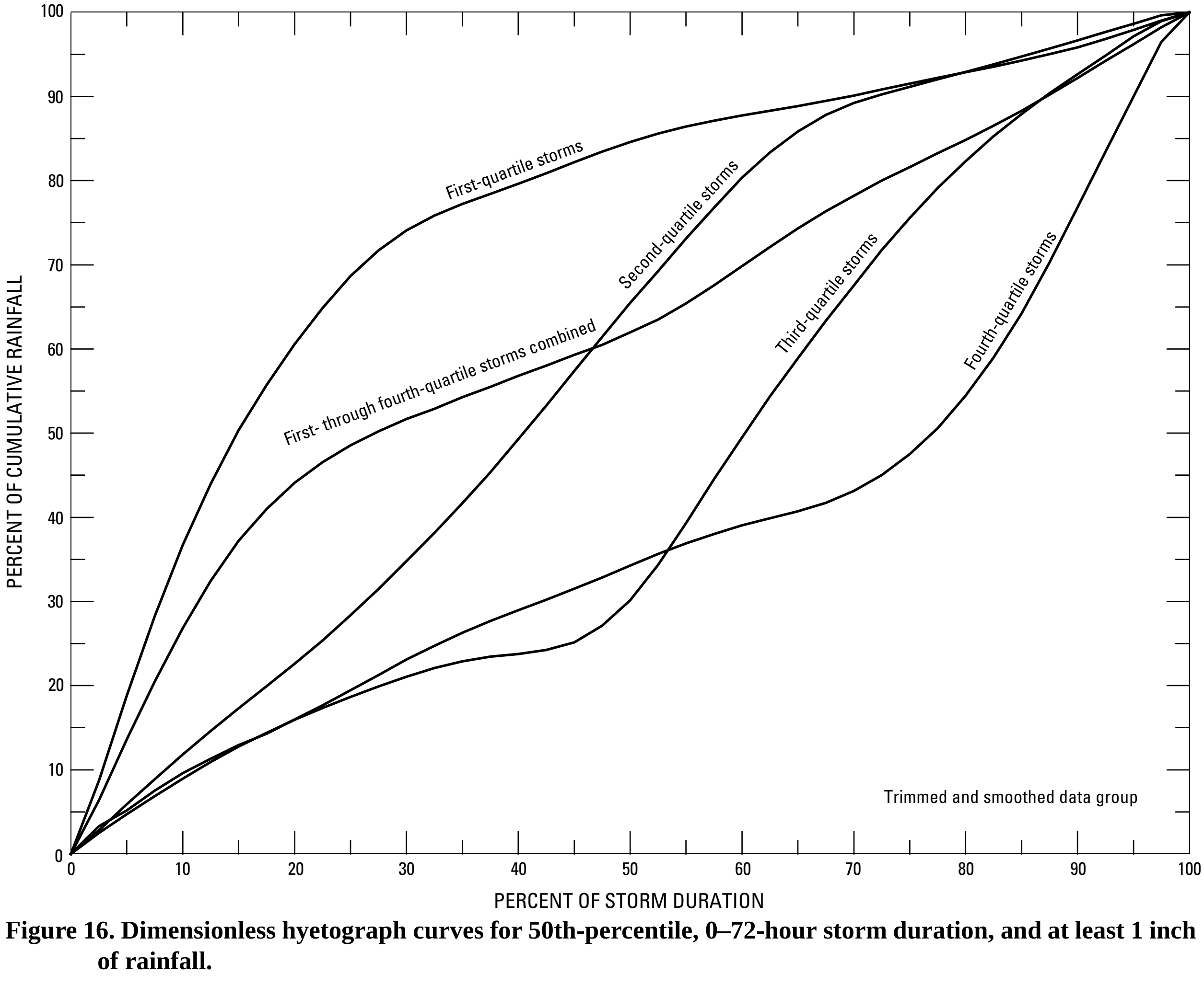

Figure 16. Dimensionless hyetograph curves for 50th-percentile, 0–72-hour storm duration, and at least 1 inch of rainfall.

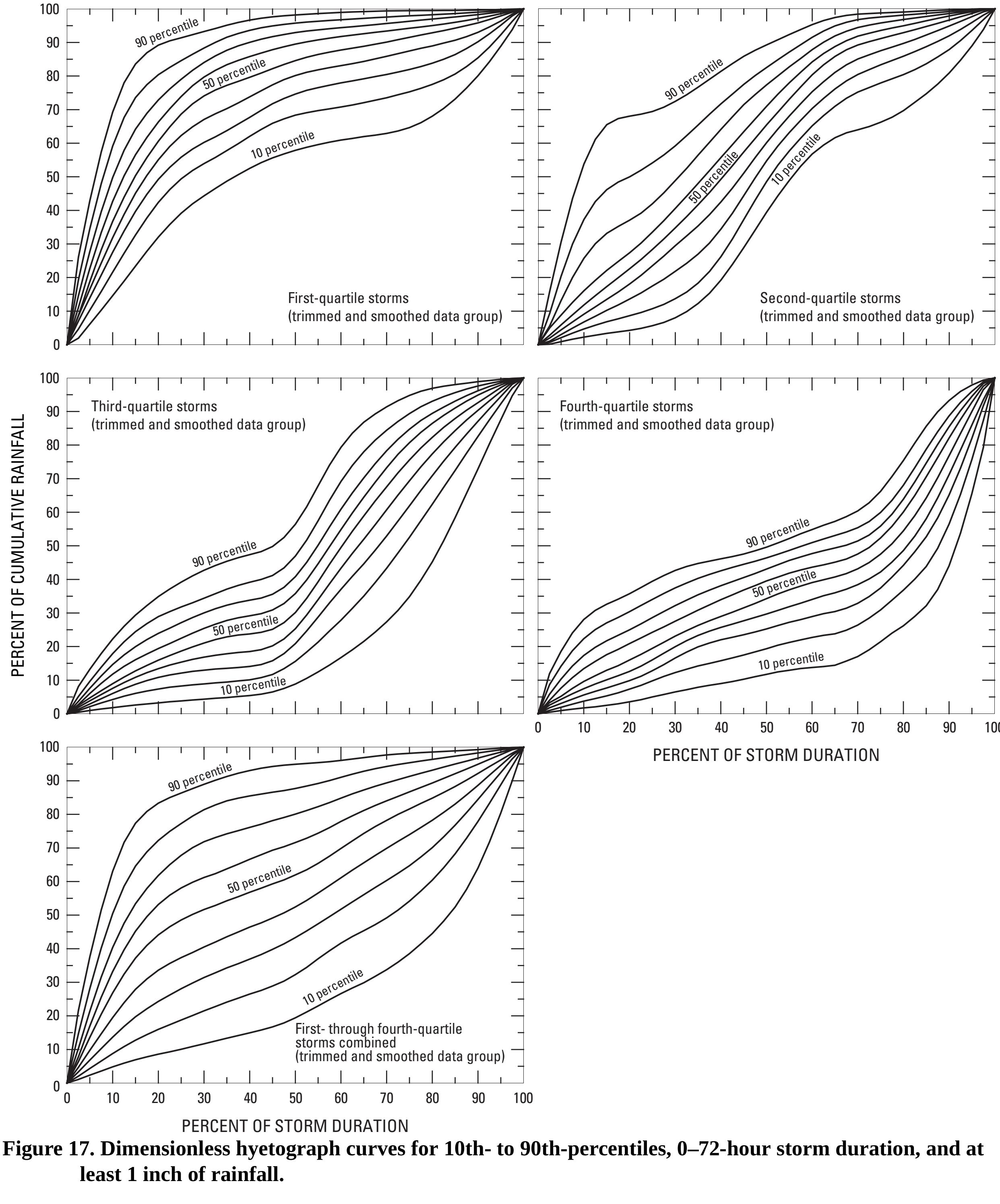

Figure 17. Dimensionless hyetograph curves for 10th- to 90th-percentiles, 0–72-hour storm duration, and at least 1 inch of rainfall.

DISTRIBUTION OF STORM DEPTH FOR TEXAS

This section provides details of the statistical analysis of storm depth for events extracted from the NWS hourly rainfall database described in section "Triangular and Wakeby Hyetographs from National Weather Service Hourly Rainfall Stations." Statistical analysis of storm events for each station was done and site-specific values of the L-moments of storm depth were computed. After the site-specific L-moments were available, a regional analysis was used to develop a procedural framework to estimate the statistics for a particular location. These statistics are necessary for detailed assessment of the performance of a "best-management practice" (BMP) in the context of total rainfall inputs to the watershed. A regional analysis is important because site-specific L-moments of storm depth are highly variable in both space and time. Many rainfall stations have short record, which implies more error for estimates of site-specific rainfall statistics. The regional analysis also provides a method to estimate more reliable statistics.

Minimum Interevent Time of Rainfall

Before the site-specific L-moments can be computed, it is necessary to establish a method to define distinct events from the hourly time series of rainfall data. Typically, distinct storms are defined using a minimum time interval of no rainfall; this time interval is referred to as a minimum interevent time (MIT).

A time series of hourly rainfall data consists of sequences of rainfall pulses. Some pulses are consecutive whereas other pulses are clustered into groups of consecutive values separated by "short" intervals of zero values. As the intervals of zero rainfall become "long," it is natural to categorize the intervals of rainfall into distinct events. Brief periods of zero rainfall (intrastorm zero values) can be and often are present within a particular storm.

One approach to distinguish between short and long time intervals is to do an autocorrelation analysis with the rainfall time series (optimal minimum interevent time). Another approach is to identify long time intervals according to the draw down or drainage time of a BMP (structural minimum interevent time). The next two sections discuss each approach.

Optimal Minimum Interevent Time

Autocorrelation measures the statistical dependency of rainfall data at a given time with the rainfall data at an earlier, or lagged, time in the time series. The space between data points to correlate is known as a lag time. If the lag time is zero, then the autocorrelation coefficient is unity (one), and a one-to-one correlation exists. As the lag time increases, however, the statistical correlation of rainfall data decreases from one to values approaching zero as rainfall becomes increasingly statistically independent; in other words, rainfall pulses become uncorrelated and therefore unrelated in time.

The meaning of "uncorrelated" requires further explanation. Logic suggests, for a given location, that rainfall on the morning of January 1, 2001, does not influence the likelihood of a storm occurring on the morning of January 1, 2002 (a year later). However, it would not be unreasonable to expect rainfall during the afternoon of January 1, 2001, because of the well-recognized temporal persistence of rainfall-producing weather.

A plot of the autocorrelation coefficient with respect to the lag time is used to determine the minimum lag time for which the autocorrelation coefficient is acceptably close to zero. This lag time is the optimal MIT; the minimum interval of no rainfall in which rainfall pulses can be considered distinct.

A plot of the autocorrelation coefficient for lag times of 0–24 hours for 449 NWS hourly rainfall stations in Texas with 5 or more years of data is shown in figure 18. Each of the many thin lines represents the autocorrelation coefficients for a single station. Superimposed on the lines are boxplots showing the distribution of autocorrelation values for each lag time. The anticipated decrease in autocorrelation coefficient with lag time is evident. The lag time for which the median autocorrelation coefficient begins to level off is judged to be between 8 and 9 hours.

The autocorrelation coefficients shown in figure 18 represent those available across Texas. It is natural to consider geographic partitioning of the MIT. Rainfall characteristics show large systematic changes from east to west across Texas (Bomar, 1995; Asquith, 1998; and Asquith and Roussel, 2003, 2004). Thus it is useful to consider autocorrelation coefficients for stations ranging from the deserts of far-West Texas to the humid forests of East Texas. The autocorrelation analysis for five selected long-term stations is shown in figure 19. From the figure, no definitive change in autocorrelation coefficient from East to West Texas is evident. A cursory analysis (results not presented here) of the autocorrelation coefficient for various regions of eastern New Mexico, Oklahoma, and Texas suggests that applying a single value of MIT throughout provides a convenient trade off between accuracy and analytical complexity. Thus an assumption for this report is that a single, optimal value for MIT is applicable throughout the study area. Weaknesses in this assumption are mitigated by the consideration of structural MITs, which are considered in the next section. Finally, although an 8- to 9-hour range is evident, for this report 8 hours is considered as the optimal MIT.

