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Cheng-Lung Chen

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**URBAN STORM RUNOFF INLET HYDROGRAPH STUDY**

**Volume 4**

**Synthetic Storms for Design of Urban Highway Drainage Facilities**

by

**Cheng-lung Chen**

**Prepared for**

**Federal Highway Administration  
Offices of Research and Development  
Washington, D.C. 20590**

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**May 1975**

**PRWG106-4**

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Department of Transportation. This report does not constitute a standard, specification, or regulation.

## ABSTRACT

The main objective of this study is to develop an accurate design method for computing inlet hydrographs of surface runoff, with average recurrence intervals of 10, 25, and 50 years, from typical urban highway by flood routing technique.

Knowledge of the time distribution of rainfall in heavy storms constitutes a basis for the design of an urban storm sewer system. A unified time-coordinate system and the rainfall intensity-duration-frequency relationships are used to develop the generalized synthetic (design) hyetograph equations for all types of storms. The hyetograph equations are further normalized for identifying the dimensionless parameters that play predominant roles in the formulation of a design storm pattern. The method of least squares and an optimization technique are applied to the evaluation of the storm parameters through the use of the rainfall intensity-duration-frequency maps in the U.S. Weather Bureau Technical Paper No. 40. It is found that the parameter evaluation method can greatly be simplified by establishing relationships among the storm parameters. However, an analysis of available actual hyetographs failed to establish any relationships between the storm skewness and the other storm parameters.

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**Key Words:** Design, Drainage, Equation, Frequency, Highways, Hydrology, Hyetographs, Inlets, Intensity-duration curves, Rainfall, Runoff, Sewers, Storm patterns, Storms, Urban



## PREFACE

The work described in this report was performed under contract COT-FH-11-7806, entitled "Urban Storm Runoff Inlet Hydrograph Study" between the Federal Highway Administration and Utah State University. This research contract aimed at the development of an accurate design method for computing inlet hydrographs of surface runoff under intense rainstorms on urban highways. One of the major tasks in this research project was the development of synthetic (design) storms for highway runoff study. Available rainstorm models and rainfall data were reviewed extensively and the most comprehensive technique was developed to compute the values of the rainstorm model parameters which characterize the storm pattern.

The research was conducted under the general supervision of Dr. Cheng-lung Chen, Professor of Civil and Environmental Engineering at Utah State University. During this study, several students helped analyze rainfall data obtained from the U.S. Weather Bureau Technical Paper Nos. 25 and 40, NOAA Atlas 2, ARS Black Book Series, and field measurements on two urban highway watersheds in the Salt Lake City area.

The contract was monitored by Dr. D. C. Woo, Contract Manager, Environmental Design and Control Division, Federal Highway Administration. The author is indebted to him for his ideas to initiate this study and overall research plan, detailed discussions of research conduct of all phases, and critical reviews and comments of the results during the course of the work.

This volume is the fourth in a series. The others in the series are:

Vol. No.	Title	UWRL Report No.
1	Computer Analysis of Runoff from Urban Highway Watersheds Under Time- and Space-Varying Rainstorms	PRWG106-1
2	Laboratory Studies of the Resistance Coefficient for Sheet Flows over Natural Turf Surfaces	PRWG106-2
3	Hydrologic Data for Two Urban Highway Watersheds in the Salt Lake City Area, Utah	PRWG106-3
5	Soil-Cover-Moisture Complex: Analysis of Parametric Infiltration Models for Highway Sidèslopes	PRWG106-5



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## LIST OF ABBREVIATIONS AND SYMBOLS

$a, b, c$	=	storm parameters
$a_1, b_1, c_1$	=	standard storm parameters describing the ratios of various-duration intensities to 1-hour intensity for the same frequency
$C$	=	coefficient
$F$	=	frequency
$j$	=	counter for data points
$k$	=	coefficient
$n$	=	exponent; number of total data points
$n_\gamma$	=	number of data points before peak intensity for positive $b$
$n_{\gamma 1}$	=	number of measured data points before the constant rate around the peak zone for negative $b$
$n_{\gamma 2}$	=	number of measured data points after the constant rate around the peak zone for negative $b$
$R$	=	rainfall depth in inches
$R^{10,1}$	=	10-year 1-hour rainfall depth in inches
$R^{10,24}$	=	10-year 24-hour rainfall depth in inches
$R^{100,1}$	=	100-year 1-hour rainfall depth in inches
$r$	=	rainfall intensity in inches per hour at any time in the synthetic storm
$r_j$	=	$j$ -th data point for rainfall intensity in inches per hour
$r_{av}$	=	average rainfall intensity in inches per hour
$r_o$	=	normalizing (reference) rainfall intensity
$r_*$	=	normalized rainfall intensity
$r_{av}^j$	=	$j$ -th data point for average rainfall intensity
$r_{av}^{T,t_d}$	=	$T$ -year $t_d$ -hour (or minute) average rainfall intensity in inches per hour
$r_{av}^{T,1}$	=	$T$ -year 1-hour average rainfall intensity in inches per hour
$r_{av}^{10,t_d}$	=	10-year $t_d$ -hour (or minute) average rainfall intensity in inches per hour
$r_{av}^{100,t_d}$	=	100-year $t_d$ -hour (or minute) average rainfall intensity in inches per hour

- $r_{av}^{10,1}$  = 10-year 1-hour average rainfall intensity in inches per hour  
 $r_{av}^{10,24}$  = 10-year 24-hour average rainfall intensity in inches per hour  
 $r_{av}^{100,1}$  = 100-year 1-hour average rainfall intensity in inches per hour  
 $T$  = return period in years  
 $t_c$  = time of concentration  
 $t_d$  = time duration of rainfall in minutes  
 $t^j$  = j-th data point for time in minutes  
 $t_o$  = normalizing (reference) time  
 $t_*$  = normalized time  
 $t_d^j$  = j-th data point for time duration in minutes  
 $x$  = exponent; ratio of 100-year to corresponding 10-year intensity for the same duration  
 $\gamma$  = storm pattern skewness, i.e., the ratio of the time before the peak to the total time duration  
 $\tau$  = integration variable for time

## INTRODUCTION

To design an economic and efficient urban storm drainage system requires an accurate estimation of inflows at all drainage inlets. However, to accomplish this objective, one must first know the manner in which storm rainfall occurs. Temporal and spatial variations in rainfall intensity or depth within an urban drainage area are reflected in the varying inlet discharges which must be accommodated in all considerations of the sizing and economics of storm sewer design. Knowledge of the time and space distribution of rainfall in heavy storms thus constitutes a basis for design of an urban storm drainage system.

To develop a design hyetograph for an urban highway watershed is a formidable task. The elemental urban highway watershed is a small drainage area of less than 0.1 square miles between two highway cross-sections which pass two adjacent highway drainage inlets (spaced from 400 to 1,000 feet) within the right-of-way (varied from 200 to 400 feet). The drainage areas under consideration consist of paved roadway, paved shoulder, sideslope or back slope (paved or grassed), median, gutter (paved or grassed), side ditch, and natural drainage areas. All the urban interstate highway cross-sections are by and large standardized in the design. However, runoff from physiographically similar urban highway watersheds may differ due mainly to rainfall input. Therefore, the formulation of a desired design hyetograph for each of such elemental watersheds is essential to the accurate computation of runoff hydrographs at the drainage inlets and hence the successful design of a storm sewer system including all the inlets. In view of a great variety of rainfall records collected for many years at many weather stations over the country, to develop a single design hyetograph for all urban highway watersheds is impractical, if not impossible. No attempt will be made to develop such a unified design hyetograph except for some general guidelines and criteria set in the evaluation of storm parameters.

Several methods have been developed to formulate the synthetic (design) storm pattern for runoff study. Most of the approaches can be grouped into four general types. Storm patterns formulated on the basis of the first approach are more or less arbitrary temporal distributions of intensity, assumed symmetrical in time or in some fashion that appears reasonable (e.g., Horner and Jens, 1942; Schiff, 1943; Ogrosky, 1964). In the second approach, storm

patterns are derived from the rainfall intensity-duration-frequency relationship to represent merely a series of average values from a variety of storms rather than a sequence of intensities in a particular burst of intense rainfall (e.g., Rousculp, 1927, 1940; Williams, 1943, 1950; U.S. Corps of Engineers, 1948; Kiefer and Chu, 1957; Bandyopadhyay, 1972; Preul and Papadakis, 1973). The third approach is the development of average storm patterns for complete storms, rather than intense bursts of individual rainfall, based on observed rain gage records (e.g., Blumenstock, 1939; Leopold, 1944; U.S. Weather Bureau, 1947; Hershfield and Wilson, 1960; Bock, 1960; Hershfield, 1962; Huff, 1967, 1970; Pilgrim and Cordery, 1975). A method combining the second and third approaches using the rainfall intensity-duration-frequency relationship has been developed by Miller and Frederick (1972) and Frederick et al. (1973) for long-duration storms. The fourth approach is the formulation of a stochastic model to generate a sequence of short-period rainfall (e.g., Raudkivi and Lagun, 1970).

If there is no reliable record of single bursts of intense rain for a particular region—usually the case for the design of urban highway drainage facilities, it appears that the second approach is the only way to formulate the temporal storm patterns without resorting to such intense rainfall records, yet gives a theoretically sound basis for the derivation of design temporal pattern. It is true that storm patterns derived from the second approach in no way represent the characteristics of complete storms with long durations. It may be justified, however, for such a small drainage area as an urban highway watershed to have a design hyetograph which represents an intense burst of a short duration rather than a complete storm of a long duration. For lack of a better method presently available in the formulation of design hyetographs for such small watersheds, the second approach will be generalized by using a unified time-coordinate system to describe a temporal pattern before and after the peak of a storm.

Following the extensive review of literature on the development of the rainfall intensity-duration-frequency relationships and the subsequent development of design storm patterns based on such relationships, a method will be developed to formulate the generalized design hyetograph equations using the unified time-coordinate system. An optimi-



zation technique similar to the method of steepest descent for optimizing an unconstrained problem will be devised to evaluate the storm parameters appearing in the resulting hyetograph equations. The "standard" rainfall intensity-duration data for a number of major cities in the United States will be calculated from Weather Bureau Technical Paper No. 40 (1961) and supplemented by NOAA Atlas 2 (Miller, Frederick, and Tracey, 1973). These "standard" data will be further utilized to evaluate the "standard" storm-pattern parameters, the values of which are expected to vary slightly with localities, but not with frequency.

For completely describing a storm pattern based on the rainfall intensity-duration-frequency relationship, the skewness of the temporal pattern must be specified or evaluated by other means. There seems to be no way to estimate the skewness except by analyzing the most intense rainfalls of various durations recorded at the location under consideration. Major storms for a number of stations will be

selected from ARS experimental watersheds (ARS Black Book Series, 1933-67) and analyzed, in addition to the major storms collected in the Salt Lake City area (Fletcher and Chen, 1975). However, the analysis may fail to produce the average storm skewness, if meaningful at all, for each station under study.

Finally, a graphical method will be proposed to evaluate the "standard" storm-pattern parameters, which with the help of Weather Bureau Technical Paper No. 40, will be used to derive a storm pattern for any station with a desired frequency.

For understanding the characteristics of the generalized design storm-pattern equations, the equations will be normalized so that dimensionless parameters which play a significant role in the formulation of the design hyetograph will be identified. Sensitivity and interaction of the parameters in the generalized design storm pattern will be studied.

## REVIEW OF LITERATURE

Because the rainfall intensity-duration-frequency relationships will be utilized to develop the design storm patterns, existing formulas used in the description of such relationships were first extensively reviewed. After the review of the rainfall intensity-duration-frequency formulas, the design storm patterns based on such formulas are appraised in terms of theoretical concepts behind their developments.

### Rainfall Intensity-Duration-Frequency Formulas

A design hyetograph for a station under study can be formulated from the corresponding rainfall intensity-duration-frequency relationship that may be either graphically portrayed as a family of curves or expressed as a formula. Very often a formula, though derived from a mere exercise in curve fitting, looks more advantageous than a family of curves for use on an electronic computer. Several formulas have been proposed for expressing intensity-frequency relations. Most of the early ones were simple in form and were summarized by Gilman (1964).

The earliest formula was probably the one developed by Meyer (1917, 1921, 1928) who analyzed excessive precipitation data from 1,962 storms, at 43 stations (east of Rockies) from 1896 to 1914. This was a hyperbolic-type formula simplest in form, but with a limitation in application.

$$r_{av} = \frac{a}{t_d + b} \dots \dots \dots (1)$$

in which  $r_{av}$  is the average rainfall intensity in inches per hour,  $t_d$  is the time duration of rainfall in minutes, and  $a$  and  $b$  are parameters, the values of which depend upon specific localities under consideration. The formula can be alternatively expressed in terms of the total rainfall depth,  $R$ , by multiplying Eq. 1 by  $t_d$  as follows:

$$R = \frac{a t_d}{60(t_d + b)} \dots \dots \dots (2)$$

which according to Schafmayer and Grant (1936) and Williams (1950) was first devised by Talbot in 1891. Bernard (1932), after analyzing data of Meyer (1928)

and Morgan (n.d.), found that Eq. 1 was suitable only for rainfall intensities of short durations such as from 5 to 120 minutes. Grunsky (1922) applied Eq. 1 to New York City data with the values of  $a$  and  $b$  found to be 150 and 20, respectively. Grunsky's formula was later referred to as the New York formula.