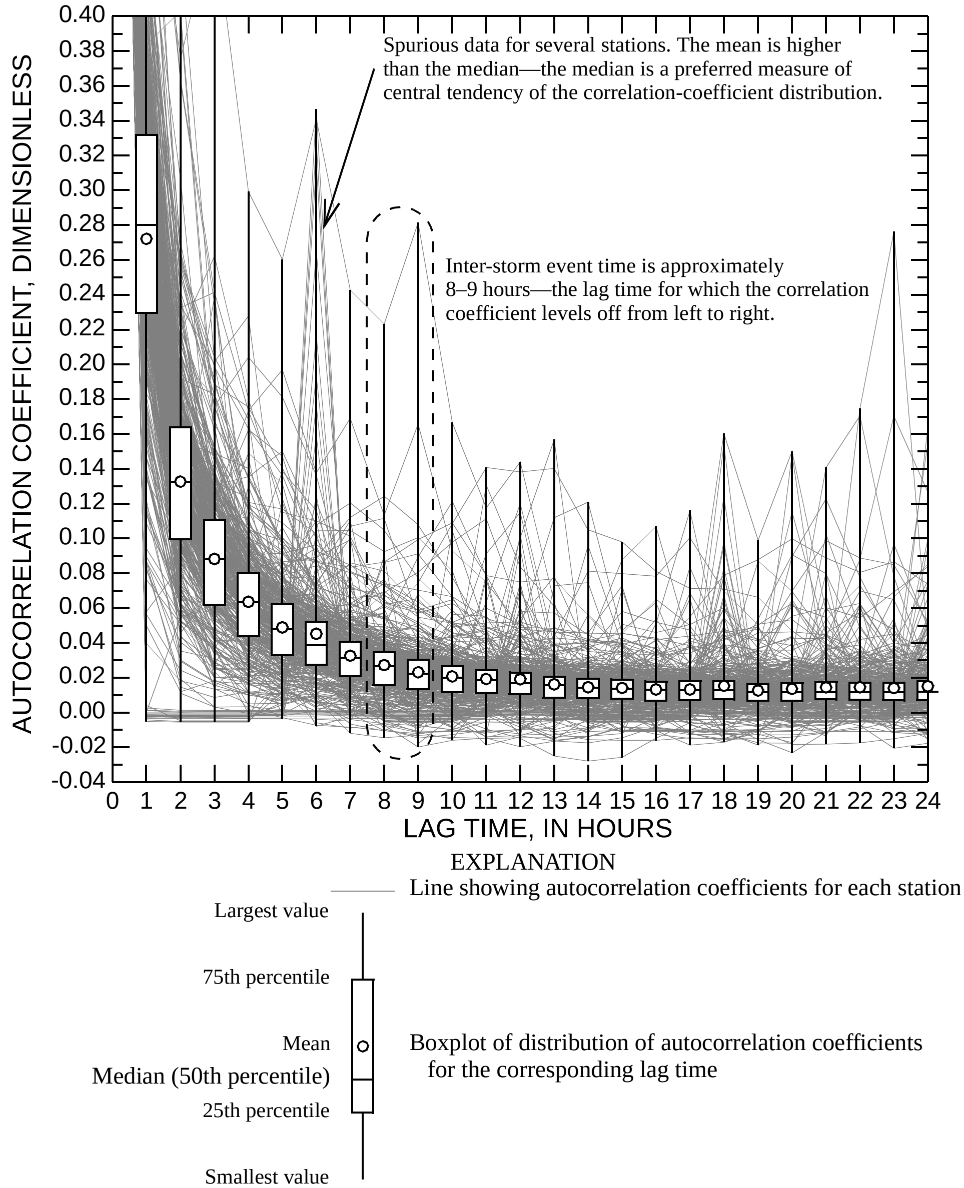

Figure 18. Autocorrelation coefficient as a function of lag time for all hourly rainfall stations in Texas with 5 or more years of data.

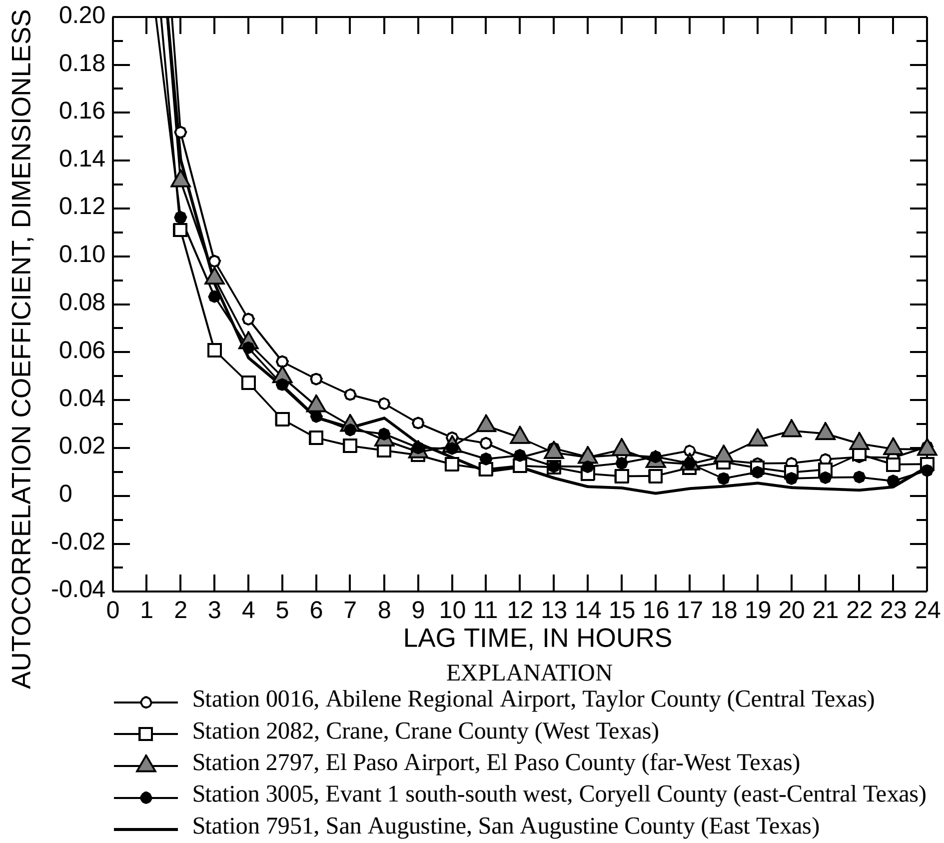

Figure 19. Autocorrelation coefficient as a function of lag time for five selected long-term hourly rainfall stations in Texas.

Structural Minimum Interevent Time

The optimal MIT described in the previous section was selected on the basis of the statistics of rainfall. An alternative definition for MIT is available based on the design characteristics of a BMP. BMP design is influenced by requirements for the draw down time, infiltration time, or treatment time—a structural MIT. The L-moments of storm depth for structural MITs are considered together with the 8-hour MIT.

To clarify the concept of structural MIT, consider a hypothetical city ordinance that requires BMPs, which start from full storage conditions and no additional excess rainfall input and end with completely drained conditions in not less than 48 hours. By convention, a 48-hour draw down time is used for BMP design by the city. If storm statistics are defined by a 48-hour MIT instead of the optimal 8-hour MIT, then the BMP in the context of excess rainfall input is said to be “memoryless.” The longer MIT, in other words, ensures that storage in the BMP is zero prior to the excess rainfall from the next storm arriving. Wanielista and Yousef (1993, p. 222–223) discuss a structural MIT (although not identifying it as such) set by the infiltration time so that the “infiltration pond” (a BMP) will be empty before the next storm begins.

Six selected values of structural MIT were chosen for the analysis. These interevent times are 6, 12, 18, 24, 48, and 72 hours. This MIT range is expected to provide adaptability and hence a great range of applications stemming from this report. The shortest MIT specifically was chosen to be less than the 8-hour MIT so that critical review of the 8-hour MIT is possible. By considering numerous values for the MIT, users of this report are able to interpolate statistics to MITs not considered here.

Distribution of Storm Depth

For each of the selected MITs, the time series of hourly rainfall for each station was parsed or separated into sequences of storms for subsequent computation of storm-depth L-moments. As part of the statistical analysis, several assumptions regarding the rainfall data, the extracted storms, and the computed statistics were made. The assumptions follow and extend Adams and Papa (2000, p. 60). The assumptions, not all mutually exclusive, are

1. Rainfall events defined by the MIT are assumed to be samples drawn from an underlying population.
2. Rainfall events are assumed to be homogeneous—that is the events are generated from the same population.
3. The MIT adequately ensures that each event is statistically independent from the others.
4. The processes that generated the events throughout the record for each rainfall station do not change with time. There are no historical changes to the frequency of storms or the distributions of depth and duration.
5. The processes that generated the events throughout the year for each rainfall station do not change with time. Seasonal differences in storm statistics can be ignored.

Nine selected percentiles characterize the observed distribution of storm depth and duration. A site-specific storm-depth distribution example for station 0016 Abilene Regional Airport is shown in figure 20. The distribution has been graphed on normal probability paper. Hourly rainfall data are reported to the nearest 0.01 inch. The step pattern on the left-hand side of the curve exists because of the limited resolution of the data in depth.

The L-moment statistics (Hosking, 1990) of the observed storm-depth distribution were computed for the data shown in figure 20. The L-moments considered are the mean, L-scale, coefficient of L-variation (L-CV), L-skew, L-kurtosis, and Tau5. L-CV is dimensionless and is defined as the ratio of L-scale to the mean. L-skew, L-kurtosis, and Tau5 also are dimensionless. The L-moments for a given station were considered missing values unless five or more storms were in the data record. The L-moments were not computed if all data points were equal. The L-moments are useful because a distribution is characterized in a few numbers. Furthermore, when a suitable probability distribution is fit to the L-moments of the observed distribution, then interpolation or extrapolation to percentiles not represented in the data is possible.

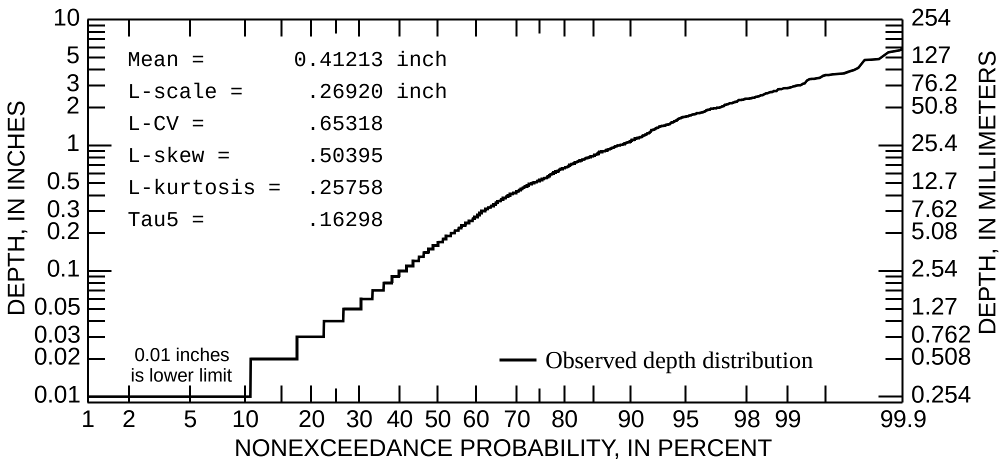

Figure 20. Observed distribution and L-moments of storm-depth distribution for 3,331 storms defined by an 8-hour minimum interevent time for station 0016 Abilene Regional Airport, Texas.

Regionwide (eastern New Mexico) or statewide (Oklahoma and Texas) record-length weighted-average values for the storm-depth L-moments consisting of the mean depth, coefficient of L-variation, L-skew, L-kurtosis, and Tau5 are listed in table 15. The requirement that mean storm depth increases with MIT is evident. Some patterns in the L-moments such as the L-skew of the storm-depth distribution decreasing with MIT are apparent. However, two important observations are made regarding the tabulated data. The first observation is that the regionwide or statewide mean values for the dimensionless L-moments (L-CV, L-skew, L-kurtosis, and Tau5) are all of the same general order as MIT increases. The second observation is that the magnitude of the dimensionless L-moments are of the same general order between eastern New Mexico, Oklahoma, and Texas.

The two observations are important because each implies that a single dimensionless frequency curve can be used to represent the scale and curvature (shape) of the distribution and only an estimate of the mean storm depth for a given location is required to construct a continuous distribution of either storm depth or duration. Specifically, the first observation implies that the general shape of a dimensionless frequency curve is relatively independent of MIT. The second observation implies that the general shape of a dimensionless frequency curve is relatively independent of spatial location in the study area. Dimensionless frequency curves are discussed and presented in section “Dimensionless Storm-Depth Frequency Curves.” However, an analysis of appropriate distribution forms for modeling the distribution of storm depth is needed.

Table 15. Regionwide or statewide record-length weighted-average values for the L-moments of storm depth
[MIT, minimum interevent time; --, dimensionless; L-CV, coefficient of L-variation (L-scale / mean)]

Region or State and MIT	Record length (hours)	L-moments of storm depth				
		Mean (inches)	L-CV (--)	L-skew (--)	L-kurtosis (--)	Tau5 (--)
Eastern New Mexico						
6 hours	18,755,667	0.276	0.554	0.530	0.305	0.178
8 hours	18,755,163	.291	.555	.515	.298	.177
12 hours	18,755,163	.315	.558	.508	.291	.177
18 hours	18,754,611	.346	.563	.502	.284	.175
24 hours	18,754,611	.386	.567	.495	.276	.172
48 hours	18,745,803	.474	.574	.484	.263	.164
72 hours	18,745,803	.556	.582	.484	.261	.162
Oklahoma						
6 hours	33,226,434	.523	.582	.485	.249	.154
8 hours	33,226,434	.555	.579	.477	.244	.153
12 hours	33,223,650	.602	.576	.469	.239	.153
18 hours	33,223,650	.660	.574	.458	.233	.150
24 hours	33,223,650	.712	.572	.452	.230	.149
48 hours	33,221,682	.874	.571	.442	.226	.145
72 hours	33,221,682	1.05	.568	.432	.220	.140
Texas						
6 hours	103,788,249	.489	.601	.506	.272	.168
8 hours	103,788,249	.518	.598	.500	.267	.168
12 hours	103,788,249	.563	.595	.492	.263	.167
18 hours	103,785,321	.619	.593	.484	.258	.167
24 hours	103,785,321	.675	.590	.477	.254	.166
48 hours	103,773,105	.821	.586	.463	.246	.162
72 hours	103,771,089	.964	.581	.452	.238	.156

An L-moment diagram comparing L-skew and L-kurtosis of depth and duration for Texas storms defined by the 8-hour MIT is shown in figure 21. Superimposed in the figure are the theoretical L-skew and L-kurtosis relations for six distributions. Hosking (1990), Vogel and Fennessey (1993), and Hosking and Wallis (1997) provide details of L-moment diagram construction and interpretation. L-moment diagrams are used to evaluate the suitability of candidate distributions for modeling the distribution of data.

The curves in the figure, with the exception of the theoretical limits of the L-moments, represent three-parameter distributions. (The one-parameter exponential distribution graphs as a single point—a star in the figure.) Several observations about suitable probability distributions with which to model the storm depth and storm distribution can be made: First, the trajectory of the three-parameter Pearson Type III distribution (not the "log" Pearson Type III distribution familiar to many engineers and hydrologists) passes close to the centers of the storm depth and duration data point clusters. However, the majority of the storm depths have slightly larger L-kurtosis than the Pearson Type III distribution; this is indicated on the graph by the open circles above the Pearson Type III line. Therefore, the L-kurtosis values for storm duration are more consistent with the Pearson Type III distribution than are the L-kurtosis values for storm depth. The distribution of storm duration, in other words, is more “Pearson Type III like” than the distribution of storm depth.

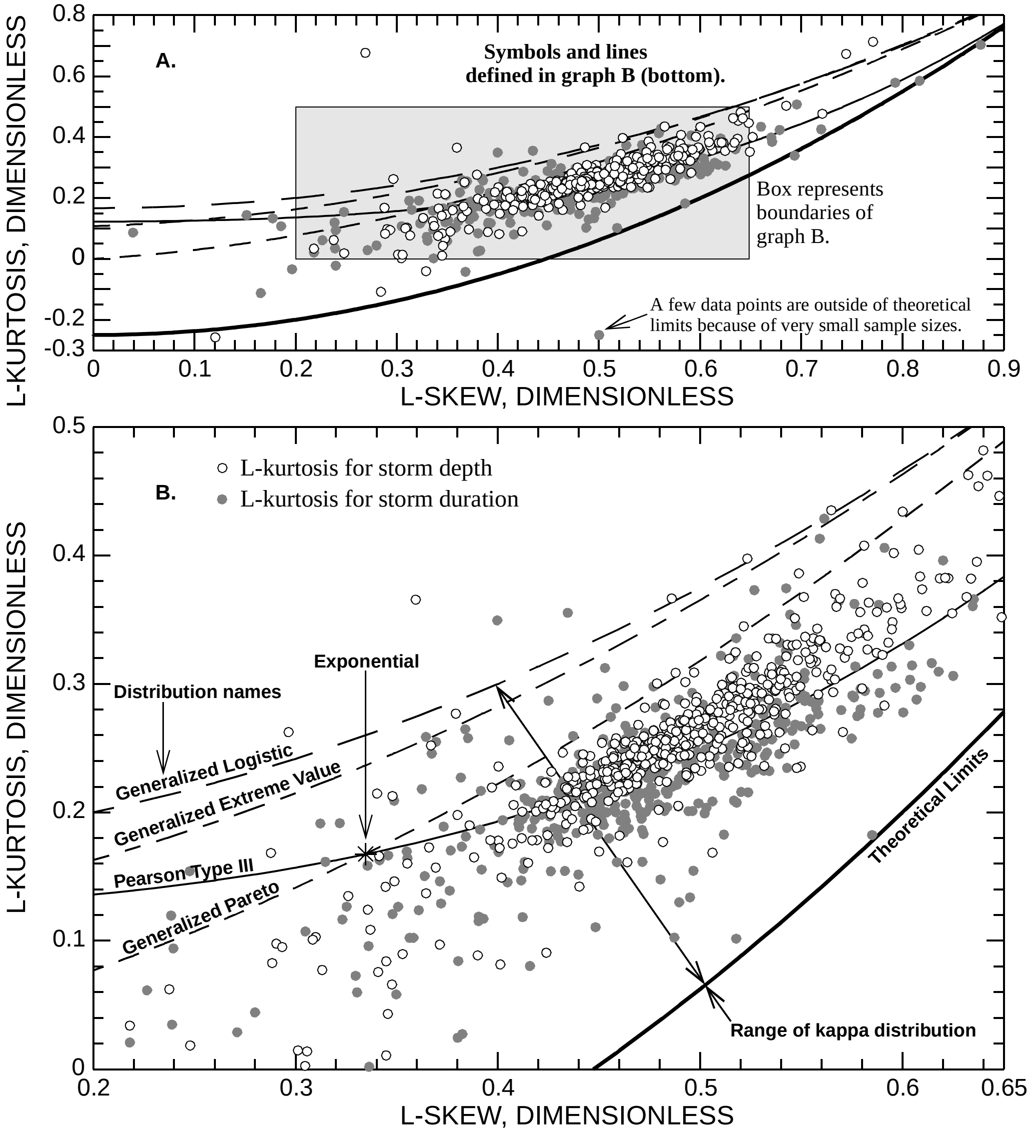

Figure 21. L-moment diagram showing relation between L-skew and L-kurtosis of the storm depth and duration distributions defined by the 8-hour minimum interevent time and theoretical relations for selected probability distributions.

The range of the four-parameter kappa distribution also is shown in figure 21. The kappa distribution can acquire any L-skew and L-kurtosis combination between the theoretical L-moment limits and the generalized logistic distribution. Thus, the kappa distribution is capable of specifically acquiring the L-kurtosis values of the data.

Adams and Papa (2000) use the one-parameter exponential distribution to model the frequency of storm arrival, depth, and duration to develop closed-form solutions for various operational characteristics of small-watershed BMPs. Wanielista and Yousef (1993, p. 52, 221) suggest and provide additional citations to support the position that the one-parameter exponential or two-parameter gamma distributions can be used to model the distributions of storm depth and duration.

Clarke (1998, p. 56) suggests the gamma distribution for modeling the distribution of daily rainfall. The gamma distribution is a special case of the Pearson Type III distribution with positive L-skew (Stedinger and others, 1992, p. 18.19) and the location parameter set to zero. The L-kurtosis and L-skew values of the gamma distribution follow the curve for the Pearson Type III distribution. However, because the gamma distribution is a special case of the Pearson Type III distribution, the gamma distribution is not fit to the L-skew of the data.

The U.S. Environmental Protection Agency (1986) suggests that the gamma distribution be used to approximate the three distributions of storm arrival, depth, and duration. The exponential and gamma distributions are readily implemented. However on the basis of the generally closer match of data points to distribution curves (or range in the case of the kappa distribution) shown in figure 21, the authors suggest that the Pearson Type III and kappa distributions would be more representative models for storm-depth distribution than the exponential or gamma distributions with a modest cost in terms of additional analytical complexity. Furthermore, because the kappa distribution has an additional parameter, can fit the L-kurtosis of the data, and is expressible as a quantile function (see next section), the kappa distribution is preferred by the authors.

Dimensionless Storm-Depth Frequency Curves

Three distributions are specifically considered for modeling the distribution of storm depth and duration for this report: exponential, gamma, and kappa distributions. Both the exponential and gamma distributions have precedence in analytical solutions to BMP performance, so their inclusion here is useful. In terms of accuracy, the analysis in the previous section suggests that the kappa distribution is preferable. The authors have chosen to consider all three distributions and compute the parameters of the gamma and kappa distributions to facilitate use of this report in a range of applications.

A quantile function or frequency curve for a random variable X (either storm depth or duration) can be written as

$$X(F) = \lambda_1 x(F), \tag{12}$$

where $X(F)$ is the variable for nonexceedance probability, F, λ_1 is the mean (first L-moment) of the variable, and $x(F)$ is the dimensionless frequency curve. This is a convenient model to implement. The dimensionless frequency curve represents constant multipliers or “frequency factors” on mean storm depth.

A dimensionless frequency curve is fit to the data using the method of L-moments by setting the mean equal to one and L-scale equal to the L-CV. The higher L-moments (L-skew, L-kurtosis, Tau5) remain unchanged. (In terms of the product moments, a dimensionless distribution is fit to the data by setting the mean equal to one, the standard deviation equal to the coefficient of variation, and all other higher moments unchanged.) This technique for dimension removal is used often in statistical hydrology (Hosking and Wallis, 1997, and references therein).

The quantile function of a dimensionless exponential distribution is

$$x(F) = -\ln(1-F), \tag{13}$$

where $x(F)$ is the dimensionless frequency curve for nonexceedance probability, F. There is no parameter to estimate. The L-CV of the dimensionless distribution is 0.5 (Hosking, 1990, p. 112). Values for L-CV for storm depth are all greater than 0.5 in table 15. The exponential distribution is extensively used by Adams and Papa (2000) in a BMP design context.

The cumulative distribution function of the gamma distribution is

$$F(x) = \frac{\beta^{-\alpha}}{\Gamma(\alpha)}\int_0^x t^{\alpha-1}e^{-t/\beta}dt, \tag{14}$$

where $F(x)$ is the nonexceedance probability, percentage, for dimensionless value x, α and β are parameters, and $\Gamma(\alpha)$ is the gamma function for α. There is no explicit solution for x in terms of F. The parameters can be computed using the mean and L-CV. Hosking (1996) provides algorithms for gamma parameter estimation using L-moments. The mean of the distribution is computed as

$$\lambda_1 = \alpha\beta\text{, and} \tag{15}$$

the L-CV (L-scale/mean or λ_2/λ_1) of the distribution is computed as

$$\text{L-CV} = \frac{\beta\Gamma(\alpha+0.5)}{\sqrt{\pi}\Gamma(\alpha)\lambda_1}. \tag{16}$$

Because the gamma distribution is considered dimensionless in the context here, the following conditions apply: $\alpha\beta = 1$ and $\text{L-CV} = [\beta\Gamma(\alpha+0.5)]/[\sqrt{\pi}\Gamma(\alpha)]$.