In view of inaccuracy resulting from the use of Eq. 1 for estimating rainfall intensities of long duration, Bernard (1932) proposed a parabolic type formula which was applicable to duration from 120 to 1,440 minutes.

$$r_{av} = \frac{C}{t_d^n} \dots \dots \dots (3)$$

in which  $C$  is the coefficient and  $n$  is the exponent ranging from 0.70 to 0.82 with the data of Meyer and Morgan. If  $n = 1$ , Eq. 3 was Nipher's formula of 1885 for St. Louis, Mo. (Schafmayer and Grant, 1936). Actually Sherman (1931) in 1905 applied Eq. 3 to Boston data with the values of  $C$  and  $n$  found to be 38.64 and 0.687, respectively, for 50-year storm and 25.12 and 0.687, respectively, for 10-year storm. Sherman (1931) further proposed that the coefficient,  $C$ , in Eq. 3 could be expressed in terms of frequency,  $F$ , as

$$C = kF^x \dots \dots \dots (4)$$

in which  $k$  is the coefficient and  $x$  is the exponent. The value of  $x$  was suggested to be 0.27 for Boston, Mass., by Sherman (1931). Powell (1932), however, in his discussion of Bernard's (1932) paper suggested that because the exponent,  $x$ , would probably vary so little with the location, an average value of  $x$  could be used. In view of the inaccuracies inherent in the rainfall records and the method of compiling them, the refinement gained in varying the exponent value of  $x$  was not judged to be warranted when many other greater discrepancies were still accepted in the course of design. Bernard (1932), nevertheless, on combination of Eqs. 3 and 4, proposed the following general intensity-duration-frequency formula for rainfall intensities of long duration such as 2 hours to 6 days.

$$r_{av} = \frac{kF^x}{t_d^n} \dots \dots \dots (5)$$

in which the exponent, n, need not vary with frequency, but only vary with geographical location, as may the exponent, x.

A more general formula, which incorporates the characteristics of a hyperbolic-type formula, Eq. 1, with those of a parabolic-type formula, Eq. 3, was first developed by Sherman (1931). It had the form:

$$r_{av} = \frac{a}{(t_d + b)^c} \dots \dots \dots (6)$$

in which a, b, and c are parameters, the values of which depend on meteorological localities. The value of a may be evaluated by using the same expression as C in Eq. 4.

Another formula similar to Eq. 6 was proposed by Kiefer and Chu (1957).

$$r_{av} = \frac{a}{(t_d^c + b)} \dots \dots \dots (7)$$

From Eqs. 6 and 7, two different types of design storm patterns could be formulated. There seems no apparent advantage of using one equation over the other as far as the derivation of the synthetic hyetograph equation is concerned. However, there is certainly a slight advantage of using Eq. 6 over Eq. 7 in the case of computing a, b, and c values because Eq. 6, but not Eq. 7, can readily be transformed into a linear form in unknowns on log-log scale.

Hathaway's (1945) study of Yarnell's (1935) rainfall intensity-frequency data for a large number of precipitation stations indicated that there were fairly consistent relationships between the average intensity of rainfall for a period of 1 hour and the average rates of comparable frequency for shorter and longer intervals, regardless of the geographical location of the stations or frequency of 1 hour rainfall. These relations were referred to as the "standard" intensity-duration curves (Williams, 1950), the use of which might eliminate the need for the formulas mentioned above. The similarity between standard intensity-duration curves for various localities was explained by Williams (1950) as the fact that high-intensity short-duration storms from which most of the data were obtained are of the convective type, accompanied by electrical phenomena. Since the physical laws governing the rainfall-producing characteristics of such storms are the same everywhere, the only variable is the frequency with which various intensities occur.

## Design Storm Temporal Patterns

The customary rainfall-duration curve or formula for any specific frequency gives only the average rainfall intensity for any particular duration and applies no information as to how the intensity varies from the average during the duration period. However, the rainfall intensity practically always does vary in nature. Nature never allows a rain to fall at one rate for the whole duration. The importance of the role played by the variation in the rainfall intensity in the design of urban drainage facility was recognized by Bernard as early as in 1936 in his discussion of Horner's (1936) paper. Sound design demands the assumption of limiting conditions, and therefore, rainfall is arranged in critical order. This special temporal arrangement of rainfall intensities tends to modify the conception of the storm as having a desired frequency. Breihan (1940) determined the probable rates at which the rainfall actually occurred.

Hicks (1944) derived the storm temporal pattern by plotting the major storms of the Los Angeles station of the U.S. Weather Bureau as mass curves with the center of the most intense 5-minute duration at a common point (90-minute elapsed time for design purposes). The result was a storm pattern between "medium" and "delayed" types.

Kiefer and Chu (1957) developed a method for determining a storm temporal pattern based on the rainfall intensity-duration-frequency formula, Eq. 7. They applied the method to a Chicago urban area for storm sewer design. Later the method using Eq. 6 was applied by Bandyopadhyay (1972) and Preul and Papadakis (1973) to an urban drainage area in Guhati, India, and Cincinnati, Ohio, respectively. In all of these previous investigations, different time-coordinate systems were utilized for the description of temporal patterns before and after the peak of a storm. From the engineering point of view, however, expressions of the storm pattern equations in two different time-coordinate systems present a big problem because they cannot be readily solved on an electronic computer.

Three types of synthetic storm patterns could be formulated from the rainfall intensity-duration-frequency formula. The storm patterns were called (1) a completely advanced (initial burst) type; (2) a completely delayed (final burst) type; (3) an intermediate type. In application, the evaluation of the storm parameters such as a, b, and c in Eq. 6 or 7 as well as the rainfall duration,  $t_d$ , and the skewness,  $\gamma$ , of the time distribution appearing in the pattern equation becomes a major task.

## Determination of design storm parameters

Some investigators such as Bleich (1935) and Preul and Papadakis (1973) determined the  $a$ ,  $b$ , and  $c$  values by plotting rainfall data points with various assumed values of  $b$  on log-log paper until a straight line was established while others such as Wagnitz and Wilcoxon (1931) evaluated  $a$ ,  $b$ , and  $c$  values using the method of least squares. The duration,  $t_d$ , of a design hyetograph must be the one that produces the maximum runoff from a given drainage area. The maximum runoff happens at the time of concentration,  $t_c$ , at which all parts of the drainage area may contribute to the flow concurrently. Although in the actual hyetograph,  $t_d$  may be greater than, equal to, or less than  $t_c$ , all previous investigators (Kiefer and Chu, 1957; Bandyopadhyay, 1972; Preul and Papadakis, 1973) set the duration of the design hyetograph equal to  $t_c$ .

## Time concentration

The strict determination of  $t_c$  is very difficult because  $t_c$  depends not only on the physiographical factors such as the slope and character of runoff surfaces, but also on the meteorological factors involved in the rainfall-runoff process. According to Jens and McPherson's (1964) study, where the drainage area served by an inlet is entirely paved,  $t_c$  is assumed to vary from about 5 to 10 minutes as the length of runoff to the inlet varies from 100 ft to about 500 ft. For turfed areas,  $t_c$  is usually considered to vary from about 10 minutes for lengths of runoff less than 100 ft to about 30 minutes for 400 to 500 ft. For bare ground,  $t_c$  may be taken somewhere between the values of paved and turfed areas, decreasing with the expected smoothness of the surface. However, detailed consideration of the several components constituting inlet concentration times is often circumvented through establishment of a fixed  $t_c$  for particular types of highly developed urban areas, with 5 to 15 minutes in common use (ASCE Manual No. 37, 1960).

Jens and McPherson (1964) have found that in small watersheds such as most urban drainage areas, the brief interval between the occurrence of short, intense rainfall and succeeding peak runoff has a more significant effect on the magnitude of the peak rate than the time of concentration. The influence of this effect becomes less, however, as the size of the watershed increases. In general urban drainage areas possess neither the overall detention storage nor long times of concentration and other peak-flow-reducing characteristics of large watersheds. Note that use of a uniform rainfall intensity for a duration equal to  $t_c$  is only a simplifying assumption since rainfall does not truly persist at a uniform intensity for even as short a time as 5 minutes.

## Storm pattern skewness

The critical arrangement (i.e., time distribution) of rainfall intensities is essential to the sound design of urban drainage systems. The most recent study by Pilgrim and Cordery (1975) has clearly indicated that heavy storms, with the exception of isolated thunderstorms, vary almost randomly in the time patterns because very heavy rainfalls are generally associated with highly turbulent unstable air-streams. A temporal pattern with average variation of intensities within the design burst can be formulated by using their method which, however, requires the recorded intense burst of a given duration.

Huff (1967) has found, after analyzing data from two concentrated rain gage networks in central Illinois, a trend for the longer, heavier storms to dominate the fourth quarter of the storm period, whereas short-duration storms account for a major portion of the first and second quarters of the storm period. His classification of the storms according to whether the heaviest rainfall occurred in the first, second, third, or fourth quarter of the storm period as well as dimensionless representation of the time distribution minimizes the effects of mean rainfall, storm duration, and other storm factors on the variability in the time distribution. Huff (1970) has also found that time variability increases with decreasing sampling area, the relative variability (percentage distribution) with respect to average rainfall intensity decreases with increasing intensity, and the absolute variability increases as the mean intensity increases.

The skewness ( $\gamma$  value) of a storm pattern varies greatly with numerous factors so that its accurate determination seems impractical, if not impossible. Various storm factors such as mean rainfall intensity and storm duration cause relatively large variations in the quartile distributions between storms, but no single parameter dictates the characteristics of the distribution (Huff, 1967). To select approximately the  $\gamma$  value for a specified frequency by using Huff's (1967) rainfall mass curves is possible, but his method is subjected to the quartile groupings of the storms recorded only in central Illinois.

Miller and Frederick's (1972) analysis of the sample of 1,484 storms over the Ohio River Basin resulted in a typical time distribution of storm which contained two bursts with the smaller one near the beginning and the larger near the end of the long duration (4 to 10 days) in their study. They found that the number of bursts and time of occurrence within the storm were independent of geography, magnitude, and season. A similar study was also conducted by Frederick (1973) for storms over the Arkansas-Canadian River Basins. Miller and Frederick

(1972) suggested that the positions of the bursts could be reversed if that is determined to be hydrologically the more critical situation. However, their view on the arrangement of bursts was not shared by Pilgrim and Cordery (1975) who contended that the sequence of intensity blocks arranged arbitrarily to give a maximum value of peak runoff in several design patterns would give the joint occurrence of a rainfall intensity of low probability and a pattern of low probability. Consequently, the frequency of exceedence of the resulting flood estimate would then be lower than that of the storm causing it.

A method proposed by Kiefer and Chu (1957), and later adopted by Bandyopadhyay (1972) and Preul and Papadakis (1973), to determine the skewness ( $\gamma$  value) of the temporal pattern was entirely based on antecedent rainfall records of arbitrarily specified durations of 15, 30, 60 minutes, etc., up to  $t_c$ , the time of concentration. The  $\gamma$  value obtained for each specified duration was weighted in proportion to the amount of antecedent rainfall preceding that duration

so that weighted average value of  $\gamma$  was computed. The  $\gamma$  value so obtained should vary with the  $a$ ,  $b$ , and  $c$  values used in the rainfall intensity-duration-frequency formula, Eq. 6 or 7, as well as the  $t_c$  value found in the drainage area under study. Therefore, by using this method, the  $\gamma$  value so obtained cannot be made independently of frequency and  $t_c$ . This result in a sense is contradictory to their original assumption that the  $\gamma$  value is independent of frequency.

Another method of evaluating the  $\gamma$  value developed by Kiefer and Chu (1957) is to calculate the mean locations of the peak within all specified durations such as 15, 30, 60, and 120 minutes and then to have the results weighted proportionally to the time of duration. In this method, the average value of  $\gamma$  for all durations considered, despite being adjusted through the weighting process, still could be biased by inaccuracy in the computed mean locations of the peak for such durations as small as 15 minutes which have only three 5-minute periods.

## SYNTHETIC HYETOGRAPH EQUATIONS

A synthetic hyetograph to be developed for design of drainage facilities is not the one seen or measured in an actual storm. It is rather a temporal pattern with average variation of intensities within the design burst and the most likely sequence of these varying intensities. We all recognize that such a synthetic hyetograph derived from the rainfall intensity-duration-frequency data does not generally represent the rainfall in complete storms, but rather represents intense bursts within storms. It is possible that a number of bursts may come at any time within the actual storms with much, or little, additional rain falling in between the bursts. Therefore, without the recorded intense bursts of a given duration, it is unlikely that a hyetograph can be constructed which represents the average rainfall in complete storms.

Since an elemental urban highway cross-section, as described before, is a small watershed with drainage area less than 0.1 square mile, it may be justified to develop a synthetic hyetograph which represents an intense burst rather than a complete storm of a long duration which consists of a series of single intense bursts. This in a sense is equivalent to assuming that a synthetic hyetograph for urban highway watersheds is a single-burst storm pattern having the duration of rainfall equal to the time of concentration for an entire storm sewer system which drains storm water collected at all drainage inlets. The basic equations to be used are the rainfall intensity-duration-frequency relationships, Eq. 6 or 7, which can be formulated by using rainfall data in Weather Bureau Technical Paper No. 25 or 40.