Use of the gamma distribution in context of estimation of BMP performance has precedent (U.S. Environmental Protection Agency, 1986). Although basing much of their work on the exponential distribution, Adams and Papa (2000, p. 72–73) also describe the gamma distribution.

The quantile function of the kappa distribution (Hosking, 1994) is

$$x(F) = \xi + \frac{\alpha}{\kappa}\left[1 - \left(\frac{1 - F^h}{h}\right)^{\kappa}\right], \quad (17)$$

where $x(F)$ is the value for a nonexceedance probability, F, and ξ, α, κ, and h are parameters. The four parameters can be computed using the mean (set to one), L-CV, L-skew, and L-kurtosis. However, kappa parameter estimation is not manually solvable. Hosking and Wallis (1997, p. 202–204) report that there are "no simple expressions for the parameters [of the kappa] in terms of the L-moments." Newton-Raphson iteration can be used for parameter estimation and is described in Hosking (1996).

For ease of application of the results of this report, the parameters for both the gamma and kappa distributions, which correspond to the L-moments of storm depth (mean set to one, and L-scale set to L-CV) listed in table 15, respectively, have been computed. The parameters for gamma and kappa distributions of dimensionless storm-depth frequency curves are listed in table 16.

Dimension is restored to the dimensionless frequency curves of storm depth and duration by multiplication of a mean value for storm depth according to equation 12. For example, the 90th-percentile storm-depth frequency factor for Texas for a kappa distribution model using the 18-hour MIT is

$$x(0.90) = -0.6336 + \frac{1.135}{-0.1367}\left[1 - \left(\frac{1 - 0.90^{1.818}}{1.818}\right)^{-0.1367}\right] \text{ and}$$

$$x(0.90) = 2.50 .$$

Thus, the 90th-percentile storm depth is about 2.50 times the mean storm depth for a particular location in Texas. The mean storm depth for the 18-hour MIT can be estimated as the mean value for a county.

Table 16. Dimensionless gamma and kappa distributions fit to the record-length weighted-average L-moments of storm depth

[MIT, minimum interevent time; parameters are dimensionless.]

Region or State and MIT	Gamma distribution (equation 14) parameters		Kappa distribution (equation 16) parameters			
	α	β	ξ	α	κ	*h*
Eastern New Mexico						
6 hours	0.7592	1.317	-0.4607	0.8958	-0.2272	1.930
8 hours	.7554	1.324	-.3352	.8498	-.2355	1.709
12 hours	.7441	1.344	-.3481	.8744	-.2231	1.690
18 hours	.7255	1.378	-.3824	.9116	-.2079	1.696
24 hours	.7111	1.406	-.4173	.9526	-.1903	1.701
48 hours	.6864	1.457	-.4865	1.030	-.1596	1.720
72 hours	.6593	1.517	-.5445	1.071	-.1506	1.759
Oklahoma						
6 hours	.6593	1.517	-.8242	1.275	-.08913	2.023
8 hours	.6694	1.494	-.7607	1.253	-.08716	1.945
12 hours	.6795	1.472	-.7030	1.234	-.08439	1.871
18 hours	.6864	1.457	-.6196	1.203	-.08368	1.761
24 hours	.6934	1.442	-.5706	1.183	-.08398	1.701
48 hours	.6969	1.435	-.4840	1.143	-.08812	1.588
72 hours	.7075	1.413	-.4357	1.133	-.08178	1.518
Texas						
6 hours	.5991	1.669	-.7991	1.186	-.1422	2.041
8 hours	.6083	1.644	-.7746	1.188	-.1354	2.001
12 hours	.6175	1.619	-.6883	1.151	-.1389	1.896
18 hours	.6238	1.603	-.6336	1.135	-.1367	1.818
24 hours	.6333	1.579	-.5790	1.115	-.1359	1.747
48 hours	.6462	1.548	-.4868	1.086	-.1326	1.617
72 hours	.6627	1.509	-.4479	1.087	-.1210	1.556

From the previous section, dimensionless frequency curves of storm depth are relatively invariant with MIT and relatively invariant with spatial location in the study area. This conclusion was based on the fact that the dimensionless L-moments (L-CV, L-skew, L-kurtosis, and Tau5) (table 15) are similar. Because the L-moments are similar, the parameter estimates for the dimensionless storm-depth distribution in table 16 also are similar. Distributions with similar parameters are similar.

To illustrate distribution similarity for the selected MITs, the dimensionless kappa distribution storm-depth frequency curves for which the parameters are listed in table 16 are shown in figure 22. The curves are similar as expected. The largest intercurve differences occur for small nonexceedance probabilities on the left side of the distribution; however, use of a base-10 log scale for the ordinate accentuates the differences. To illustrate the spatial insensitivity of the dimensionless frequency curves, the storm depth and duration curves for the 24-hour MIT for eastern New Mexico, Oklahoma, and Texas are shown in figure 23. It is evident from the figure that these curves also are similar.

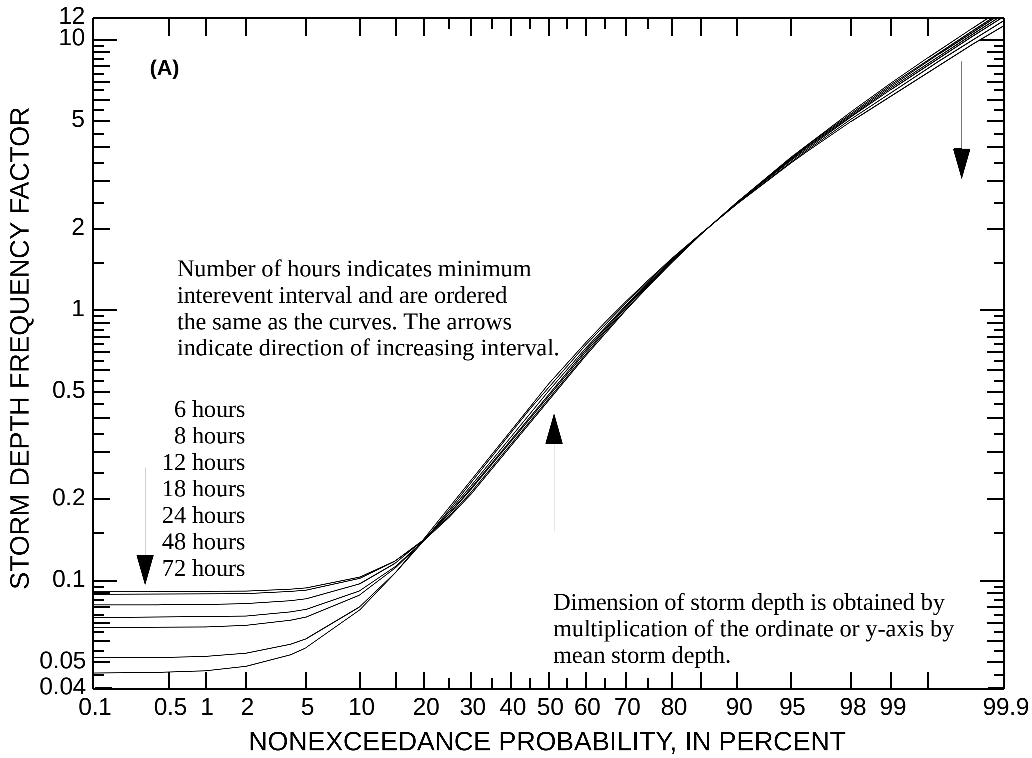

Figure 22. Dimensionless kappa distribution frequency curves for storm depth in Texas for indicated values of minimum interevent time.

Because the dimensionless kappa storm-depth frequency curves are similar for each of the selected MIT values, it might be preferable to use a single dimensionless frequency curve for general application. The 24-hour MIT is in the approximate middle of the MIT values; therefore, a 24-hour MIT dimensionless kappa storm-depth frequency curve could provide a standard curve. The ordinates or "upper-tail storm-depth frequency factors" for a 24-hour MIT are listed in table 17.

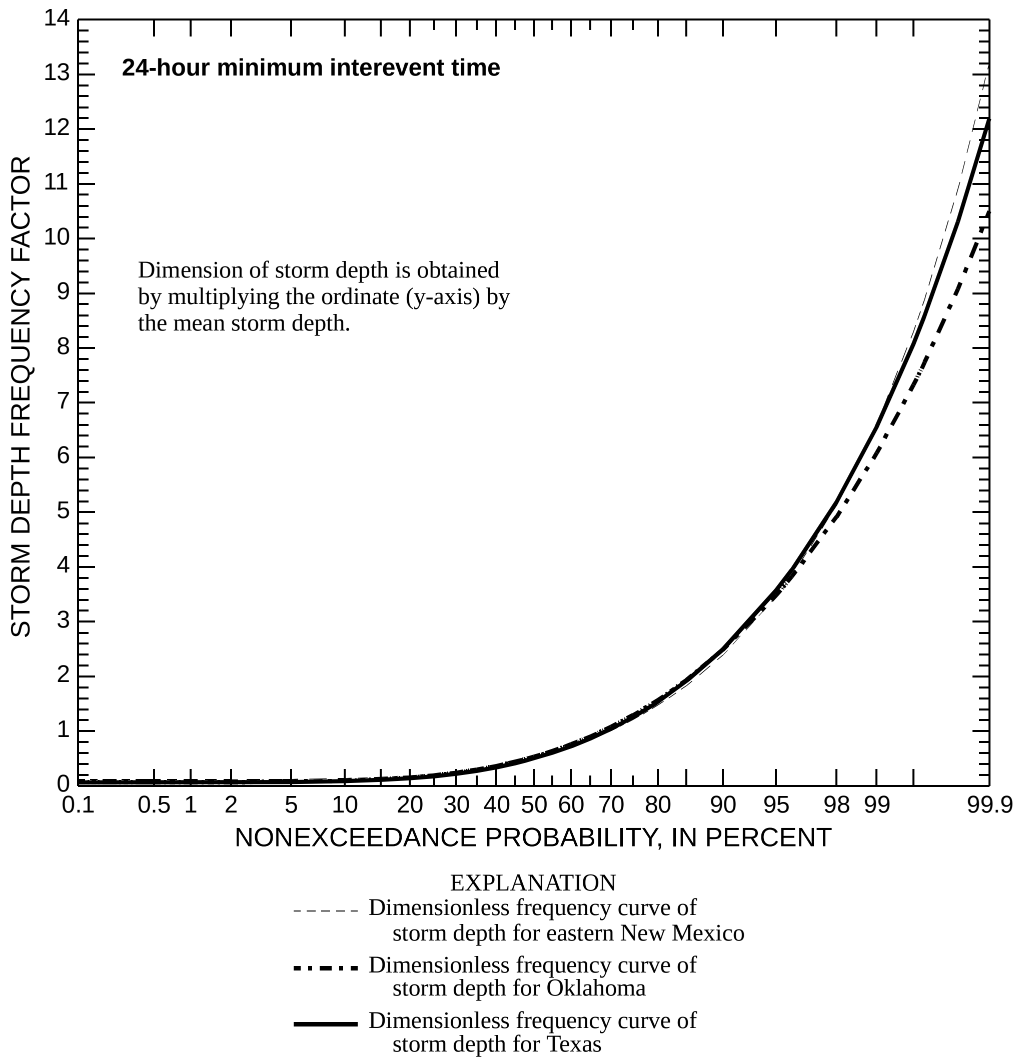

Figure 23. Dimensionless kappa distribution frequency curves for storm depth for 24-hour minimum interevent time for eastern New Mexico, Oklahoma, and Texas.

Table 17. Upper-tail storm-depth frequency factors for Texas based on 24-hour minimum interevent time kappa distribution model

[The kappa distribution parameter values are -0.5790, 1.115, -0.1359, and 1.747 for ξ, α, κ, and h, respectively (see table 16).]