### Formulation of Hyetograph Equations

As mentioned in the previous section, the rainfall intensity-duration-frequency relationship, Eq. 6 or 7, can be used to derive a synthetic hyetograph equation which produces the same total amount (or depth) of rainfall as described by the corresponding intensity-duration-frequency curve up to any time,  $t$ , for given frequency (or return period),  $F$ . Mathematically it is expressed as

$$\int_0^t r \, d\tau = r_{av} t \dots\dots\dots (8)$$

in which  $r$  is the rainfall intensity in inches per hour at any time in the synthetic storm;  $\tau$  is the

integration variable for time; and  $r_{av}$  is the average rainfall intensity in inches per hour and is assumed to be expressible in the form of Eq. 6 or 7. Because of the reasons as stated previously, only Eq. 6 is used in the present analysis.

The rainfall intensity-duration-frequency formula, Eq. 6, has a parameter,  $b$ , the value of which may be either positive or negative. In the case of a negative  $b$ , Eq. 6 is not valid for  $t_d \leq |b|$ . A preliminary analysis of rainfall data obtained from Weather Bureau Technical Paper Nos. 25 and 40 has indicated that a positive  $b$  mainly applies to a large section of the country—perhaps to the portion east of the Rocky Mountains—while a negative  $b$  generally applies to the west of the Rocky Mountains. However, in some special meteorological areas such as Hawaii (Weather Bureau Technical Paper No. 43, 1962; Cheng and Lau, 1973), the value of  $b$  was found to be, or almost, zero. In light of the variety of the  $b$  value to be found in nature, it is suggested that Eq. 6 be modified to include the cases of negative and zero  $b$ . Therefore, Eq. 6 is expressed in the following form in order that the  $b$  value is always kept positive.

$$r_{av} = \frac{a}{(t_d \pm b)^c} \dots\dots\dots (9)$$

Substituting the expression of  $r_{av}$  (from Eq. 9 after changing its  $t_d$  to  $t$ ) into Eq. 8 and then differentiating the result with respect to  $t$  yields a set of hyetograph equations for three types of storm patterns, which are defined according to the skewness of the pattern,  $\gamma$ , (i.e., the ratio of the time before the peak to the total time duration). Because of the nature of Eq. 9 which also breaks down for  $t_d \leq b$  in the case of  $-b$ , the hyetograph equations need to be separately formulated for both cases of  $+b$  and  $-b$ .

### Hyetograph equations for positive $b$

Three types of storm patterns are specified by using the different values of  $\gamma$ . A completely advanced (initial burst) type storm pattern has  $\gamma = 0$  and a completely delayed (final burst) type storm pattern,  $\gamma = 1$ . Both types which seldom occur in nature may be regarded as extreme cases of the third type, namely an intermediate type storm pattern, which has  $0 < \gamma < 1$ . Hyetograph equations for the three types are derived and listed as follows:

(1) For  $\gamma = 0$

$$r = \frac{a[(1-c)t + b]}{(t+b)^{1+c}} \dots\dots\dots (10)$$

(2) For  $\gamma = 1$

$$r = \frac{a[(1-c)(t_d - t) + b]}{[(t_d - t) + b]^{1+c}} \quad 0 \leq t \leq t_d \dots\dots (11)$$

(3) For  $0 < \gamma < 1$

$$r = \frac{a[(1-c)(t_d - t/\gamma) + b]}{[(t_d - t/\gamma) + b]^{1+c}} \quad 0 \leq t \leq \gamma t_d \dots (12)$$

$$r = \frac{a[(1-c)(t - \gamma t_d)/(1-\gamma) + b]}{[(t - \gamma t_d)/(1-\gamma) + b]^{1+c}} \\ \gamma t_d \leq t \leq t_d \dots\dots\dots (13)$$

**Hyetograph equations for negative b**

In this case, the value of c cannot exceed unity. Moreover, because of the nature of Eq. 9, a small portion of hyetograph for all three types must be given a constant intensity,  $(a/b^c)[(1-c)/(1+c)]^c$  in order to avoid the breakdown when  $t \leq b$ . Hyetograph equations for the three types are derived and listed as follows:

(1) For  $\gamma = 0$

$$r = \frac{a}{b^c} \left( \frac{1-c}{1+c} \right)^c \quad t \leq \frac{2b}{1-c} \dots\dots\dots (14)$$

$$r = \frac{a[(1-c)t - b]}{(t-b)^{1+c}} \quad t \geq \frac{2b}{1-c} \dots\dots (15)$$

(2) For  $\gamma = 1$

$$r = \frac{a[(1-c)(t_d - t) - b]}{[(t_d - t) - b]^{1+c}} \\ 0 \leq t \leq t_d - \frac{2b}{1-c} \dots\dots\dots (16)$$

$$r = \frac{a}{b^c} \left( \frac{1-c}{1+c} \right)^c \quad t_d - \frac{2b}{1-c} \leq t \leq t_d \dots (17)$$

(3) For  $0 < \gamma < 1$

$$r = \frac{a[(1-c)(t_d - t/\gamma) - b]}{[(t_d - t/\gamma) - b]^{1+c}} \\ 0 \leq t \leq \gamma t_d - \frac{2b\gamma}{1-c} \dots\dots\dots (18)$$

$$r = \frac{a}{b^c} \left( \frac{1-c}{1+c} \right)^c \\ \gamma t_d - \frac{2b\gamma}{1-c} \leq t \leq \gamma t_d + \frac{2b(1-\gamma)}{1-c} \dots\dots\dots (19)$$

$$r = \frac{a[(1-c)(t - \gamma t_d)/(1-\gamma) - b]}{[(t - \gamma t_d)/(1-\gamma) - b]^{1+c}} \\ \gamma t_d + \frac{2b(1-\gamma)}{1-c} \leq t \leq t_d \dots\dots\dots (20)$$

For examining the validity of Eqs. 10 through 20, substituting the equation or equations for each case into Eq. 8 and performing the integration over the respective integration limits as specified gives exactly  $r_{av}t_d$ . However, for negative b, if Eq. 8 is satisfied, there is an apparent discontinuity in r, for example, at  $t = 2b/(1-c)$  in the case of  $\gamma = 0$  with  $r = (a/b^c)[(1-c)/(1+c)]^{1+c}$  obtained by substituting  $t = 2b/(1-c)$  into Eq. 15. For application, the values of the parameters characterizing the hyetograph equations such as a, b, c,  $t_d$ , and  $\gamma$  need to be evaluated.

**Evaluation of Hyetograph Parameters**

**Parametric values, a, b, and c**

Taking logarithm of both sides of Eq. 9 yields

$$\log r_{av} = \log a - c \log (t_d \pm b) \dots\dots\dots (21)$$

Preul and Papadakis (1973) determined the a, b, and c values by plotting data points  $(r_{av}^j, t_d^j)$  for  $j = 1, 2, \dots, n$  with various assumed values of b on log-log paper until a straight line was established. Because Eq. 21 is linear in  $\log r_{av}$  and  $\log (t \pm b)$  for a given value of b, the determination of the a, b, and c values can be accomplished in a systematic way by using the method of least squares and an optimization technique similar to the method of steepest descent for optimizing an unconstrained problem. The optimization problem formulated herein is tantamount to the one to find the a, b, and c values for minimizing the expression

$$F(a,b,c) = \sum_{j=1}^n [\log r_{av}^j - \log a \\ + c \log (t_d^j \pm b)]^2 \dots\dots\dots (22)$$

The rainfall intensity-duration-frequency data obtained from Weather Bureau Technical Paper Nos. 25 and 40 can be used for this computation.

**Duration of rainfall,  $t_d$**

Although the rainfall duration,  $t_d$ , of an actual storm can be almost any length of time, the design  $t_d$  of a synthetic hyetograph may be assumed to be the one that produces the maximum runoff from a given highway drainage area which consists of a number of elemental urban highway watersheds, as described previously. For a storm of uniform intensity, the maximum runoff happens at the time of concentration,  $t_c$ , at which all parts of the drainage area may contribute to the flow concurrently at the outlet of a storm sewer system. However, for a storm having time- or space-varying intensities, the preceding statement is no longer true. Even under a uniform-intensity storm, the strict determination of the  $t_c$  value is very difficult because  $t_c$  depends on both the meteorological and physiographical factors involved in the rainfall-runoff process on the given drainage area as well as the hydraulic characteristics of a storm sewer system under study. Many methods (see, e.g. Jens and McPherson, 1964) are available in urban hydrology for evaluating the  $t_c$  that includes the time of lot runoff; time of flow in gutters, open swales, or channels to an inlet; and time of flow in the storm drain. However, they are not further discussed herein because it is beyond the scope of the present study.

In an actual storm,  $t_d$  may be greater than, equal to, or less than  $t_c$ . However, for design purposes, it may be more appropriate to set

$$t_d \geq t_c \dots\dots\dots (23)$$

since  $t_d < t_c$  yields a smaller peak discharge at the inlet.

**Pattern skewness,  $\gamma$**

Theoretically, the  $\gamma$  value of a design storm pattern should be evaluated on the basis of the same criterion as used in the determination of the  $t_d$  value. In other words, the design  $\gamma$  value must be such that the design storm pattern, if applied as an input to the surface runoff computation, will produce the maximum runoff from a given drainage area. The most practical, if not the best, way to determine the  $\gamma$  value is thus to maximize the computed runoff discharge by using the surface runoff model subjected to an excitation of the design hyetograph (Eqs. 12 and 13 for +b and Eqs. 18 through 20 for -b) with various assumed values of  $\gamma$ . It is conceivable that the  $\gamma$  value so determined for geometrically different drainage areas at the same meteorological locality may be different even though the a, b, and c values

used in the hyetograph equations are exactly the same. Conversely, if a drainage area (or  $t_c$ ) is given such as in the present case of an elemental urban highway watershed, the  $\gamma$  value so determined depends on the a, b, and c values and hence on the frequency of a design storm. This unique feature of the design  $\gamma$  value cannot reflect in the computation based solely on rainfall records.

The determination of the  $\gamma$  value based on the design criterion of the maximum runoff would give the joint occurrence of a rainfall intensity of low probability and a pattern of low probability (Pilgrim and Cordery, 1975). From the engineering point of view, it would be too conservative to use such  $\gamma$  value. Because an actual storm pattern is a meteorological phenomenon resulting from the interaction of meteorological and physiographical variables relevant to the study basin, the runoff computation and hence drainage design based on the  $\gamma$  value determined from rainfall records alone may be acceptable.

The  $\gamma$  value determined from the maximum runoff criterion will be included in another phase of this research project and it is not further treated herein. Instead, the  $\gamma$  values will be computed directly from actual rainfall records for both selected ARS experimental watersheds (ARS Black Book Series, 1933-1967) and two urban highway watersheds in the Salt Lake City area (Fletcher and Chen, 1975).

**Normalized (Dimensionless) Hyetograph Equations**

For gaining an insight into the significant parameters that control the design hyetograph, Eqs. 10 through 20 are further normalized. The normalizing quantities selected in the case of +b are  $r_o = a/b^c$ , the maximum intensity in the hyetograph, and  $t_o = t_d$  and those in the case of -b are  $r_o = (a/b^c)[(1 - c)/(1 + c)]^c$ , also the maximum intensity in the hyetograph, and  $t_o = t_d$ . The normalized hyetograph equations for +b are obtained as follows:

(1) For  $\gamma = 0$

$$r_* = \left(\frac{b}{t_d}\right)^c \frac{[(1 - c)t_* + (b/t_d)]}{[t_* + (b/t_d)]^{1 + c}}$$

$$0 \leq t_* \leq 1 \dots\dots\dots (24)$$

in which  $r_* = r/r_o$  is the normalized rainfall intensity and  $t_* = t/t_o$  is the normalized time.

(2) For  $\gamma = 1$



$$r_* = \left(\frac{b}{t_d}\right)^c \frac{[(1-c)(1-t_*) + (b/t_d)]}{[(1-t_*) + (b/t_d)]^{1+c}}$$

$$0 \leq t_* \leq 1 \dots \dots \dots (25)$$

(3) For  $0 < \gamma < 1$

$$r_* = \left(\frac{b}{t_d}\right)^c \frac{[(1-c)(1-t_*/\gamma) + (b/t_d)]}{[(1-t_*/\gamma) + (b/t_d)]^{1+c}}$$

$$0 \leq t_* \leq \gamma \dots \dots \dots (26)$$

$$r_* = \left(\frac{b}{t_d}\right)^c \frac{[(1-c)(t_* - \gamma)/(1-\gamma) + (b/t_d)]}{[(t_* - \gamma)/(1-\gamma) + (b/t_d)]^{1+c}}$$

$$\gamma \leq t_* \leq 1 \dots \dots \dots (27)$$

The following normalized hyetograph equations for  $-b$  are derived by normalizing Eqs. 14 through 20.