Nonexceedance probability	Frequency factor
0.50	0.503
.55	.605
.65	.868
.70	1.04
.75	1.26
.80	1.54
.85	1.92
.90	2.49
.95	3.58
.98	5.19
.99	6.57

Mean Storm Depth for Texas Counties

A spatial or regional analysis of the mean storm depth was conducted for eastern New Mexico, Oklahoma, and Texas; however, only Texas results are reported here. The analysis is a two-step process. First, a "neighborhood smoothing" of the mean depth storm for a particular MIT is done for each NWS hourly rainfall station. Second, geostatistical analysis is done on the smoothed statistics at the stations to produce a continuously varying "grid" of the statistic. The grid is used to estimate mean values for the mean storm depth for Texas counties.

Neighborhood smoothing is a process by which a particular statistic at a particular station is combined or "pooled" with the statistics at surrounding stations to develop a more reliable estimate of the statistic for each particular station than can be derived from the data for the station alone. In other words, the neighborhood of m-stations surrounding a particular station contains more information—more hours of record—about the characteristics of rainfall in that area than is available for any one station.

The neighborhood smoothing for each station consists of computing the "smoothed" statistic through a weighted average of the statistic for the station and the statistics for the four nearest stations. Five stations thus constitute the neighborhood. Record length, as measured by the total number of hours of rainfall record, is the weighting factor. If a missing value for mean storm depth occurs for one or more of the neighboring stations, the station with a missing value is dropped from the neighborhood; no additional stations are sought. Thus, the number of stations in the neighborhood is reduced by the number of stations with missing values. No cases occurred in which an entire neighborhood had all missing values.

The smoothing reduces the point-to-point variability of mean storm depth through the incorporation of record length and facilitates more reliable regionalization of the statistic. The smoothing is necessary because of large disparity in record lengths. The authors made an explicit decision to not remove stations from the regional analysis because of short record length: all storm data were considered. Thus, the authors chose to include additional spatial information at the expense of increases in station-to-station variability because of the inclusion of stations with short record length.

The second step of the spatial analysis of mean storm depth involved geostatistically based mapping using the method of kriging (Isaaks and Srivastava, 1989). The kriging was done using a spherical model of the semivariogram. The semivariogram model was selected on the basis of intermediate spatial analysis (not presented here) as part of the kriging process in an integrated software system (ESRI, 2002). The semivariogram was automatically fitted by the computer software. The fit of the semivariogram was confirmed by the authors through the graphical interface of the integrated software system. Other semivariogram models were evaluated in intermediate analysis; most of the maps are relatively insensitive to the choice of semivariogram model. The neighborhood for the kriging process used a search radius of 12 stations in conjunction with a circular search method. The output cell size for the kriging process was 4,799.55 meters, which translates to a 263-row by 251-column orthogonal grid. The grid was then “clipped” to the external boundaries of the study area.

Another component of the spatial analysis was an assessment of the spatial variation of the station residuals. The residuals should show little or no spatial variation. For example, a residual grid should show little or no systematic change from one side of the study area to another. The residual for the statistics showed essentially no spatial dependency.

Summary statistics and diagnostic statistics of each grid are important. These statistics for the spatially analyzed mean storm depth are listed in table 18. The mean biases are approximately zero as expected. Negative values of the percentage change imply that the spatial analysis provides a more accurate estimate of a statistic than the overall mean statistic for the study area.

Table 18. Summary statistics and diagnostic statistics of spatially analyzed mean storm depth for each minimum interevent time

[Record length used as weighting factor. WSD, weighted standard deviation; RWMSE, root-weighted-mean-square error; bias is computed as observed value for station minus the value predicted from the spatial analysis.]

Minimum interevent time (hours)	No. of stations	Weighted mean of storm depth for study area (inches)	WSD of storm depth for study area (inches)	Weighted mean bias of storm depth map (inches)	RWMSE of storm depth map (inches)	Percent change from WSD to RWMSE (percent)
6	755	0.470	0.114	-5.19×10^{-5}	0.032	-71.9
8	754	.498	.124	-6.56×10^{-5}	.033	-73.4
12	753	.541	.136	-2.99×10^{-5}	.036	-73.5
18	751	.595	.151	4.14×10^{-5}	.039	-74.2
24	751	.648	.163	1.03×10^{-4}	.043	-73.6
48	745	.790	.207	8.95×10^{-5}	.059	-71.5
72	744	.933	.261	8.48×10^{-5}	.076	-70.9

Finally, the mean storm depth values for each county were computed using the grid of a particular statistic and the spatial extent of each county. The mean values for storm depth for each of the 254 counties in Texas are listed in table 19 at the end of this report. The list of storm depths for each county indicates that there is a clear tendency for smaller storm depths to occur in the western parts of Texas. The changes in storm depth are far more influenced by east-west location than north-south location. A notable exception is that the storm depths in southern Texas are relatively smaller than the east-west position of this region might indicate. See example 4 in the appendix for an application and solution for estimation of the distribution of storm depth in a runoff detention structure.

SUMMARY AND CONCLUSIONS

During 2000–2004, a consortium of researchers at Texas Tech University, Lamar University, the University of Houston, and USGS, under the direction of TxDOT Research Management Committee No. 3, did a study to (1) determine if NRCS storm hyetographs are representative of storms in Texas, (2) provide new procedures for hyetograph estimation if NRCS hyetographs are not representative, and (3) provide a procedure to estimate the distribution of storm depth for Texas. This report describes the research and results of the consortium study, with specific focus toward definition of design storms for application by TxDOT engineers. Currently (2004), the results of the research have been published in Al-Asaadi (2002), Asquith (2003), Asquith and others (2003), Asquith and others (2004), and Williams-Sether and others (2004). The research results of each have been discussed in this report. This section provides enumerated summary information and conclusions regarding the research that could be beneficial to TxDOT engineers seeking to refine design storm characteristics from previous TxDOT guidelines (Texas Department of Transportation, 2004).

Dimensionless Texas Hyetographs

1. The dimensionless hyetographs generated by several investigators, different analytical directions, and differing databases strongly indicates that the NRCS Type II and Type III hyetographs are not representative of observed storms in Texas. Therefore, consideration of alternative dimensionless hyetographs is warranted. These alternative hyetographs are collectively termed "Dimensionless Texas Hyetographs."

2. The <u>triangular dimensionless hyetographs</u> derived from runoff-producing storms in Texas (Asquith and others, 2003) are comparable to those derived from the NWS hourly rainfall data (Hydrosphere, 2003). The triangular hyetograph models (equations 1 and 2) are "moment" based, which means that the parameters of the model are estimated using the moments of the hyetograph distribution. Because the hyetographs derived from NWS hourly rainfall are based on a much more extensive NWS hourly rainfall database that those of Asquith and others (2003), the hourly-rainfall-based hyetographs are preferable. For general application it is reasonable to extend the 5–12-hour duration to a 0–12-hour duration. Finally, although the triangular hyetographs are based on rainfall depths of 1 inch or more, it is reasonable to extend application to all rainfall depths. The preferable triangular dimensionless hyetographs for fractional percentage of storm duration, F, and fractional percentage of storm depth, p, are listed below [see triangular model parameters (a and b) in tables 7–9 and equations 1 and 2].

   a. The triangular dimensionless hyetograph for the 0–12-hour duration is

$$p_1(0 \le F \le 0.02197) = 45.52F^2 \text{, and} \qquad (18)$$

$$p_2(0.02197 < F \le 1) = -1.022F^2 + 2.045F - 0.02246 \,. \qquad (19)$$

b. The triangular dimensionless hyetograph for the 13–24 hour duration is (20)

$$p_1(0 \le F \le 0.28936) = 3.456F^2\text{, and} \quad (21)$$

$$p_2(0.28936 < F \le 1) = -1.407F^2 + 2.814F - 0.4072\,. \quad (22)$$

c. The triangular dimensionless hyetograph for the 25–72-hour duration is

$$p_1(0 \le F \le 0.38959) = 2.567F^2\text{, and} \quad (23)$$

$$p_2(0.38959 < F \le 1) = -1.638F^2 + 3.276F - 0.6382\,. \quad (24)$$

3. The Wakeby dimensionless hyetographs have five parameters and are derived from the NWS hourly rainfall data. The Wakeby hyetographs are fit to more L-moments of the data (five) than the triangular model (one) or the L-gamma model (two). However, the Wakeby hyetograph models are less convenient to use, are physically inconsistent without truncation, and produce rainfall rates that are essentially uniform. The fit of the very flexible Wakeby model potentially illustrates shortcomings of the moment-based hyetograph models. The Wakeby hyetographs are purpose not listed in this section.

4. The L-gamma dimensionless hyetographs have two parameters and are derived from runoff-producing storms in Texas. The L-gamma hyetographs are better fit to the moments of the data than the triangular models. The L-gamma hyetographs are more front-loaded than the triangular hyetographs and better reflect the front-loadedness of observed storms. The L-gamma hyetographs provide TxDOT engineers with alternative temporal distributions of the temporal distribution of design storms. However, specifically choosing either the L-gamma hyetographs or triangular hyetographs over the other is a difficult. Although the L-gamma hyetographs are based on rainfall depths of at least 1 inch, it is reasonable to extend application to all rainfall depths.The L-gamma hyetographs for fraction of storm duration, F, and fraction of storm depth, p, are listed below. (Note that the duration range is slightly different from that of the triangular hyetographs listed above. The differences occur because of the nature of the underlying databases. The runoff-producing database has as small as 5-minute resolution on storm duration, where as the NWS hourly database has hourly resolution.)

a. The L-gamma dimensionless hyetograph for the 0–12-hour duration is

$$p(F) = F^{1.262}e^{1.227(1-F)}\,. \quad (25)$$

b. The L-gamma dimensionless hyetograph for the 12–24-hour duration is

$$p(F) = F^{0.7830}e^{0.4368(1-F)}\,. \quad (26)$$

c. The L-gamma dimensionless hyetograph for the 24–72-hour duration is

$$p(F) = F^{0.3388} e^{-0.8152(1-F)}. \quad (27)$$

Empirical hyetograph analysis, as summarized below, might be preferable to moment-based triangular, L-gamma, and Wakeby hyetographs described above.

5. The empirical dimensionless hyetograph analysis for runoff producing storms in Texas provides hyetograph curves associated with cumulative probability, such as the 90th-percentile hyetograph. Asquith (2003) provides tables of smooth hyetograph ordinates that comprise the 10th-, 25th-, 50th-, 75th-, and 90th-percentiles of percentages of storm depth for 0–12-hour, 12–24-hour, and 24–72-hour storm durations for runoff-producing storms with rainfall depths of at least 1 inch. The smoothed ordinates are reproduced for this report in tables 10–12. These hyetographs provide TxDOT engineers with a substantial array of alternative hyetographs to apply when seeking the most critical design hyetograph for specialized applications. Asquith (2003) does not distinguish between storm quartile or storm loadedness. Williams-Sether and others (2004) provide extensive supplemental tables of hyetograph ordinates with a greater probability resolution than Asquith (2003). Williams-Sether and others (2004) chose a single 0–72-hour duration range for maximum data available for probability analysis. Graphically the results for the 0–72-hour duration are reproduced in figure 17 of this report. Tabulated ordinates (percentiles of percentage of cumulative rainfall) of the curves in figure 17 for each quartile for each duration range of 0–6, 6–12, 12–24, and 24–72 hours are available in Williams-Sether and others (2004). Based on the lack of substantial spatial variation in hyetograph shape in the NWS database, it is reasonable to conclude that the empirical hyetographs, although defined from a database of small spatial extent, are suitable throughout Texas. Finally, although the empirical hyetographs are based on rainfall depths of at least 1 inch, it is reasonable to extend application to all rainfall depths.

6. General conclusions regarding the dimensionless Texas hyetographs investigated are listed below:

   a. Storm duration has limited but a potentially important influence on the dimensionless temporal distribution of rainfall.

   b. Storm depth has remarkably little influence on the dimensionless hyetograph. Emphasis on the "dimensionless" is needed. Once a hyetograph is scaled by multiplication with a storm depth and duration, the actual rainfall intensities produced from the hyetograph are substantially influenced by rainfall magnitude (frequency, recurrence interval) and duration.

   c. Dimensionless hyetographs appear to be affected by month or season of occurrence—presumably reflected changes in storm type. However, for the purposes of engineering design and because of other uncertainties in fundamental hydrology, the authors conclude that month or season of design-storm occurrence is not important for hyetograph specification.