(1) For  $\gamma = 0$

$$r_* = 1 \quad t_* \leq \frac{2}{1-c} \left(\frac{b}{t_d}\right) \dots \dots \dots (28)$$

$$r_* = \left(\frac{b}{t_d}\right)^c \left(\frac{1+c}{1-c}\right)^c \frac{[(1-c)t_* - (b/t_d)]}{[t_* - (b/t_d)]^{1+c}}$$

$$t_* \geq \frac{2}{1-c} \left(\frac{b}{t_d}\right) \dots \dots \dots (29)$$

(2) For  $\gamma = 1$

$$r_* = \left(\frac{b}{t_d}\right)^c \left(\frac{1+c}{1-c}\right)^c \frac{[(1-c)(1-t_*) - (b/t_d)]}{[(1-t_*) - (b/t_d)]^{1+c}}$$

$$0 \leq t_* \leq 1 - \frac{2}{1-c} \left(\frac{b}{t_d}\right) \dots \dots \dots (30)$$

$$r_* = 1 \quad 1 - \frac{2}{1-c} \left(\frac{b}{t_d}\right) \leq t_* \leq 1 \dots \dots \dots (31)$$

(3) For  $0 < \gamma < 1$

$$r_* = \left(\frac{b}{t_d}\right)^c \left(\frac{1+c}{1-c}\right)^c \frac{[(1-c)(1-t_*/\gamma) - (b/t_d)]}{[(1-t_*/\gamma) - (b/t_d)]^{1+c}}$$

$$0 \leq t_* \leq \gamma - \frac{2\gamma}{1-c} \left(\frac{b}{t_d}\right) \dots \dots \dots (32)$$

$$r_* = 1$$

$$\gamma - \frac{2\gamma}{1-c} \left(\frac{b}{t_d}\right) \leq t_* \leq \gamma + \frac{2(1-\gamma)}{1-c} \left(\frac{b}{t_d}\right) \dots (33)$$

$$r_* = \left(\frac{b}{t_d}\right)^c \left(\frac{1+c}{1-c}\right)^c$$

$$\frac{[(1-c)(t_* - \gamma)/(1-\gamma) - (b/t_d)]}{[(t_* - \gamma)/(1-\gamma) - (b/t_d)]^{1+c}}$$

$$\gamma + \frac{2(1-\gamma)}{1-c} \left(\frac{b}{t_d}\right) \leq t_* \leq 1 \dots \dots \dots (34)$$

An inspection of Eqs. 24 through 34 reveals that there are three dimensionless parameters which control the storm pattern. They are  $b/t_d$ ,  $c$ , and  $\gamma$ . The  $\gamma$  value that indicates the position of the peak in the hyetograph ranges from 0 to 1, but the ranges of the other two values are unknown. There seems to be no apparent physical meaning for  $b/t_d$  and  $c$ . For illustration, Eqs. 26 and 27 for  $+b$  are plotted in Fig. 1 for  $\gamma = 0.3$  with various values of  $b/t_d$  and  $c$ . It can be seen readily from Fig. 1 that the hyetograph is uniform as  $c \rightarrow 0$  or  $b/t_d \rightarrow \infty$ . For given  $b$  and  $c$  values, the storm pattern with  $b/t_d \rightarrow \infty$  corresponds to the one with  $t_d$  approaching zero. This implies that as a first-order approximation a uniform design hyetograph can be applied to a small drainage area which has a very short time of concentration,  $t_c$ . In this case, the  $\gamma$  value is no longer important. However, when a drainage area and hence  $t_c$  under consideration are larger and longer, respectively, the position of the peak in the hyetograph (i.e.,  $\gamma$  value) becomes more important. In the limit as  $t_d \rightarrow \infty$  or  $b/t_d \rightarrow 0$ ,  $r_*$  becomes zero everywhere in the hyetograph.

The fact that the parameter,  $a$ , is not one of the controlling factors in the formulation of a storm pattern, as manifested itself in the normalized hyetograph equations, Eqs. 24 through 34, suggests the possibility of "standardizing" for each location the values of  $b$  and  $c$  which do not seem to vary with duration. This and other interesting aspects of design storms derived on the basis of the rainfall intensity-duration-frequency relationships will be further discussed in the following section.

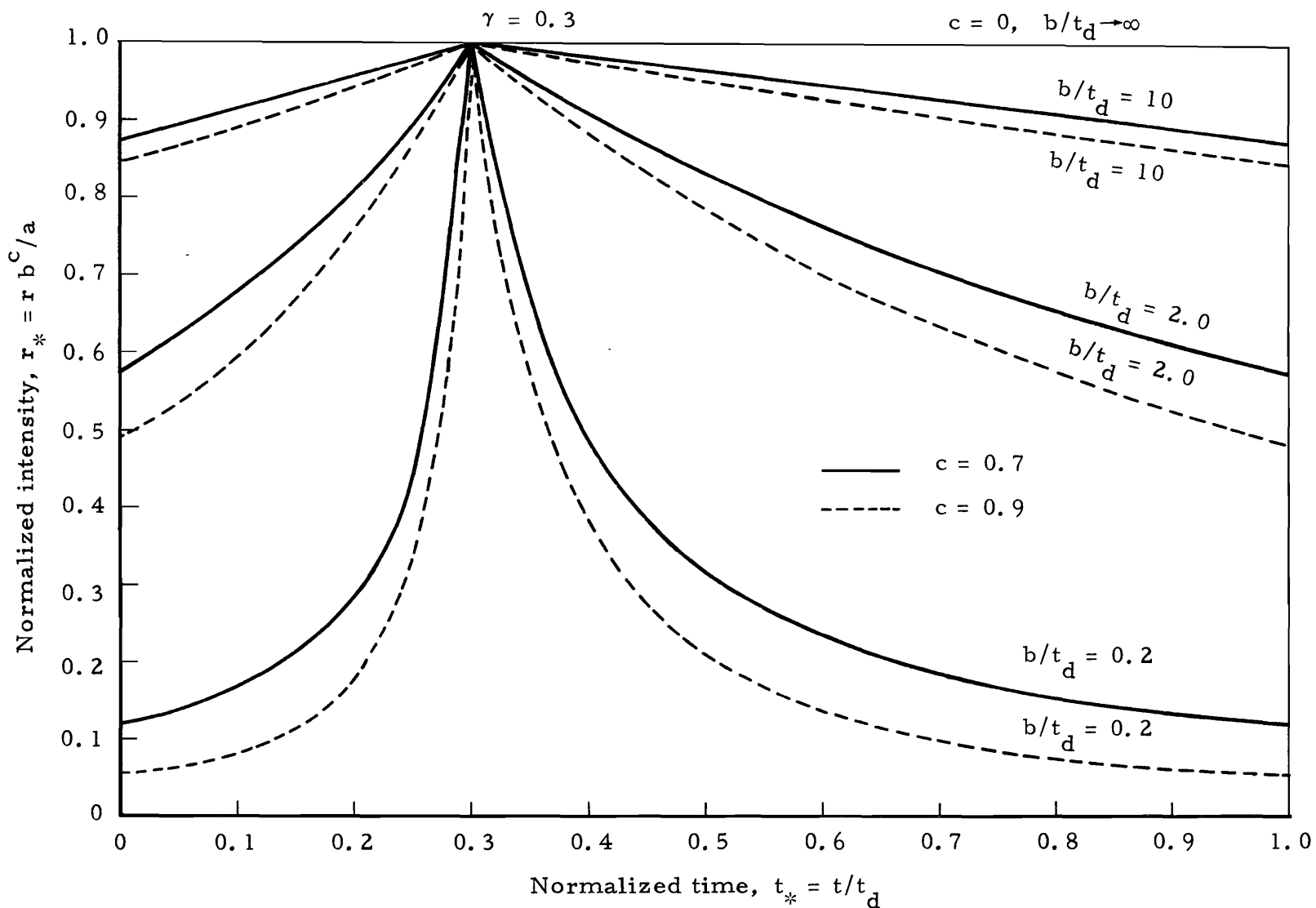


Figure 1. Typical normalized 0.3 - advanced design storm pattern with different  $b/t_d$  and  $c$  values for positive  $b$ .



## STANDARD INTENSITY-DURATION RELATIONSHIPS

To answer a question of whether there are fairly consistent relationships between the average intensity of rainfall for a period of one hour and the average rates of comparable frequency for shorter and longer intervals, regardless of the geographical location of the stations or frequency of 1-hour rainfall, rainfall values for various durations and return periods at selected stations must be examined. Rainfall data obtained from the U.S. Weather Bureau Technical Paper No. 40 are used for this purpose. However, before any conclusion can be drawn from the standard intensity-duration relationships formulated by use of 49 isopluvial maps in the Technical Paper No. 40, attention is first called to the procedures with which these isopluvial maps have been constructed.

There are 49 isopluvial maps in the Technical Paper No. 40, among which the following four are the key maps: 2-year 1-hour, 2-year 24-hour, 100-year 1-hour, and 100-year 24-hour. These four key maps were used jointly with the duration and frequency relationships for obtaining rainfall values for the other 45 maps. Actually, only the 2-year 1-hour and 2-year 24-hour key maps were directly plotted from all available rainfall data through smoothing isopluvial lines. The other two 100-year 1-hour and 100-year 24-hour maps were plotted by use of rainfall values which were the product of the values from the 2-year maps and the 100-year to 2-year ratio maps. Programming of the duration and return-period relationships plus the four rainfall values for each of 3,500 selected stations permitted digital computer computation for the 45 additional rainfall values from which the other 45 isopluvial maps were constructed. The key device in these mapping procedures apparently lay in the use of the duration-frequency relationships developed at each (or a group) of the stations. Are they unique enough to be standardized? If so, would it not be much simpler to derive the standard intensity-duration formulas than construct 49 isopluvial maps? While the derivation of such standard intensity-duration formulas will be attempted, the basic questions regarding the uniqueness and implications of the results obtained from the isopluvial maps need to be answered.

A generalized duration relationship was developed in the Weather Bureau Technical Paper No. 40 to compute the rainfall depth for a selected return

period for any duration between 1 and 24 hours when the 1- and 24-hour values for that particular return period are given. This generalization was obtained empirically from data for the 200 Weather Bureau first-order stations. The ratio of 1-hour to corresponding 24-hour values for the same return period does not vary greatly over a small region. On the windward sides of high mountains in western United States, the 1- to 24-hour ratio is as low as 10 percent. In southern Arizona and some parts of midwestern United States, it is greater than 60 percent. In general, except for Arizona, the ratio is less than 40 percent west of the Continental Divide and greater than 40 percent to the east. A 1- to 24-hour ratio of 40 percent is approximately the average for the United States. There is a fair relationship between this ratio and the climate factor, mean annual number of thunderstorm days. The two parameters, 2-year daily rainfall and the mean annual number of thunderstorm days, have been used jointly to provide an estimate of short-duration rainfalls by Hershfield, Weiss, and Wilson (1955).

A return-period diagram used in the Technical Paper No. 40 is partly empirical and partly theoretical. From 1 to 10 years it is entirely empirical, based on freehand curves drawn through plottings of partial-duration series data. For the 20-year and longer return periods reliance was placed on the Gumbel procedure for fitting annual series data to the Fisher-Tippett Type I distribution. The transition was smoothed subjectively between 10- and 20-year return periods. Consequently, if rainfall values for return periods between 2 and 100 years are plotted on either Gumbel or log-normal paper, the points will nearly approximate a straight line, but are found to be independent of duration. Undoubtedly these features in the return-period relationship will manifest themselves in the standard duration-frequency relationships which are developed herein.

Rainfall depths for various durations and frequency at a number of geographical points in the United States need to be estimated for the construction of the standard intensity-duration relationships. The Technical Paper No. 25 that contains a series of rainfall intensity-duration-frequency curves for the 200 Weather Bureau stations can also be used for this purpose, although the average difference between the two Technical Papers

is approximately 10 percent with no bias. The differences were ascribed mainly to the considerable areal generalization used in the Technical Paper No. 40, except for the fact that the Technical Paper No. 40 is for the partial-duration series and No. 25 is for the annual series. In this study, only the isopluvial maps in Technical Paper No. 40 are used.

A total of 34 major cities including 23 metropolis in order of population size and 11 capitals of the western United States were selected and rainfall depths for 1-, 2-, 5-, 10-, 25-, 50-, and 100-year return periods for 30-minute, 1-, 2-, 3-, 6-, 12-, and 24-hour durations at each city are estimated from the corresponding isopluvial maps in the Technical Paper No. 40, as appended to this report (see Appendix A).

It is noted in the Technical Paper No. 40 that the empirical relationship, 0.79 times the 60-minute rainfall, was used in the estimation of the 30-minute rainfall. In the case of those which have duration shorter than 30 minutes such as the 5-, 10-, and 15-minute rainfalls, rainfall depths are estimated on the basis of the average relationships between 30-minute rainfall and shorter duration rainfall for the same return period, as given in Table 3 of the Technical Paper No. 40. Because the empirical ratio between the 30-minute rainfall and the 60-minute rainfall is 0.79, the 5-, 10-, and 15-minute rainfalls can also be estimated based on the same 60-minute rainfall with the modified ratios shown respectively in Table 1. From the ratios between the 60-minute rainfall and the shorter-duration rainfalls, the relationships between the 60-minute intensity and the shorter-duration intensities can be derived, as listed in Table 1. These intensity ratios, if derived from the Technical Paper No. 40, should also appear in the standard intensity-duration relationships. Any deviations from these ratios may be attributed to the smoothing and areal generalization during construction of the 49 isopluvial maps, errors in estimation from the maps, or a combination thereof.

**Table 1. Average relationships between 60-minute rainfall and shorter duration rainfalls for the same return period.**

Duration (minutes)	Ratio for	
	Rainfall depth	Rainfall intensity
5	0.292	3.51
10	0.450	2.70
15	0.569	2.28
30	0.790	1.58
60	1.000	1.00

Supplemental rainfall values for 2-, 5-, 10-, 25-, 50-, and 100-year return periods for 6- and 24-hour durations can be obtained from the NOAA Atlas 2 (Miller, Frederick, and Tracey, 1973) which provides precipitation-frequency isopluvial maps for the 11 western states. Rainfall values for the selected points in the NOAA Atlas 2 were estimated and entered in the same tables in parenthesis for comparison with those values obtained from the Technical Paper No. 40. However, it appears that the supplemental values obtained from the NOAA Atlas 2 cannot be used in the present analysis because of the difficulty in maintaining the internal consistency between the two sources of data.