Distribution of Storm Depth for Texas

7. The distribution of storm depth is useful in evaluating design involving best-management practices such as for runoff-control structures on small watersheds. For TxDOT engineers, the distribution of storm depth enhances the understanding of rainfall-related risk. The distribution of storm depth for seven definitions (6, 8, 12, 18, 24, 48, and 72 hours) of minimum interevent time (MIT) for each of the 254 counties in Texas are preferably defined through a kappa-distribution dimensionless storm-depth frequency curve and the mean storm depth for a given county. The research also suggests that there is no substantial spatial variation in dimensionless storm-depth frequency curves; an individual curve is applicable across Texas. Furthermore, because dimensionless frequency curves are relatively invariant with MIT, it is reasonable to conclude that the curve for the 24-hour MIT is applicable for all other MIT values. The upper-tail storm-depth frequency factors for selected values of nonexceedance probability for the 24-hour MIT dimensionless frequency curve are listed in table 17. The mean storm depths for each MIT and each county are listed in table 19. The equation for the 24-hour MIT dimensionless storm-depth frequency curve, $x(F)$, for nonexceedance probability, F, (parameters used in equation 17 are listed in table 16) is

$$x(F) = -0.5790 - \frac{1.135}{-0.1367}\left[1 - \left(\frac{1 - F^{1.747}}{1.747}\right)^{-0.1359}\right]. \qquad (28)$$

Final comments concerning selection of MIT for a design problem follow. The MIT should be selected to approximate the temporal scale of the design problem.

a. For example, the storm depth for a 90th-percentile storm for a watershed with a 5-hour time of concentration is needed. The MIT could be chosen as 6 hours and the 90th-percentile storm computed or a graph of 90th-percentile storm depth (y-axis) as a function of MIT (x-axis) could be used, with engineering judgement, to extrapolate to a 5-hour MIT.

b. For example, a flood-detention basin has a 24-hour draw down time. For the basin to function in a “memoryless” fashion—the basin is empty before next storm arrives—the 24-hour MIT is suitable.

c. For example, a spill-containment berm built to contain the 99th-percentile storm depth is to have an emergency response in no more than 36 hours. An appropriate MIT for the design thus is 36 hours. This MIT is not explicitly considered; however, the 99th-percentile depth for the 24-hour and 48-hour MIT can be computed and linear interpolation made to estimate the 99th-percentile storm for the 36-hour MIT.

REFERENCES

Adams, B.J., and Papa, F., 2000, Urban stormwater management planning with analytical probabilistic models: New York, John Wiley, 358 p.

Al-Asaadi, Rawaa, 2002, Hyetograph estimation for the State of Texas: Lubbock, Texas, Texas Tech University, M.S. thesis, 96 p.

Asquith, W.H., 1998, Depth-duration frequency of precipitation for Texas: U.S. Geological Survey Water-Resources Investigations Report 98–4044, 107 p.

Asquith, W.H., 1999, Areal-reduction factors for the precipitation of the 1-day design storm in Texas: U.S. Geological Survey Water-Resources Investigations Report 99–4267, 81 p.

Asquith, W.H., 2003, Modeling of runoff-producing rainfall hyetographs in Texas using L-moment statistics: Austin, Texas, the University of Texas at Austin, Ph.D. dissertation, 386 p.

Asquith, W.H., Bumgarner, J.R., and Fahlquist, L.S., 2003, A triangular model of dimensionless runoff-producing rainfall hyetographs in Texas: Journal American Water Resources Association, v. 39, no. 4, p. 911–921.

Asquith, W.H., and Famiglietti, J.S., 2000, Rainfall areal-reduction factor estimation using an annual-maxima centered approach: Journal of Hydrology, v. 230, p. 55–69.

Asquith, W.H., and Roussel, M.C., 2003, Atlas of interoccurrence intervals for selected thresholds of daily precipitation in Texas: U.S. Geological Survey Water-Resources Investigations Report 03–4281, 204 p.

Asquith, W.H., and Roussel, M.C., 2004, Atlas of depth-duration frequency of precipitation in Texas: U.S. Geological Survey Scientific Investigations Report 2004–5041, 106 p.

Asquith, W.H., and Thompson, D.B., 2003, Modeling of runoff-producing rainfall hyetographs in Texas using L-moments: Texas Section, Spring Meeting, American Society of Civil Engineers, Corpus Christi, Tex., April 2–5., 2003, p. __–__.

Asquith, W.H., Thompson, D.B., Cleveland, T.G., and Fang, Xing, 2004, Synthesis of rainfall and runoff data used for Texas Department of Transportation Research Projects 0–4193 and 0–4194: U.S. Geological Survey Open-File Report 2004–1035, 1,050 p.

Bomar, G.W., 1995, Texas weather: Austin, University of Texas Press, 275 p.

Bonta, J.V., and Rao, A.R., 1989, Regionalization of storm hyetographs: Water Resources Bulletin, v. 25, no. 1, p. 211–217.

Chow, V.T., Maidment, D.R., Mays, L.W., 1988, Applied hydrology: New York, McGraw-Hill Publishing Company, 572 p.

Clarke, R.T., 1998, Stochastic processes for water scientists—Developments and applications: New York, John Wiley, 183 p.

ESRI, 2002, ArcGIS 8.2: Geographical Information System and Mapping Software: Redlands, Calif., ESRI.

Frederick, R.H., Meyers, V.A., and Auciello, E.P., 1977, Five- to 60-minute precipitation frequency for the eastern and central United States: Silver Springs, Md., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, NOAA Technical Memorandum NWS HYDRO–35, 36 p.

Haan, C.T., Barfield, B.J., and Hayes, J.C., 1994, Design hydrology and sedimentology for small catchments: San Diego, Academic Press, 558 p.

Hershfield, D.M., 1962, Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years: U.S. Weather Bureau Technical Paper 40, 61 p.

Hosking, J.R.M., 1990, L-moments—Analysis and estimation of distributions using linear combination of order statistics: Journal Royal Statistical Society, B, v. 52, no. 1, p. 105–124.

Hosking, J.R.M., 1996, Fortran routines for use with the method of L-moments—version 3: Research Report RC 20525, IBM Research Division, Yorktown Heights, N.Y.

Hosking, J.R.M., and Wallis, J.R., 1997, Regional frequency analysis—An approach based on L-moments: Cambridge, U.K., Cambridge University Press, 224 p.

Huff, F.A., 1967, Time distributions in heavy storms: Water Resources Research, no. 4, p. 1,007–1,019.

Huff, F.A., 1990, Time distributions of heavy rainstorms in Illinois: Illinois State Water Survey Circular 173, Champaign, 18 p.

Hydrosphere, 2003, NCDC Hourly Precipitation—West: Hydrosphere Data Products, Inc., CD-ROM, v. 13.2.

Isaaks, E.H., and Srivastava, R.M., 1989, An introduction to applied geostatistics: New York, Oxford University Press, 561 p.

Lanning-Rush, Jennifer, Asquith, W.H., and Slade, R.M., 1998, Extreme precipitation depths for Texas, excluding the Trans-Pecos region: U.S. Geological Survey Water-Resources Investigations Report 98–4099, 38 p.

Pani, E.A., and Haragan, D.R., 1981, A comparison of Texas and Illinois temporal rainfall distributions: Fourth Conference on Hydrometeorology, American Meteorological Society, p. 76–80.

Williams-Sether, Tara, Asquith, W.H., Thompson, D.B., Cleveland, T.G., and Fang, Xing, 2004, Empirical, dimensionless, cumulative-rainfall hyetographs developed from 1959–86 storm data for selected small watersheds in Texas: U.S. Geological Survey Scientific Investigations Report 2004–5057, 132 p.

Soil Conservation Service, 1973, A method for estimating volume and rate of runoff in small watersheds: SCS-TP-149, U.S. Department of Agriculture, Soil Conservation Service, 19 p.

Stedinger, J.R., Vogel, R.M., and Foufoula-Georgiou, Efi, 1992, Frequency analysis of extreme events, *in* Maidment, D.A., ed., Handbook of Hydrology: New York, McGraw-Hill, ch. 18, p. 18.1–18.66.

Strand, M.C., 2003, Depth-duration frequency of precipitation annual maxima in Texas: Austin, Texas, the University of Texas at Austin, M.S. thesis, 195 p.

Texas Department of Transportation, 2004, Hydraulic design manual: accessed June 3, 2004, at URL http://manuals.dot.state.tx.us/dynaweb/colbridg/hyd

Texas Department of Water Resources, 1980, HIPLEX 1980 operations plan, Big Spring, Texas, LP-125: Austin, Tex., 47 p.

Thompson, D.B., Cleveland, T.G., and Fang, Xing, 2002, Regional characteristics of storm hyetographs—Literature review: Texas Tech University TechMRT, Lubbock, Technical Texas Department of Transportation Research Report 0–4194–1, 14 p.

U.S. Environmental Protection Agency, 1986, Methodology for analysis of detention basins for control of urban runoff quality: EPA 440/S-87-001, [variously paged].

Vogel, R.M., and Fennessey, N.M., 1993, L-moment diagrams should replace product moment diagrams: Water Resources Research, v. 29, no. 6, p. 1,745–1,752.

Wanielista, M.P., and Yousef, Y.A., 1993, Stormwater management: New York, John Wiley, 579 p.

Table 19. Mean values of storm depth for each minimum interevent time by county for Texas

County name	Mean storm depth in inches for corresponding minimum interevent interval						
	6 hours	8 hours	12 hours	18 hours	24 hours	48 hours	72 hours
Anderson	0.575	0.611	0.664	0.731	0.799	0.982	1.19
Andrews	.334	.351	.378	.409	.440	.516	.584
Angelina	.612	.648	.707	.779	.864	1.08	1.33
Aransas	.482	.513	.561	.627	.698	.877	1.05
Archer	.473	.502	.548	.599	.648	.781	.919
Armstrong	.372	.393	.428	.468	.508	.623	.729
Atascosa	.494	.524	.571	.629	.691	.834	.967
Austin	.566	.599	.654	.724	.803	.988	1.18
Bailey	.359	.377	.407	.444	.485	.582	.673
Bandera	.509	.542	.602	.671	.730	.884	1.03
Bastrop	.513	.550	.605	.674	.738	.921	1.10
Baylor	.491	.518	.564	.616	.664	.801	.926
Bee	.494	.523	.568	.628	.699	.860	1.01
Bell	.533	.563	.606	.661	.715	.870	1.02
Bexar	.479	.510	.560	.626	.689	.846	.987
Blanco	.532	.567	.616	.678	.734	.882	1.02
Borden	.394	.416	.450	.492	.532	.633	.722
Bosque	.524	.557	.607	.667	.725	.880	1.04
Bowie	.628	.666	.726	.804	.876	1.10	1.32
Brazoria	.537	.569	.619	.688	.773	.979	1.21
Brazos	.546	.579	.632	.703	.779	.963	1.15
Brewster	.337	.351	.372	.404	.447	.536	.613
Briscoe	.389	.411	.447	.487	.527	.637	.739
Brooks	.454	.480	.524	.579	.639	.778	.883
Brown	.516	.543	.589	.645	.695	.831	.952
Burleson	.552	.583	.632	.701	.768	.945	1.12
Burnet	.530	.563	.612	.668	.720	.872	1.01
Caldwell	.524	.564	.620	.689	.754	.927	1.10
Calhoun	.509	.541	.593	.659	.739	.938	1.14
Callahan	.446	.476	.519	.574	.626	.753	.875
Cameron	.381	.410	.453	.511	.583	.730	.866
Camp	.632	.672	.734	.807	.877	1.08	1.30

Table 19. Mean values of storm depth for each minimum interevent time by county for Texas—Continued

County name	Mean storm depth in inches for corresponding minimum interevent interval						
	6 hours	8 hours	12 hours	18 hours	24 hours	48 hours	72 hours
Carson	.376	.397	.431	.471	.512	.628	.738
Cass	.622	.659	.717	.789	.864	1.08	1.31
Castro	.369	.389	.421	.458	.498	.596	.689
Chambers	.516	.552	.613	.694	.790	1.03	1.31
Cherokee	.582	.618	.673	.740	.812	1.00	1.22
Childress	.436	.465	.502	.550	.588	.699	.809
Clay	.501	.532	.580	.639	.691	.835	.982
Cochran	.369	.388	.418	.457	.497	.595	.683
Coke	.450	.475	.513	.562	.601	.712	.801
Coleman	.522	.551	.596	.649	.701	.844	.966
Collin	.584	.618	.672	.734	.792	.961	1.14
Collingsworth	.441	.468	.505	.552	.592	.716	.835
Colorado	.548	.583	.635	.704	.779	.957	1.14
Comal	.548	.583	.633	.701	.758	.911	1.05
Comanche	.524	.549	.589	.636	.683	.807	.922
Concho	.460	.485	.527	.570	.614	.732	.837
Cooke	.547	.579	.630	.694	.750	.912	1.08
Coryell	.544	.577	.625	.683	.737	.883	1.03
Cottle	.445	.470	.510	.558	.602	.718	.826
Crane	.363	.380	.405	.435	.463	.532	.586
Crockett	.414	.435	.468	.507	.547	.638	.718
Crosby	.410	.433	.469	.512	.555	.665	.766
Culberson	.281	.293	.313	.339	.369	.436	.497
Dallam	.333	.349	.373	.406	.446	.538	.627
Dallas	.533	.569	.625	.691	.754	.924	1.11
Dawson	.363	.383	.415	.452	.489	.584	.669
Deaf Smith	.505	.538	.587	.651	.724	.891	1.06
Delta	.371	.392	.423	.458	.500	.599	.692
Denton	.631	.673	.735	.811	.877	1.08	1.30
Dewitt	.548	.579	.631	.691	.746	.904	1.07
Dickens	.436	.459	.497	.543	.587	.700	.802
Dimmit	.488	.517	.557	.608	.662	.788	.895
Donley	.403	.427	.463	.507	.546	.668	.781
Duval	.480	.508	.553	.607	.672	.805	.927
Eastland	.519	.548	.592	.647	.696	.834	.957
Ector	.340	.356	.383	.413	.442	.512	.571
Edwards	.473	.501	.548	.606	.657	.773	.891
El Paso	.213	.223	.237	.253	.275	.326	.365
Ellis	.575	.611	.663	.727	.791	.959	1.13
Erath	.523	.553	.598	.654	.709	.855	.992
Falls	.519	.548	.591	.651	.710	.874	1.05
Fannin	.620	.662	.722	.794	.860	1.05	1.26
Fayette	.536	.570	.624	.692	.759	.939	1.11
Fisher	.446	.475	.516	.566	.613	.729	.828
Floyd	.404	.426	.462	.503	.545	.654	.754
Foard	.497	.522	.567	.619	.669	.807	.932
Fort Bend	.596	.628	.677	.744	.819	1.01	1.21
Franklin	.633	.673	.735	.810	.875	1.08	1.30
Freestone	.569	.606	.658	.724	.791	.970	1.16
Frio	.497	.528	.576	.633	.691	.827	.953
Gaines	.353	.371	.399	.433	.468	.555	.631
Galveston	.499	.535	.595	.673	.760	.977	1.24
Garza	.405	.428	.465	.508	.550	.658	.756
Gillespie	.503	.535	.586	.646	.698	.842	.975
Glasscock	.402	.423	.453	.489	.526	.612	.683
Goliad	.502	.533	.580	.642	.716	.887	1.06
Gonzales	.512	.546	.597	.660	.730	.894	1.05
Gray	.405	.428	.463	.506	.547	.671	.789
Grayson	.575	.610	.662	.726	.785	.957	1.14
Gregg	.620	.659	.719	.797	.863	1.06	1.28

Table 19. Mean values of storm depth for each minimum interevent time by county for Texas—Continued

County name	Mean storm depth in inches for corresponding minimum interevent interval						
	6 hours	8 hours	12 hours	18 hours	24 hours	48 hours	72 hours
Grimes	.567	.600	.657	.727	.813	1.00	1.20
Guadalupe	.512	.545	.595	.661	.725	.883	1.03
Hale	.386	.406	.439	.479	.520	.625	.722
Hall	.412	.437	.475	.519	.558	.669	.774
Hamilton	.521	.552	.598	.652	.703	.843	.983
Hansford	.369	.386	.417	.452	.490	.585	.684
Hardeman	.469	.497	.540	.592	.638	.763	.883
Hardin	.594	.633	.696	.782	.887	1.15	1.45
Harris	.554	.590	.646	.720	.810	1.03	1.27
Harrison	.618	.656	.712	.783	.855	1.05	1.27
Hartley	.354	.372	.399	.436	.476	.569	.662
Haskell	.476	.507	.553	.609	.659	.801	.918
Hays	.527	.564	.615	.685	.743	.897	1.05
Hemphill	.419	.443	.479	.523	.563	.684	.800
Henderson	.595	.633	.690	.759	.821	1.01	1.20
Hidalgo	.433	.459	.502	.557	.618	.751	.841
Hill	.552	.586	.635	.696	.756	.923	1.08
Hockley	.374	.394	.426	.466	.507	.610	.705
Hood	.527	.558	.604	.660	.717	.872	1.02
Hopkins	.624	.665	.726	.800	.863	1.07	1.29
Houston	.578	.614	.668	.736	.811	.998	1.21
Howard	.397	.419	.452	.490	.530	.625	.703
Hudspeth	.250	.260	.278	.302	.329	.392	.448
Hunt	.608	.647	.707	.777	.838	1.03	1.23
Hutchinson	.384	.404	.437	.475	.517	.621	.726
Irion	.411	.434	.468	.511	.549	.646	.728
Jack	.509	.540	.590	.649	.702	.846	.993
Jackson	.540	.574	.627	.696	.776	.972	1.17
Jasper	.625	.662	.721	.799	.899	1.14	1.41
Jeff Davis	.310	.324	.346	.379	.426	.524	.601
Jefferson	.576	.615	.679	.767	.875	1.14	1.45
Jim Hogg	.454	.483	.524	.573	.631	.756	.856
Jim Wells	.467	.495	.541	.601	.668	.818	.957
Johnson	.538	.571	.619	.678	.738	.901	1.05
Jones	.450	.481	.527	.580	.633	.764	.876
Karnes	.502	.532	.577	.636	.706	.861	1.01
Kaufman	.590	.629	.686	.752	.816	.990	1.17
Kendall	.533	.569	.623	.687	.745	.892	1.03
Kenedy	.431	.459	.504	.564	.627	.781	.920
Kent	.438	.464	.503	.550	.595	.709	.811
Kerr	.495	.527	.582	.645	.699	.843	.976
Kimble	.457	.483	.529	.581	.626	.754	.863
King	.461	.485	.526	.576	.622	.745	.859
Kinney	.445	.468	.511	.562	.614	.735	.845
Kleberg	.453	.482	.529	.592	.656	.812	.963
Knox	.489	.515	.558	.612	.661	.801	.927
La Salle	.478	.508	.550	.600	.655	.782	.899
Lamar	.639	.679	.740	.818	.884	1.09	1.31
Lamb	.373	.392	.423	.462	.504	.605	.700
Lampasas	.517	.549	.596	.649	.697	.840	.976
Lavaca	.524	.559	.611	.678	.751	.926	1.10
Lee	.540	.571	.623	.691	.755	.931	1.10
Leon	.562	.598	.648	.716	.785	.962	1.15
Liberty	.552	.588	.644	.723	.820	1.06	1.34
Limestone	.542	.575	.623	.686	.751	.924	1.11
Lipscomb	.402	.425	.457	.497	.534	.648	.760
Live Oak	.491	.520	.565	.624	.692	.844	.990
Llano	.497	.525	.570	.626	.673	.813	.943
Loving	.320	.336	.360	.387	.416	.479	.537
Lubbock	.385	.406	.439	.480	.522	.628	.726

Table 19. Mean values of storm depth for each minimum interevent time by county for Texas—Continued

County name	Mean storm depth in inches for corresponding minimum interevent interval						
	6 hours	8 hours	12 hours	18 hours	24 hours	48 hours	72 hours
Lynn	.376	.397	.430	.471	.510	.613	.707
Madison	.573	.609	.661	.731	.802	.982	1.16
Marion	.622	.659	.714	.781	.858	1.06	1.29
Martin	.355	.374	.404	.439	.475	.562	.638
Mason	.465	.492	.538	.593	.639	.775	.896
Matagorda	.582	.616	.670	.743	.826	1.04	1.26
Maverick	.469	.493	.534	.588	.640	.762	.861
Mcculloch	.483	.509	.556	.608	.654	.779	.894
Mclennan	.505	.537	.582	.644	.703	.863	1.03
Mcmullen	.491	.520	.565	.621	.682	.820	.952
Medina	.507	.540	.598	.666	.729	.882	1.03
Menard	.457	.481	.525	.570	.613	.733	.839
Midland	.356	.374	.403	.436	.468	.547	.613
Milam	.538	.569	.615	.678	.739	.908	1.07
Mills	.507	.534	.579	.632	.677	.803	.924
Mitchell	.428	.454	.490	.533	.574	.673	.756
Montague	.534	.564	.615	.678	.733	.889	1.04
Montgomery	.572	.607	.661	.733	.824	1.04	1.27
Moore	.380	.399	.431	.469	.510	.605	.701
Morris	.632	.671	.731	.804	.876	1.09	1.31
Motley	.424	.447	.486	.530	.572	.683	.786
Nacogdoches	.617	.655	.715	.784	.862	1.06	1.29
Navarro	.594	.632	.686	.752	.814	.997	1.18
Newton	.637	.674	.733	.812	.913	1.16	1.43
Nolan	.432	.459	.497	.545	.589	.700	.796
Nueces	.456	.485	.532	.596	.661	.823	.980
Ochiltree	.380	.400	.430	.467	.503	.604	.709
Oldham	.363	.382	.410	.447	.488	.584	.678
Orange	.602	.642	.707	.796	.908	1.18	1.49
Palo Pinto	.524	.553	.598	.654	.711	.860	1.01
Panola	.608	.649	.708	.780	.848	1.03	1.26
Parker	.528	.559	.607	.666	.722	.878	1.03
Parmer	.354	.373	.402	.438	.479	.573	.665
Pecos	.380	.396	.420	.452	.484	.561	.628
Polk	.605	.642	.697	.772	.863	1.09	1.34
Potter	.359	.379	.411	.449	.489	.596	.698
Presidio	.302	.314	.337	.366	.409	.496	.566
Rains	.603	.642	.701	.772	.836	1.03	1.24
Randall	.356	.378	.412	.448	.488	.597	.697
Reagan	.409	.430	.459	.494	.530	.615	.684
Real	.486	.516	.571	.635	.689	.830	.964
Red River	.642	.681	.742	.820	.883	1.09	1.31
Reeves	.309	.323	.343	.370	.399	.463	.512
Refugio	.488	.519	.567	.632	.705	.883	1.06
Roberts	.398	.420	.453	.494	.533	.648	.760
Robertson	.550	.585	.635	.704	.767	.942	1.11
Rockwall	.581	.618	.675	.740	.804	.977	1.16
Runnels	.513	.540	.581	.630	.676	.812	.924
Rusk	.616	.655	.714	.788	.856	1.05	1.27
Sabine	.617	.650	.705	.776	.864	1.09	1.34
San Augustine	.622	.657	.715	.785	.868	1.08	1.33
San Jacinto	.596	.633	.683	.758	.849	1.07	1.30
San Patricio	.466	.495	.541	.605	.673	.838	.998
San Saba	.496	.523	.570	.627	.672	.806	.933
Schleicher	.427	.451	.489	.535	.580	.688	.790
Scurry	.425	.451	.489	.534	.577	.683	.774
Shackelford	.453	.483	.526	.578	.628	.758	.879
Shelby	.618	.655	.713	.783	.860	1.06	1.29
Sherman	.366	.383	.414	.449	.488	.580	.674
Smith	.579	.615	.673	.746	.812	1.02	1.23

Table 19. Mean values of storm depth for each minimum interevent time by county for Texas—Continued