The rainfall depths in inches obtained for each station are next converted to the average rainfall intensities in inches per hour by multiplying (for shorter than 60-minute durations) or dividing (for longer than 60-minute durations) the corresponding rainfall depths by the ratios of their durations to 1 hour. The results are also tabulated and appended to this report (see Appendix B).

The so-called standard intensity-duration curves (Hathaway, 1945; Williams, 1949) were plotted on the basis of the relations of 1-hour rainfall intensity to those for other durations. The formulation of these curves is equivalent to find the ratios of various-duration intensities to 60-minute intensity for the same frequency at each station, as tabulated in Appendix C. It is not surprising to see from Appendix C that the ratios for duration shorter than 1 hour have the values very close to those listed in Table 1. Any deviations from the listed ratios, as reasoned before, are probably caused by the smoothing and areal generalization during the construction of the 49 isopluvial maps in the Technical Paper No. 40 or errors in estimation from the maps, or both.

In the Technical Paper No. 40, the generalized duration relationship used in the computation of rainfall values between 1 and 24 hours is the ratio of 1-hour to corresponding 24-hour values. However, this ratio, though it appears to be independent of frequency, varies from 10 to 60 percent with the average of 40 percent in the United States, as mentioned previously. Rainfall values for other durations between 1 and 24 hours were interpolated linearly by means of the rainfall depth-duration diagram given in the Technical Paper No. 40. If the 1-hour rainfall depth is arbitrarily chosen as 1 inch, the range of the preceding 1- to 24-hour ratio can readily be plotted in the rainfall depth-duration diagram, as shown in Fig. 2. The range of rainfall depths and corresponding intensities for durations between 1 and 24 hours can thus readily be computed from this diagram (see Table 2). For convenience in later analysis, the rainfall

depth-duration relations for the intermediate ratios of 15, 20, and 30 percent are also plotted in Fig. 2. Incorporating the values for the intermediate ratios with those listed in Tables 1 and 2 results in the standard intensity-duration relationships for various ratios of 1-hour to corresponding 24-hour rainfall depth, as shown in Table 3 and Fig. 3. The storm parameters, a, b, and c (Eq. 6) for the standard intensity-duration curves can be evaluated by using the method of least squares with the aid of an optimization technique similar to the method of steepest descent for optimizing an unconstrained problem. The possible relationships between these parameters and the ratio of 1-hour to corresponding 24-hour rainfall depth were investigated. Such relationships, if existent, can be used to estimate the a, b, and c values at any location in the United States without resorting to all of the 49 isopluvial maps in the Technical Paper No. 40. For this method to be

valid, at most two isopluvial maps for any frequency, say 10-year 1-hour and 10-year 24-hour, are needed so that the ratio of 1-hour to corresponding 24-hour rainfall depth can be computed.

Since the ratio of 1-hour to corresponding 24-hour rainfall depth in the Technical Paper No. 40 was shown to be nearly independent of frequency as mentioned previously, accuracy-wise it does not really matter which frequency of the two maps is used as long as the present method is valid. However, due mainly to convenience in application, there is definitely an advantage of using 10-year 1-hour and 10-year 24-hour maps over the 2-year 1-hour and 2-year 24-hour key maps, as will be compared later.

Applying the method of least squares and the optimization technique to a set of the rainfall intensities in Table 3 for the same ratio of 1-hour to

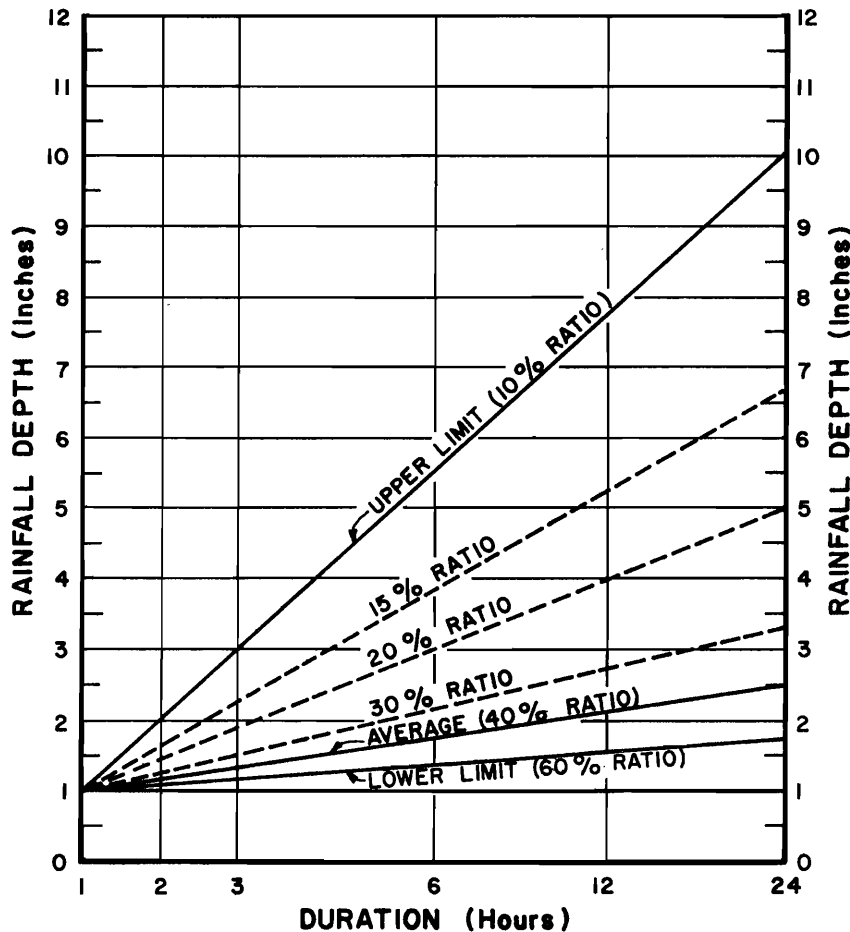


Figure 2. Rainfall depth-duration diagram for the United States (after U.S. Weather Bureau Technical Paper No. 40).

**Table 2. Range of rainfall depths and corresponding intensities for various durations between 1 and 24 hours based on unit 1-hour depth and intensity rainfall.**

Duration (hours)	Upper Limit (10% Ratio)*		Average (40% Ratio)*		Lower Limit (60% Ratio)*	
	Rainfall Depth (inches)	Rainfall Intensity (in/hr)	Rainfall Depth (inches)	Rainfall Intensity (in/hr)	Rainfall Depth (inches)	Rainfall Intensity (in/hr)
1	1.0	1.000	1.0	1.000	1.0	1.0
2	2.0	1.000	1.25	0.625	1.1	0.55
3	3.0	1.000	1.4	0.467	1.2	0.400
6	5.5	0.917	1.75	0.292	1.4	0.233
12	7.75	0.646	2.1	0.175	1.55	0.129
24	10.0	0.417	2.5	0.104	1.667	0.0694

\* Ratio of 1-hour to corresponding 24-hour rainfall depth

**Table 3. Standard rainfall intensity-duration relationships for various ratios of 1-hour to corresponding 24-hour rainfall depth.**

Duration	Ratio* (%)					
	10	15	20	30	40	60
5 min.	3.51	3.51	3.51	3.51	3.51	3.51
10 min.	2.70	2.70	2.70	2.70	2.70	2.70
15 min.	2.28	2.28	2.28	2.28	2.28	2.28
30 min.	1.58	1.58	1.58	1.58	1.58	1.58
60 min.	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	1.00	0.850	0.750	0.650	0.625	0.550
3 hrs.	1.00	0.767	0.650	0.517	0.467	0.400
6 hrs.	0.917	0.650	0.500	0.375	0.292	0.233
12 hrs.	0.646	0.438	0.333	0.229	0.175	0.129
24 hrs.	0.417	0.278	0.208	0.139	0.104	0.0694

\* Ratio of 1-hour to corresponding 24-hour rainfall depth

corresponding 24-hour rainfall depth, yields the values of the "standard" storm parameters,  $a_1$ ,  $b_1$ , and  $c_1$  as shown in Table 4. Note that computation of standard data points for the 10- and 15-percent ratios resulted in a negative  $b_1$  which must be treated differently from the case of a positive  $b_1$ , as mentioned previously. The values of other relevant parameters identified in the normalization of the hyetograph equations are also computed and given in Table 4. For general use in engineering practice, the values of  $a_1$ ,  $b_1$ , and  $c_1$  are plotted against the ratio

of 1-hour to corresponding 24-hour rainfall depth, as shown in Fig. 4. The validity of these storm parameters versus 1- to 24-hour rainfall ratio curves can be examined by comparing the  $a_1$ ,  $b_1$ , and  $c_1$  values obtained from these curves with those estimated directly from the 49 isopluvial maps.

The standard intensity-duration relationship (Appendix C) that seems independent of frequency may be written in a mathematical form:

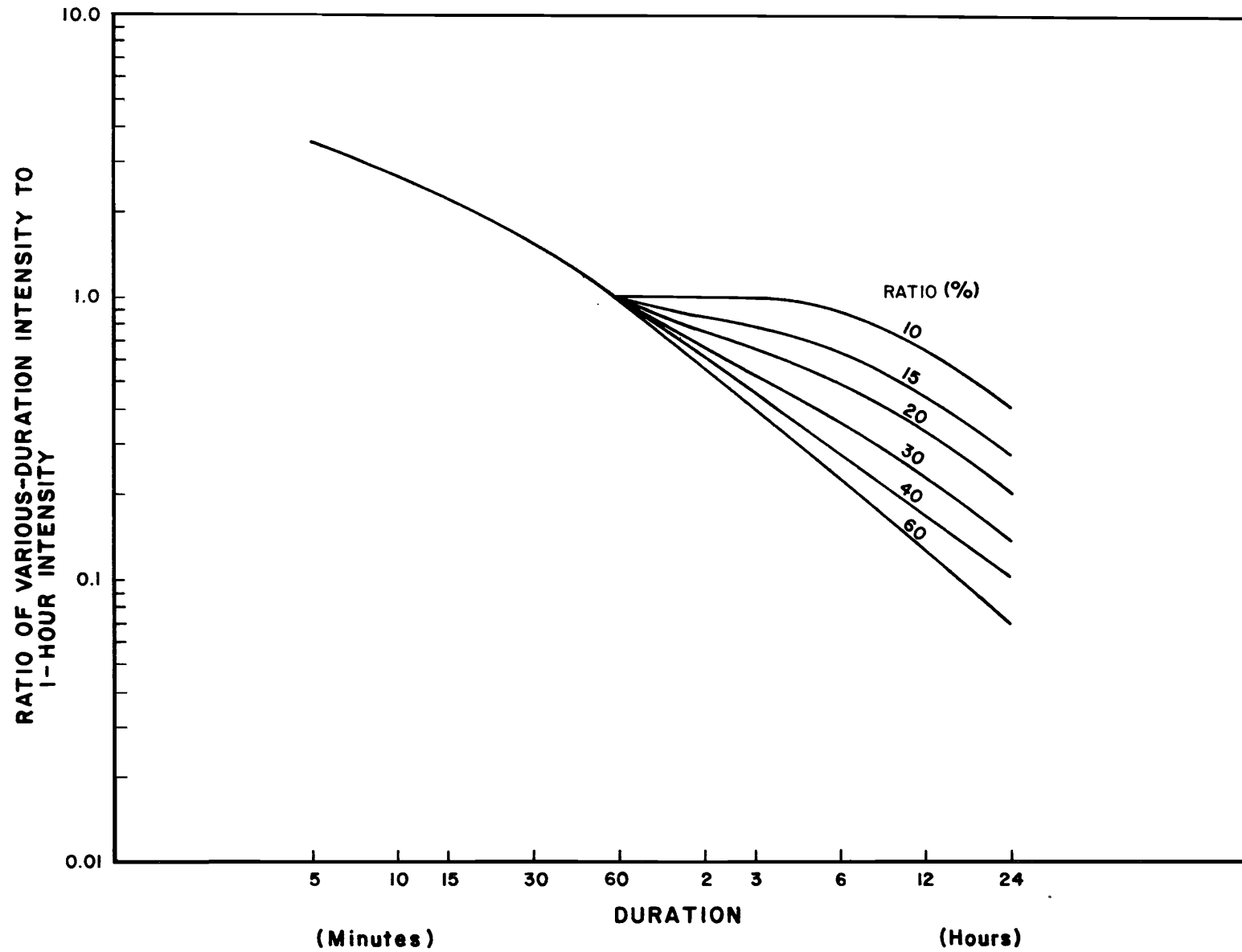


Figure 3. Standard rainfall intensity-duration curves for various ratios of 1-hour to corresponding 24-hour rainfall depth.



**Table 4. Values of standard storm parameters for various ratios of 1-hour to corresponding 24-hour rainfall depth computed from the standard intensity-duration relationships in Table 3 and Figure 3.**

Rainstorm Parameter	Ratio# (%)					
	10	15	20	30	40	60
$a_1$	4.58	6.57	8.91	14.35	22.57	40.01
$b_1$	-2.84	-0.80	1.04	4.12	7.48	11.52
$c_1$	0.309	0.420	0.507	0.632	0.738	0.872
$\frac{a_1}{b_1^{c_1}}$	--	--	8.74	5.86	5.11	4.75
$\frac{a_1}{b_1^{c_1}} \left( \frac{1-c_1}{1+c_1} \right)^{c_1}$	2.72*	4.95*	--	--	--	--
$\frac{a_1}{b_1^{c_1}} \left( \frac{1-c_1}{1+c_1} \right)^{1+c_1}$	1.43*	2.02*	--	--	--	--
$\frac{2b_1}{1-c_1}$	8.22*	2.77*	--	--	--	--

\* For negative b only.

#Ratio of 1-hour to corresponding 24-hour rainfall depth.

$$\frac{r_{av}^{T,t_d}}{r_{av}^{T,1}} = \frac{a_1}{(t_d + b_1)^{c_1}} \dots \dots \dots (35)$$

$$b = b_1 \dots \dots \dots (37)$$

$$c = c_1 \dots \dots \dots (38)$$

whence

$$r_{av}^{T,t_d} = \frac{a_1 r_{av}^{T,1}}{(t_d + b)^c} \dots \dots \dots (39)$$

in which  $r_{av}^{T,t_d}$  is the T-year  $t_d$ -hour (or minute) average rainfall intensity;  $r_{av}^{T,1}$  is the T-year 1-hour average rainfall intensity; and  $a_1$ ,  $b_1$ , and  $c_1$  are the standard storm parameters describing the ratios of various-duration intensities to 1-hour intensity for the same frequency, as shown in Appendix C. If Eqs. 6 and 35 are identical, comparing the parameters of both equations yields

$$a = a_1 r_{av}^{T,1} \dots \dots \dots (36)$$

Given or knowing the ratio of 1-hour to corresponding 24-hour rainfall depth for any frequency, the values of  $a_1$ ,  $b_1 (= b)$ , and  $c_1 (= c)$  can readily be determined from Fig. 4. Substituting the  $a_1$ ,  $b$ , and  $c$  values so estimated and the known T-year

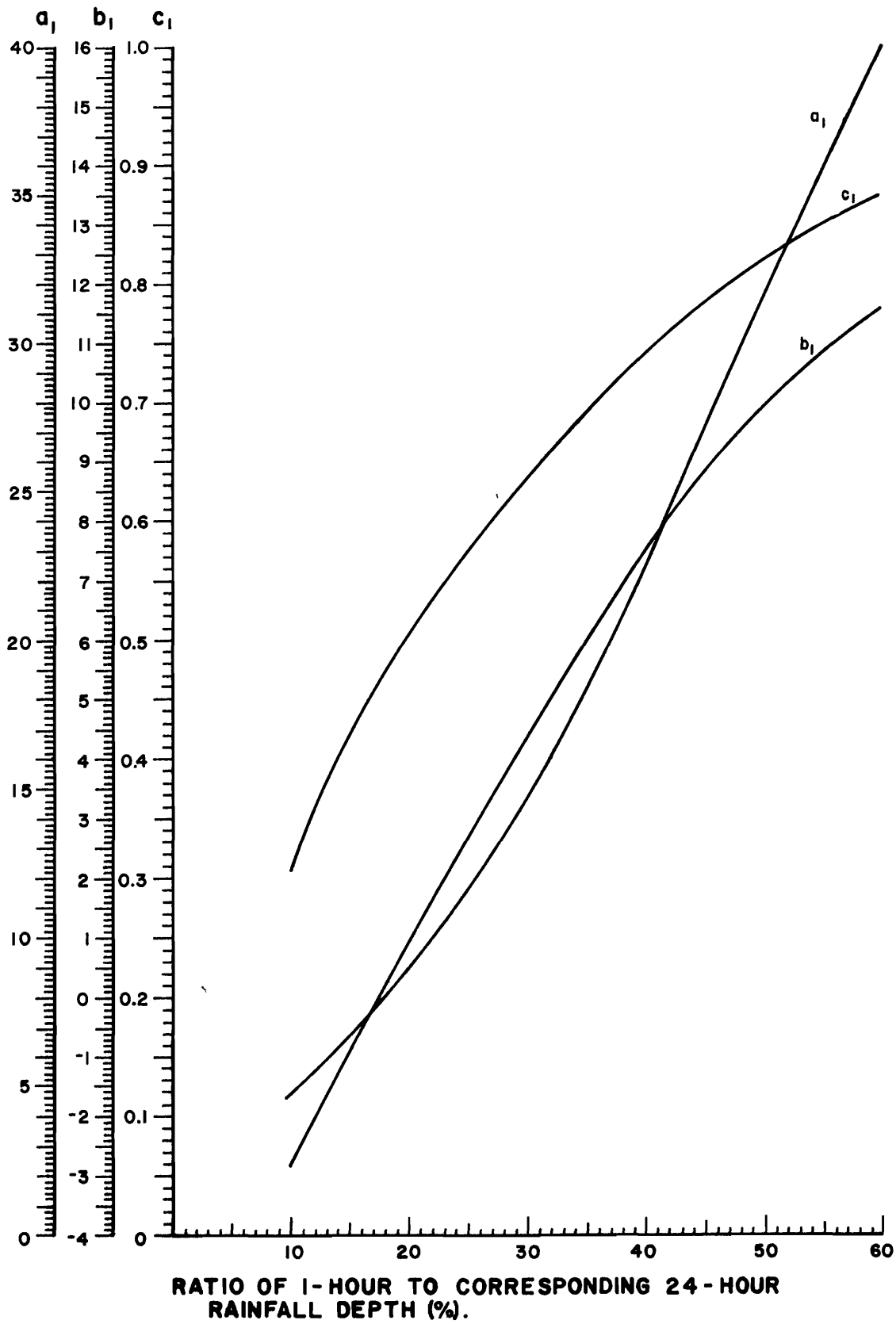


Figure 4. Relationships between standard storm parameters and the ratio of 1-hour to corresponding 24-hour rainfall depth.

1-hour average intensity,  $r_{av}^{T,1}$ , into Eq. 39 gives the average rainfall intensity for T years and  $t_d$  hours (or minutes),  $r_{av}^{T,t_d}$ . The method of determining the  $r_{av}^{T,1}$  value can be simplified if the relationships between 10-year intensity and those for other return periods can be established. The possibility of formulating such relationships is explored herein.

According to the frequency analysis made in the Technical Paper No. 40, a semi-empirical frequency diagram was actually used in the computation of rainfall values for return periods other than 2 and 100 years and hence in the construction of the 49 isopluvial maps. Thus, in reverse, the intensity-frequency relationship to be formulated from the isopluvial maps should be independent of duration and should approximate a straight line on log-normal paper if the smoothing and areal adjustment during the construction of the maps did not take place. To examine this, the ratios of various-frequency intensities to 10-year intensity for the same duration at each of the 34 cities are calculated and listed in Appendix D. An inspection of the tables given in Appendix D reveals that these ratios so calculated vary, though slightly with duration for the same frequency, in a much less distinguishable manner than with return period for the same duration on semi-log paper. For illustration, these ratios for 60-minute duration for the 34 cities are plotted on semi-log paper, as shown in Fig. 5. The figure demonstrates different ranges of the ratios for various return periods. In Fig. 5 a straight line is drawn to pass approximately through the middle ranges of the ratios, but in no way it represents the average return-period relationship. Despite these discrepancies, if we still assume for simplicity that the "standard" intensity-frequency relationship is independent of duration and nearly approximate a straight line on semi-log paper, the relationship can be expressed mathematically as

$$\frac{r_{av}^{T,t_d}}{r_{av}^{10,t_d}} = \log_{10} (10^{2-x} T^x - 1) \dots \dots \dots (40)$$

in which x is the ratio of 100-year to corresponding 10-year intensity for the same duration, defined as

$$x = \frac{r_{av}^{100,t_d}}{r_{av}^{10,t_d}} \dots \dots \dots (41)$$

For the "center" line shown in Fig. 5, the value of x is always equal to 1.5 so that Eq. 40 can be further simplified. However, it is felt that this assumption is not necessary. We assume that the standard

intensity-frequency relationship is a straight-line relationship, but not necessarily a "central" one. Specifically for 1-hour rainfall, Eqs. 40 and 41 become

$$r_{av}^{T,1} = r_{av}^{10,1} \log_{10} (10^{2-x} T^x - 1) \dots \dots (42)$$

$$x = \frac{r_{av}^{100,1}}{r_{av}^{10,1}} \dots \dots \dots (43)$$

respectively. Substituting Eq. 42 into Eq. 39 yields

$$r_{av}^{T,t_d} = \frac{a_1 r_{av}^{10,1} \log_{10} (10^{2-x} T^x - 1)}{(t_d + b)^c} \dots (44)$$

This is the general expression of the rainfall intensity-duration-frequency relationship. To make use of Eq. 44, one must first determine the values of the parameters,  $a_1$ , b, c, and x from the three isopluvial maps with the help of Fig. 4. The three isopluvial maps used in the present study are ones for 10-year 1-hour rainfall ( $R^{10,1}$ ), 10-year 24-hour rainfall ( $R^{10,24}$ ), and 100-year 1-hour rainfall ( $R^{100,1}$ ). In other words, from the ratio of 1-hour to 24-hour rainfall depth for 10-year frequency,  $R^{10,1}/R^{10,24}$ , the values of  $a_1$ ,  $b_1 (= b)$ , and  $c_1 (= c)$  can be estimated from Fig. 4. The ratio of 100-year to 10-year rainfall intensity (or depth) for 1-hour duration,  $r_{av}^{100,1}/r_{av}^{10,1} = R^{100,1}/R^{10,1}$ , is actually equal to the value of x, as expressed by Eq. 43. Therefore, use of Eq. 44 with Fig. 4 greatly reduces the number of the isopluvial maps (from 49 to 3) needed in the evaluation of the storm parameters, a, b, and c (Eq. 6) at any location in the United States. Because Eq. 44 is expressed in the same form as Eq. 6, the parameters, a and  $a_1$ , must be related by

$$a = a_1 r_{av}^{10,1} \log_{10} (10^{2-x} T^x - 1) \dots \dots (45)$$

If the 2-year 1-hour and 2-year 24-hour key maps were used in the evaluation of the parameters,  $a_1$ ,  $b_1 (= b)$ , and  $c_1 (= c)$ , it would be better to express the parameter, a, in terms of  $r_{av}^{2,1}$  than  $r_{av}^{10,1}$  as shown in Eq. 45. In that case, the standard intensity-frequency relationship, as portrayed in Fig. 5, should be calculated on the basis of 2-year intensity rather than 10-year intensity and the expressions of Eqs. 40 through 45 would change accordingly, possibly becoming more complicated than the present forms due mainly to the odd expression of  $\log_{10} 2$  instead of  $\log_{10} 10$  which is unity. The validity of the present method using the three isopluvial maps with the help of Eq. 44 and Fig. 4 is examined by comparing the rainfall intensities of

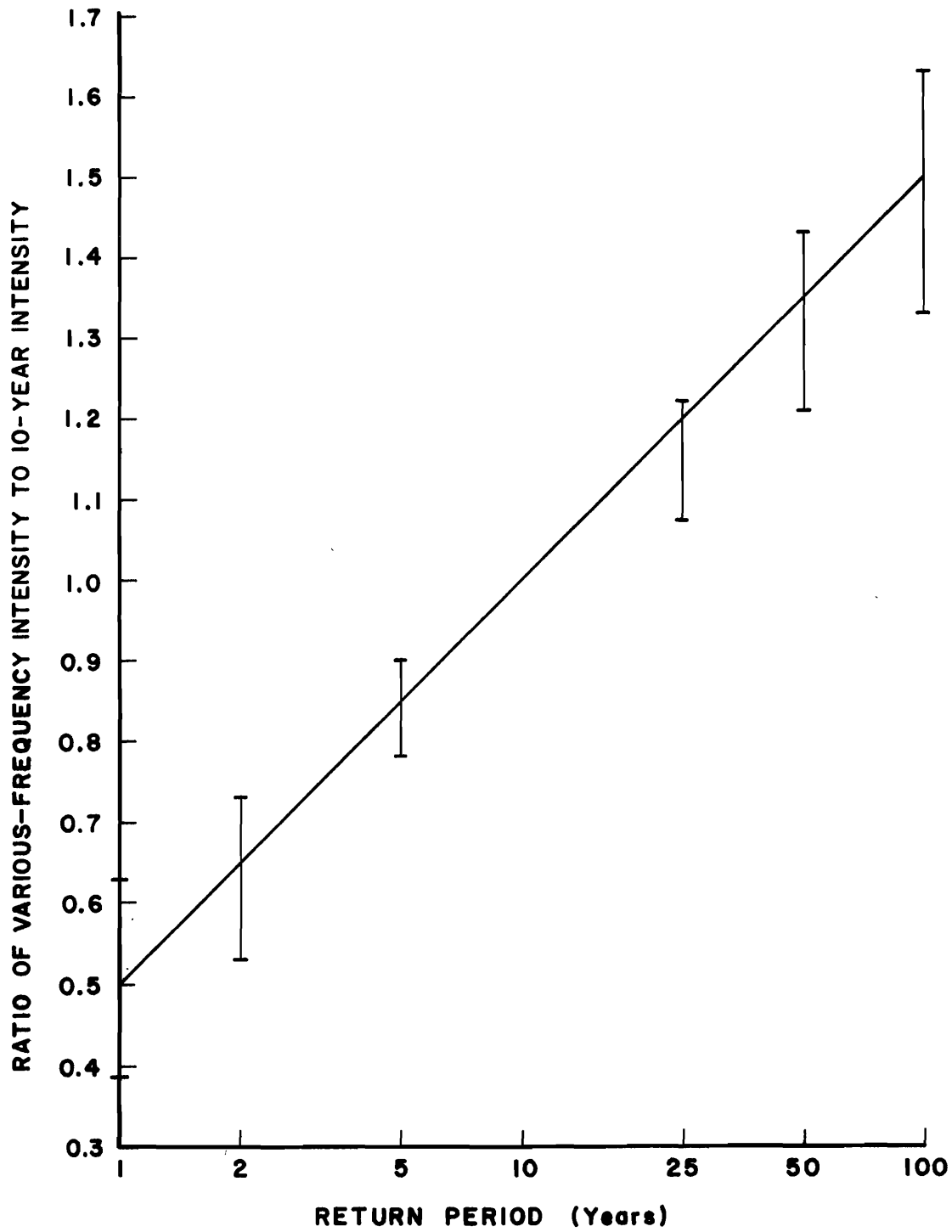


Figure 5. Standard rainfall intensity-frequency relationship for 60-minute duration for the 34 cities studied.

various durations and frequencies obtained from the present method with those obtained from the 49 isopluvial maps in the Technical Paper No. 40.