County name	Mean storm depth in inches for corresponding minimum interevent interval						
	6 hours	8 hours	12 hours	18 hours	24 hours	48 hours	72 hours
Somervell	.529	.561	.610	.668	.725	.880	1.03
Starr	.438	.466	.506	.554	.608	.732	.821
Stephens	.507	.536	.580	.633	.683	.820	.949
Sterling	.434	.457	.489	.528	.566	.656	.729
Stonewall	.461	.491	.535	.587	.635	.760	.868
Sutton	.449	.474	.516	.564	.611	.721	.828
Swisher	.376	.397	.430	.469	.508	.614	.711
Tarrant	.521	.554	.604	.666	.725	.889	1.05
Taylor	.424	.452	.492	.542	.592	.713	.829
Terrell	.405	.425	.456	.495	.534	.620	.694
Terry	.366	.385	.416	.454	.492	.590	.676
Throckmorton	.490	.519	.565	.619	.668	.807	.933
Titus	.637	.677	.739	.814	.881	1.09	1.30
Tom Green	.399	.424	.458	.505	.542	.647	.733
Travis	.459	.494	.547	.609	.672	.843	1.01
Trinity	.596	.633	.688	.760	.842	1.05	1.27
Tyler	.611	.648	.706	.784	.880	1.12	1.39
Upshur	.623	.661	.721	.794	.865	1.07	1.29
Upton	.384	.403	.430	.461	.494	.570	.631
Uvalde	.496	.525	.578	.642	.699	.840	.971
Val Verde	.438	.462	.501	.552	.598	.697	.788
Van Zandt	.598	.637	.695	.765	.828	1.02	1.22
Victoria	.507	.540	.591	.658	.735	.922	1.11
Walker	.586	.622	.675	.746	.829	1.03	1.23
Waller	.589	.626	.685	.762	.845	1.04	1.24
Ward	.332	.348	.371	.399	.426	.490	.543
Washington	.553	.583	.635	.703	.779	.961	1.15
Webb	.450	.478	.517	.564	.620	.741	.849
Wharton	.578	.613	.666	.738	.816	1.01	1.21
Wheeler	.432	.457	.495	.542	.583	.711	.832
Wichita	.491	.518	.563	.616	.666	.794	.921
Wilbarger	.506	.533	.579	.635	.687	.818	.937
Willacy	.403	.433	.476	.532	.598	.746	.874
Williamson	.521	.556	.606	.666	.724	.892	1.05
Wilson	.499	.530	.577	.639	.706	.862	1.00
Winkler	.331	.347	.372	.401	.429	.496	.553
Wise	.539	.570	.621	.682	.738	.894	1.04
Wood	.604	.641	.701	.774	.844	1.05	1.27
Yoakum	.363	.381	.410	.446	.483	.576	.654
Young	.498	.528	.575	.631	.681	.820	.958
Zapata	.440	.470	.508	.552	.607	.728	.826
Zavala	.498	.525	.567	.624	.678	.806	.912

APPENDIX

This section provides example applications and solutions to suggested uses of the statistics presented in this report. The comprehensive statistical characterization of storms in this report facilitates application of the results by a wide-ranging audience and to a large breadth of problems.

Example 1: Estimation of a Hyetograph from Dimensionless Triangular Hyetograph Model

PROBLEM: A hyetograph from the dimensionless triangular hyetograph model for a 100-year, 6-hour storm in northern Brazoria County, Tex., is needed for a rainfall-runoff model. Using the map of the 100-year, 6-hour storm in Texas from Asquith and Roussel (2004, fig. 69), the depth for northern Brazoria County is 10 inches. The triangular dimensionless hyetograph model from section “Triangular and Wakeby Hyetographs from National Weather Service Hourly Rainfall Stations” is selected by the analyst.

SOLUTION: The triangular dimensionless hyetograph for a 6-hour storm is the 0–12-hour duration model. Parameters a and b from table 7 are used in equations 1 and 2. The two equations for this dimensionless hyetograph are

$$p_1(0 \le F \le 0.02197) = 45.52F^2 \text{, and} \tag{A1}$$

$$p_2(0.02197 < F \le 1) = -1.022F^2 + 2.045F - 0.02246\,. \tag{A2}$$

The two equations for the rainfall hyetograph for the design storm are constructed by dividing the fraction of storm duration F by the storm duration (6 hours) and multiplying the fraction of storm depth p by storm depth (10 inches). In the subsequent equations T is time (hours) and P is storm depth as a function of time. The first equation is

$$P_1\left(0 \le \left(\frac{T}{6}\right) \le 0.02197\right) = 10 \times 45.52\left(\frac{T}{6}\right)^2, \tag{A3}$$

$$P_1(0 \le T \le 0.02197 \times 6) = 10 \times \frac{45.52}{36}(T)^2 \text{, and} \tag{A4}$$

$$P_1(0 \le T \le 0.13182) = 12.64T^2\,. \tag{A5}$$

The second equation is

$$P_2\left(0.02197 < \left(\frac{T}{6}\right) \le 1\right) = 10 \times \left(-1.022\left(\frac{T}{6}\right)^2 + 2.045\left(\frac{T}{6}\right) - 0.02246\right) \tag{A6}$$

$$P_2(0.02197 \times 6 < T \le 1 \times 6) = 10 \times \left(-\frac{1.022}{36}T^2 + \frac{2.045}{6}T - 0.02246\right) \tag{A7}$$

$$P_2(0.13182 < T \le 6) = -0.2839T^2 + 3.408T - 0.2246\,. \tag{A8}$$

The ordinates of the hyetograph for 0.5-hour increments are shown in table A1. The incremental precipitation intensity for each time step is the difference in incremental depths divided by the time increment. For example, the rainfall intensity at T of 2 hours is (5.46-4.25)/0.5 = 2.42 inches per hour. The incremental rainfall intensity might be of interest in some hydrologic applications.

Example 2: Estimation of a Hyetograph from Dimensionless L-gamma Hyetograph Model

PROBLEM: A hyetograph for a design storm of 10 inches of rainfall in 24 hours is needed for a rainfall-runoff model for a Texas watershed. The L-gamma dimensionless hyetograph model is selected by the analyst.

SOLUTION: The dimensionless L-gamma hyetograph for a 24-hour storm is the 12–24-hour duration model. The equation for this dimensionless hyetograph (equation 11 and parameters b and c listed in text of section “L-gamma Hyetographs for Runoff-Producing Storms in Texas”) is

$$p(F) = F^{0.7830} e^{0.4368(1-F)}. \tag{A9}$$

The equation for the hyetograph for the design storm is constructed by dividing the fraction of storm duration F by the storm duration (24 hours) and multiplying the fraction of storm depth p by storm depth (10 inches). The resulting equation is

$$P(T) = 10 \times \left(\frac{T}{24}\right)^{0.7830} e^{0.4368\left(1-\left(\frac{T}{24}\right)\right)} \quad \text{and} \tag{A10}$$

$$P(T) = 0.8304 T^{0.7830} e^{0.4368 - 0.0182T} \tag{A11}$$

where T is time and P is storm depth. Finally, the ordinates of the hyetograph for 2-hour increments are shown in table A2.

Table A1. Hyetograph from triangular dimensionless hyetograph model for example 1

[Rainfall intensity computed by backwards finite difference method.]

Time (hours)	Rainfall depth (inches)	Rainfall intensity (inches/hour)	Applicable equation
0	0	0	P_1
.5	1.41	2.82	P_2
1.0	2.90	2.98	P_2
1.5	4.25	2.70	P_2
2.0	5.46	2.42	P_2
2.5	6.52	2.12	P_2
3.0	7.45	1.86	P_2
3.5	8.23	1.56	P_2
4.0	8.87	1.28	P_2
4.5	9.36	.98	P_2
5.0	9.72	.72	P_2
5.5	9.93	.42	P_2
6.0	10.0	.14	P_2

Table A2. Hyetograph from L-gamma hyetograph model for example 2

[Rainfall intensity computed by backwards finite difference method.]

Time (hours)	Rainfall depth (inches)	Rainfall intensity (inches/hour)
0	0	0
2	2.13	1.07
4	3.54	.705
6	4.69	.575
8	5.66	.485
10	6.50	.420
12	7.23	.365
14	7.87	.320
16	8.42	.275
18	8.90	.240
20	9.32	.210
22	9.69	.185
24	10	.155

Example 3: Estimation of a First-Quartile 90th-percentile Hyetograph

PROBLEM: A hyetograph for a design storm of 6 inches of rainfall in 10 hours is needed for a rainfall-runoff model. Additional design guidance indicates that the 90th-percentile empirical dimensionless hyetograph is to be used.

SOLUTION: The analyst consults the dimensionless hyetograph curves in figure 17. The top-left graph shows the percentile dimensionless hyetographs for first-quartile storms. For 10-percent increments of storm duration, the fraction of storm depth (percentage of cumulative rainfall) is estimated graphically. The estimated fraction of storm depth ordinates are 0, .69, .88, .93, .96, .97, .98, .99, .995, 1, and 1 (table A3). Therefore, the storm depth for 30 percent of storm duration or 3 hours (0.30×10 hours) is 5.58 inches (.93×6 inches).

Example 4: Estimation of the Distribution of Storm Depth

PROBLEM: A runoff detention structure is to be built with a 36-hour drawdown time in Randall County, Tex. The distribution of storm depth, specifically, the 50th, 75th, 90th, 98th, and 99th percentiles, are needed as part of the design process. The countywide mean storm depths and dimensionless storm depth frequency curves are to be used.

SOLUTION: Storm-depth percentiles for a 36-hour minimum interevent time (MIT) is not a statistic provided in this report. However, 24-hour and 48-hour MIT bracket 36 hours. The mean storm depths for the county (table 19) are 0.488 inches (24-hour MIT) and 0.597 inches (48-hour MIT). The dimensionless-storm depth frequency factors for the 24-hour MIT using the kappa distribution (eq. 17 and table 16) is

$$x(F) = -0.5790 + \frac{1.115}{-0.1359}\left[1 - \left(\frac{1 - F^{1.747}}{1.747}\right)^{-0.1359}\right]. \quad \text{(A12)}$$

The dimensionless storm-depth frequency factors for the 48-hour MIT using the kappa distribution (eq. 17 and table 16) is

$$x(F) = -0.4868 + \frac{1.086}{-0.1326}\left[1 - \left(\frac{1 - F^{1.617}}{1.617}\right)^{-0.1326}\right]. \quad \text{(A13)}$$

The frequency factors for the 50th, 75th, 90th, 98th, and 99th storm-depth percentiles computed from equations 40 and 41 are listed in columns 2 and 5 of table A4 for the 24-hour and 48-hour MIT, respectively. The storm depths are computed by multiplying the countywide mean storm depth by the frequency factors. The storm depths are listed in columns 3 and 6 of the table. The 36-hour MIT storm depths are computed by linear interpolation and are listed in column 4 (shaded) of the table.

The values listed in table A4 show that, for a runoff detention structure in Randall County, Tex., to capture 90 percent of all storms (assuming total conversion of rainfall to runoff), the structure should have a minimum storage capacity of about 1.35 inches.

Table A3. Hyetograph for first-quartile 90th-percentile dimensionless hyetograph for example 3
[Rainfall intensity computed by backwards finite difference method. in., inches]

Fraction of storm duration	Time (hours)	Fraction of storm depth	Storm depth (in.)	Rainfall intensity (in./hour)
0	0	0	0	0
.10	1	.69	4.14	4.14
.20	2	.88	5.28	1.14
.30	3	.93	5.58	.30
.40	4	.96	5.76	.18
.50	5	.97	5.82	.06
.60	6	.98	5.88	.06
.70	7	.99	5.94	.06
.80	8	.995	5.97	.03
.90	9	1	6	.03
1	10	1	6	0

Table A4. Regional values for selected percentiles of storm depth in Randall County, Texas for example 4
[--, dimensionless; in., inches. Linear interpolation is used to estimate the storm depths for the 36-hour minimum interevent time.]

	24-hour minimum interevent time		Storm depth for percentile for storms defined by 36-hour minimum interevent time	48-hour minimum interevent time	
Storm-depth percentile (percent)	Storm depth frequency factor (--)	Storm depth for percentile (in.)	(in.)	Storm-depth frequency factor (--)	Storm-depth for percentile (in.)
50	0.503	0.246	0.279	0.521	0.311
75	1.26	.614	.688	1.28	.761
90	2.49	1.22	1.35	2.48	1.48
98	5.19	2.53	2.79	5.09	3.04
99	6.57	3.20	3.52	6.41	3.83