**EXAMPLE.** The values of the storm parameters, a, b, and c for New York, N.Y. (40.4° N., 74.0° W.) are required in the formulation of design storm patterns. The 10-year 1-hour, 10-year 24-hour, and 100-year 1-hour rainfall values are estimated from the maps (Figs. 6, 7, and 8) to be 2.15, 5.20, and 3.11 inches, respectively (see also Table A-1 in Appendix A). The ratios of 2.15/5.20 and 3.11/2.15 are 0.413 and 1.447 (= x), respectively. (Note that the ratio of 2-year 1-hour and 2-year 24-hour rainfall values is 1.43/3.38 = 0.423 from Table A-1 in Appendix A.) From Fig. 4, corresponding to the ratio of 0.413, one can readily find a<sub>1</sub> = 23.9, b (= b<sub>1</sub>) = 7.85, and c (= c<sub>1</sub>) = 0.75, which are within the accuracy of the values directly computed from the corresponding standard intensity-duration relationships (Table C-1 in Appendix C), as tabulated in Appendix E (see Table E-1). Because r<sub>av</sub><sup>10,1</sup> (= R<sup>10,1</sup>) = 2.15 in./hr, from Eq. 45, on substitution of the x value, the parameter, a, is now expressed as

$$a = 51.39 \log_{10}(10^{0.553} T^{0.447}) \dots \dots \dots (46)$$

For various return periods, T-years, the corresponding values of a can thus be computed from Eq. 46. For instance, the a values so computed for T = 1, 2, 5, 10, 25, 50, and 100 years are 28.42, 35.33, 44.48, 51.39, 60.53, 67.45, and 74.36, respectively. Substituting the a, b, and c values so obtained into Eq. 6 yields the following intensity-duration relationships for various return periods:

$$r_{av} = \frac{28.42}{(t_d + 7.85)^{0.75}} \quad T = 1 \dots \dots \dots (47)$$

$$r_{av} = \frac{35.33}{(t_d + 7.85)^{0.75}} \quad T = 2 \dots \dots \dots (48)$$

$$r_{av} = \frac{44.48}{(t_d + 7.85)^{0.75}} \quad T = 5 \dots \dots \dots (49)$$

$$r_{av} = \frac{51.39}{(t_d + 7.85)^{0.75}} \quad T = 10 \dots \dots \dots (50)$$

$$r_{av} = \frac{60.53}{(t_d + 7.85)^{0.75}} \quad T = 25 \dots \dots \dots (51)$$

$$r_{av} = \frac{67.45}{(t_d + 7.85)^{0.75}} \quad T = 50 \dots \dots \dots (52)$$

$$r_{av} = \frac{74.36}{(t_d + 7.85)^{0.75}} \quad T = 100 \dots \dots \dots (53)$$

Average rainfall intensities for durations of 5 min, 10 min, 15 min, 30 min, 60 min, 2 hrs, 3 hrs, 6

hrs, 12 hrs, and 24 hrs are computed by using Eqs. 47 through 53 for various return periods, one at a time, and tabulated in Table 5. A comparison of Table 5 with Table B-1 in Appendix B reveals that the average rainfall intensities computed from Eqs. 47 through 53 (or, in general, from Eq. 44) are about of the same magnitudes as those obtained directly from the 49 isopluvial maps within the tolerable accuracy. This comparison in a sense leads to the conclusion that Eq. 44 or, more specifically for New York City, the relationship

$$r_{av} = \frac{51.39 \log_{10}(10^{0.553} T^{0.447})}{(t_d + 7.85)^{0.75}} \dots \dots \dots (54)$$

can be used to compute the average rainfall intensity, r<sub>av</sub>(in./hr), for any duration, t<sub>d</sub>(min), the return period, T (years). Consequently, the a, b, and c values so determined are believed to be as accurate as those computed directly from the 49 isopluvial maps.

The advantage of using Eq. 54 over the 49 isopluvial maps is obvious because Eq. 54 can compute the average rainfall intensity for any duration and any return period including those which do not belong to one of those specified in the 49 maps. Thus, Eq. 54 (only for New York City) or a general form thereof, Eq. 44, (for any location) is believed to be in the most suitable form for use in the computer modeling of the rainfall intensity-duration-frequency relationship.

If the value of x defined in Eq. 41 is assumed to be always 1.5, as portrayed as the "center" line relationship in Fig. 5, Eq. 54 can be further simplified and hence a new set of intensity-duration relationships for various return periods corresponding to Eqs. 47 through 53 can be obtained. However, average rainfall intensities computed from this new set of the relationships based on x = 1.5 were found to be not so accurate as those obtained from Eqs. 47 through 53; therefore they are not tabulated herein for comparison.

For further examining the validity of the present method, data of several major cities obtained directly from the Technical Paper No. 40, as appended to this report, are compared with those computed by using the present method. The rainfall data for cities representing typical meteorological localities of the northeast, southwest, midwest, southeast, deep south, Rocky Mountains, and northwest areas in the United States, one from each area, are investigated. The general rainfall intensity-duration-frequency relationship, Eq. 54, for New York City which represents the northeast region was already developed and tabulated in Table 5. Other cities investigated include Los Angeles, Chicago, Miami, Houston, Denver, and Olympia. The

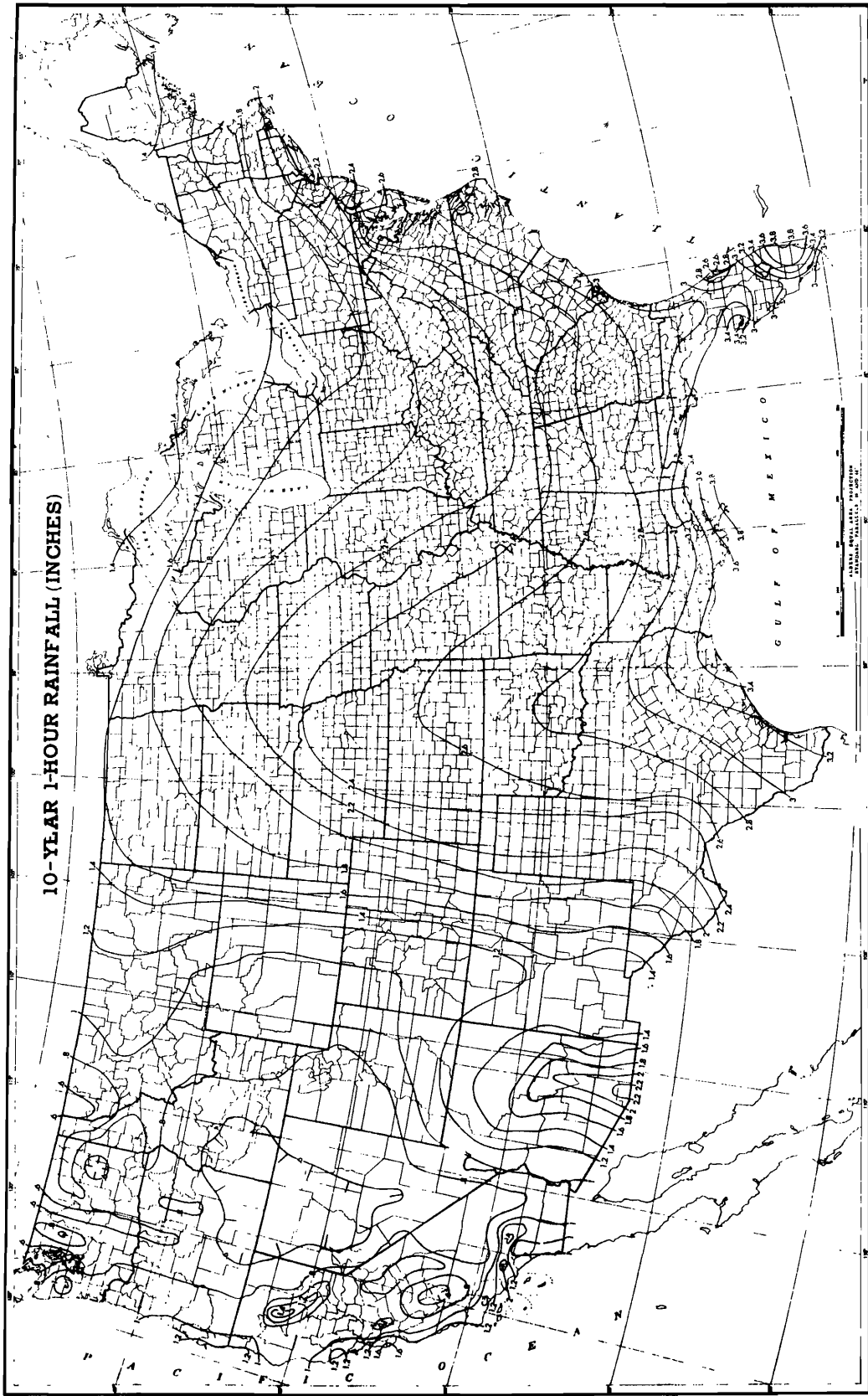


Figure 6. Ten-year 1-hour rainfall (inches) map (after U.S. Weather Bureau Technical Paper No. 40).

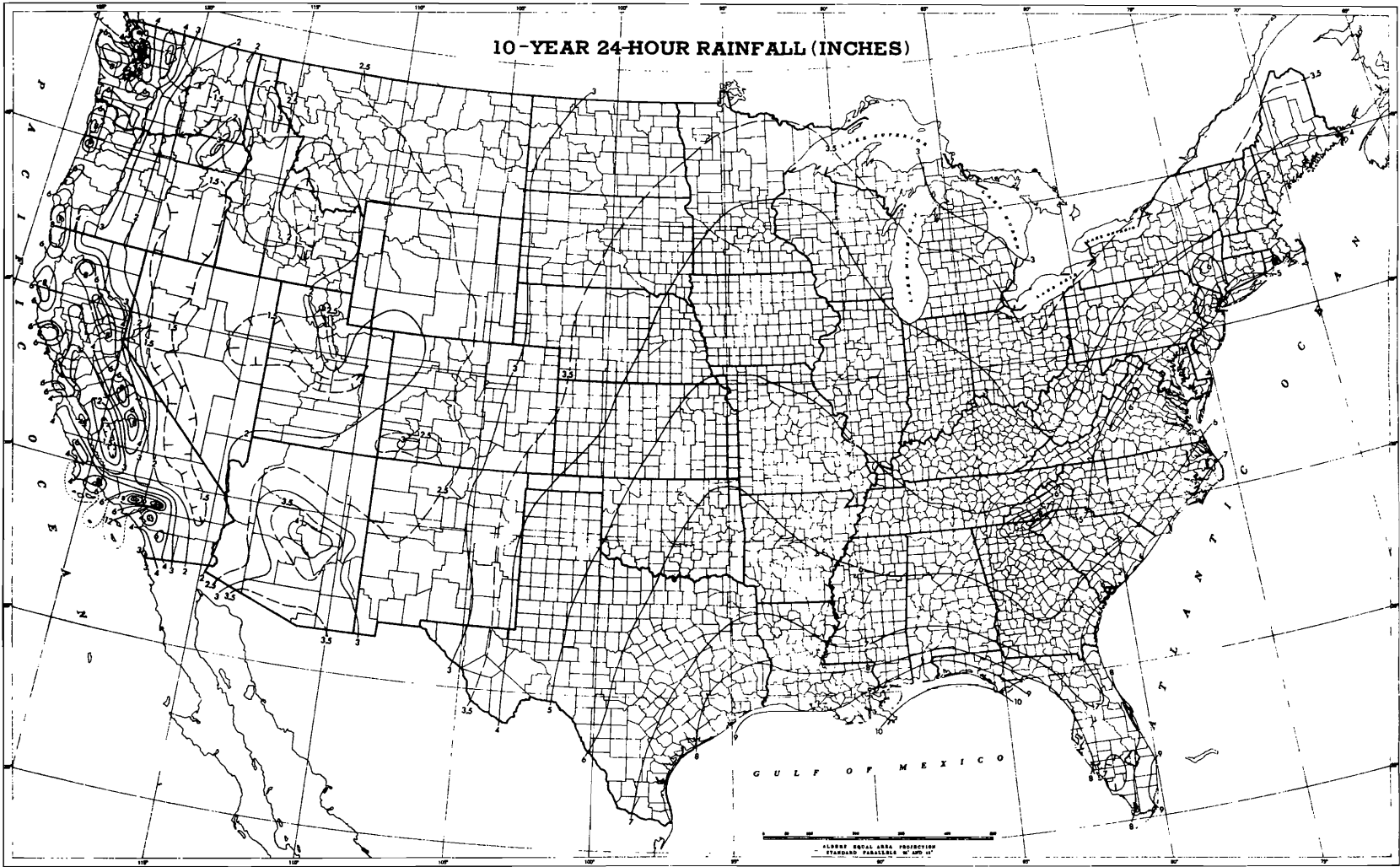


Figure 7. Ten-year 24-hour rainfall (inches) map (after U.S. Weather Bureau Technical Paper No. 40).

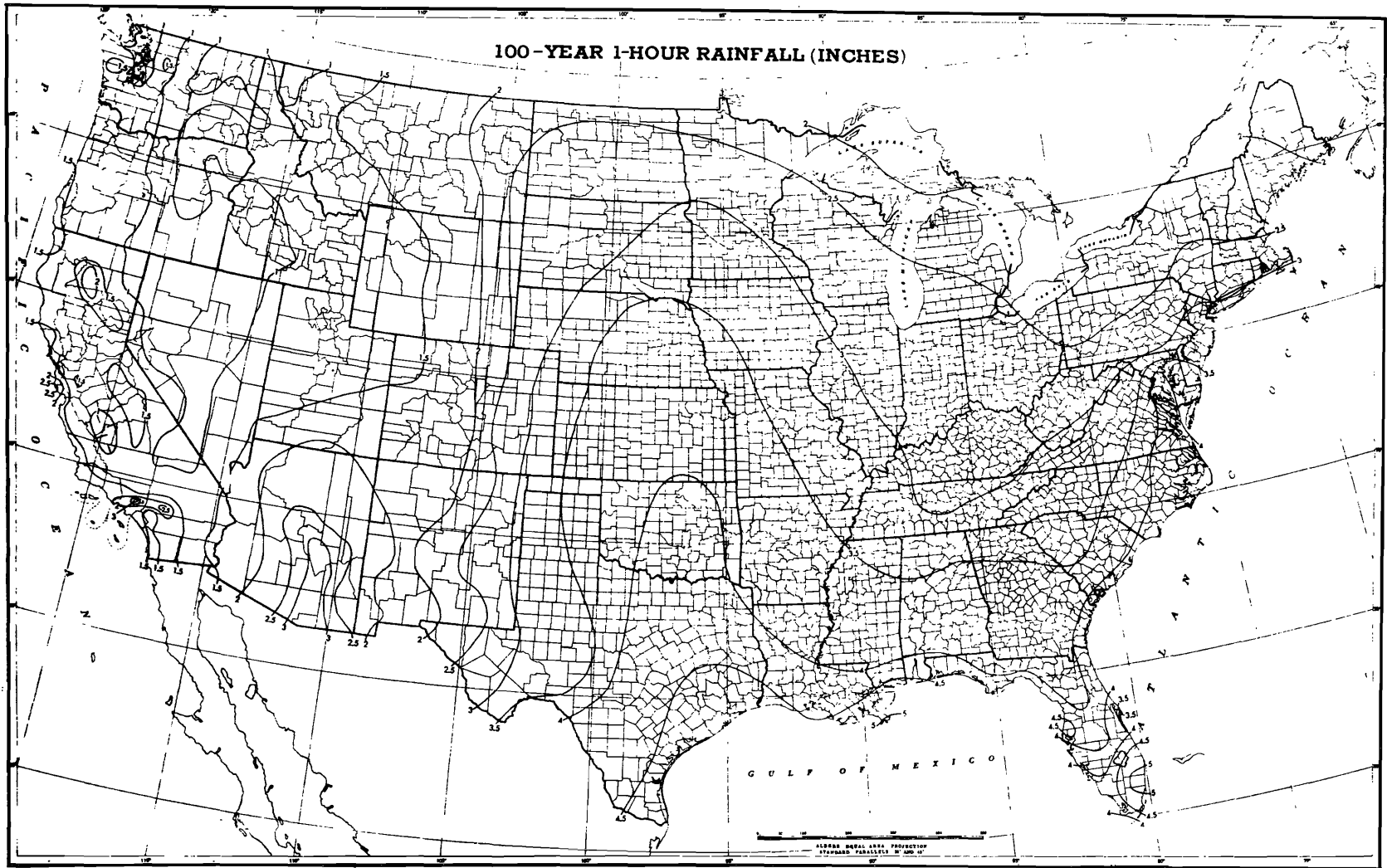


Figure 8. One hundred-year 1-hour rainfall (inches) map (after U.S. Weather Bureau Technical Paper No. 40).



Table 5. Rainfall intensity in inches per hour for various duration and frequency at New York City computed from Eq. 54.

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.19	5.21	6.55	7.57	8.92	9.94	10.96
10 min.	3.27	4.07	5.12	5.92	6.97	7.77	8.56
15 min.	2.71	3.38	4.26	4.92	5.79	6.45	7.11
30 min.	1.86	2.32	2.91	3.37	3.97	4.42	4.87
60 min.	1.20	1.49	1.88	2.17	2.56	2.85	3.15
2 hrs.	0.75	0.93	1.17	1.35	1.59	1.77	1.96
3 hrs.	0.56	0.70	0.88	1.01	1.19	1.33	1.47
6 hrs.	0.34	0.42	0.53	0.61	0.72	0.80	0.89
12 hrs.	0.20	0.25	0.32	0.37	0.43	0.48	0.53
24 hrs.	0.12	0.15	0.19	0.22	0.26	0.29	0.32

values of storm parameters, as tabulated in Appendix E, were consulted in the selection of the cities, for a broad spectrum of the ratio of 1-hour to corresponding 24-hour rainfall depth is desired in the verification of the intensity-duration-frequency relationship that for each city investigated is formulated as follows: For Los Angeles,

$$r_{av} = \frac{10.95 \log_{10}(10^{0.412} T^{0.588})}{(t_d + 1.15)^{0.512}} \dots\dots (55)$$

For Chicago,

$$r_{av} = \frac{60.90 \log_{10}(10^{0.596} T^{0.404})}{(t_d + 9.56)^{0.808}} \dots\dots (56)$$

For Miami,

$$r_{av} = \frac{79.94 \log_{10}(10^{0.658} T^{0.342})}{(t_d + 7.24)^{0.732}} \dots\dots (57)$$

For Houston,

$$r_{av} = \frac{98.26 \log_{10}(10^{0.638} T^{0.362})}{(t_d + 9.30)^{0.798}} \dots\dots (58)$$

For Denver,

$$r_{av} = \frac{50.81 \log_{10}(10^{0.503} T^{0.497})}{(t_d + 10.5)^{0.838}} \dots\dots (59)$$

For Olympia,

$$r_{av} = \frac{6.30 \log_{10}(10^{0.667} T^{0.333})}{(t_d + 0.6)^{0.485}} \dots\dots (60)$$

Rainfall intensities calculated by using Eqs. 55 and 60 for various durations and frequencies are tabulated in Tables 6 through 11, respectively, which are then compared with Tables B-2, B-3, B-14, B-15, B-26, and B-32, respectively, in Appendix B. It is found from these comparisons that in most cases the calculated values compatible with data obtained directly from the Technical Paper No. 40. Consequently, the values of the standard storm parameters  $a_1$ ,  $b_1$ , and  $c_1$  so determined are judged to be unique and adequate for each location studied.

The values of the parameters  $a$ ,  $b$ , and  $c$  for any other cities in the United States can be determined. Data of several major cities appended to this report have been examined and it is found that the parameter values so obtained for most of the cities examined produce as good as, if not better than, rainfall results provided for New York City. However, for simplicity, they are not further discussed herein. It will be interesting to see whether maps with iso- $a$ , iso- $b$ , and iso- $c$  lines can be constructed for the United States. It appears very promising in the light of the limited number of graphs (three isopluvial maps and Fig. 4) being used in the determination of the parameters. To do this, however, is another major task which is beyond the scope of the present study.

**Table 6. Rainfall intensity in inches per hour for various duration and frequency at Los Angeles computed from Eq. 55.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.78	2.54	3.55	4.32	5.33	6.10	6.86
10 min.	1.31	1.88	2.62	3.19	3.93	4.49	5.06
15 min.	1.09	1.55	2.17	2.64	3.25	3.72	4.19
30 min.	0.78	1.11	1.55	1.88	2.32	2.66	2.99
60 min.	0.59	0.79	1.10	1.33	1.64	1.88	2.12
2 hrs.	0.39	0.55	0.77	0.94	1.16	1.33	1.49
3 hrs.	0.31	0.45	0.63	0.76	0.94	1.08	1.21
6 hrs.	0.22	0.32	0.44	0.54	0.66	0.76	0.85
12 hrs.	0.16	0.22	0.31	0.38	0.46	0.53	0.60
24 hrs.	0.11	0.16	0.22	0.26	0.33	0.37	0.42

**Table 7. Rainfall intensity in inches per hour for various duration and frequency at Chicago computed from Eq. 56.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.17	5.02	6.14	6.99	8.12	8.97	9.82
10 min.	3.31	3.95	4.84	5.51	6.40	7.07	7.74
15 min.	2.73	3.29	4.03	4.58	5.32	5.88	6.44
30 min.	1.86	2.24	2.74	3.12	3.62	4.00	4.38
60 min.	1.18	1.42	1.74	1.98	2.29	2.54	2.78
2 hrs.	0.71	0.86	1.05	1.20	1.39	1.53	1.68
3 hrs.	0.52	0.63	0.77	0.88	1.02	1.13	1.23
6 hrs.	0.31	0.37	0.45	0.51	0.60	0.66	0.72
12 hrs.	0.18	0.21	0.26	0.30	0.34	0.38	0.42
24 hrs.	0.10	0.12	0.15	0.17	0.20	0.22	0.24

**Table 8. Rainfall intensity in inches per hour for various duration and frequency at Miami computed from Eq. 57.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	8.41	9.72	11.46	12.78	14.52	15.83	17.15
10 min.	6.54	7.57	8.92	9.95	11.30	12.32	13.35
15 min.	5.43	6.28	7.40	8.25	9.38	10.23	11.08
30 min.	3.72	4.31	5.08	5.66	6.43	7.01	7.60
60 min.	2.42	2.79	3.29	3.67	4.17	4.55	4.93
2 hrs.	1.51	1.75	2.07	2.30	2.62	2.85	3.09
3 hrs.	1.14	1.32	1.56	1.74	1.97	2.15	2.33
6 hrs.	0.70	0.81	0.95	1.06	1.20	1.31	1.42
12 hrs.	0.42	0.49	0.58	0.64	0.73	0.80	0.86
24 hrs.	0.26	0.30	0.35	0.39	0.44	0.48	0.52

**Table 9. Rainfall intensity in inches per hour for various duration and frequency at Houston computed from Eq. 58.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	7.50	8.78	10.48	11.76	13.45	14.74	16.02
10 min.	5.91	6.92	8.25	9.26	10.59	11.60	12.61
15 min.	4.91	5.75	6.86	7.70	8.81	9.65	10.49
30 min.	3.35	3.92	4.68	5.25	6.00	6.57	7.15
60 min.	2.13	2.49	2.97	3.34	3.82	4.18	4.55
2 hrs.	1.29	1.52	1.81	2.03	2.32	2.54	2.76
3 hrs.	0.96	1.12	1.33	1.50	1.71	1.88	2.04
6 hrs.	0.56	0.66	0.78	0.88	1.00	1.10	1.20
12 hrs.	0.33	0.38	0.45	0.51	0.58	0.64	0.69
24 hrs.	0.19	0.22	0.26	0.29	0.34	0.37	0.40

**Table 10. Rainfall intensity in inches per hour for various duration and frequency at Denver computed from Eq. 59.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	2.57	3.34	4.35	5.11	6.12	6.89	7.65
10 min.	2.03	2.64	3.44	4.04	4.84	5.45	6.05
15 min.	1.69	2.20	2.86	3.37	4.03	4.54	5.04
30 min.	1.15	1.49	1.94	2.29	2.74	3.08	3.42
60 min.	0.72	0.94	1.22	1.44	1.72	1.93	2.15
2 hrs.	0.43	0.56	0.73	0.86	1.03	1.15	1.28
3 hrs.	0.31	0.41	0.53	0.62	0.75	0.84	0.93
6 hrs.	0.18	0.23	0.30	0.36	0.43	0.48	0.54
12 hrs.	0.10	0.13	0.17	0.20	0.24	0.27	0.30
24 hrs.	0.057	0.074	0.097	0.11	0.14	0.15	0.17

**Table 11. Rainfall intensity in inches per hour for various duration and frequency at Olympia computed from Eq. 60.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.82	2.09	2.46	2.73	3.09	3.37	3.64
10 min.	1.34	1.54	1.80	2.00	2.27	2.47	2.67
15 min.	1.11	1.27	1.50	1.66	1.88	2.05	2.22
30 min.	0.80	0.92	1.08	1.20	1.36	1.48	1.60
60 min.	0.57	0.66	0.77	0.86	0.97	1.06	1.15
2 hrs.	0.41	0.47	0.55	0.62	0.70	0.76	0.82
3 hrs.	0.34	0.39	0.46	0.51	0.57	0.63	0.68
6 hrs.	0.24	0.28	0.33	0.36	0.41	0.45	0.48
12 hrs.	0.17	0.20	0.23	0.26	0.29	0.32	0.35
24 hrs.	0.12	0.14	0.17	0.19	0.21	0.23	0.25

## PATTERN SKEWNESS IN ACTUAL STORMS

The computation of the storm pattern skewness,  $\gamma$ , can proceed by means of either Eqs. 12 and 13 (for positive  $b$ ) or Eqs. 18, 19, and 20 (for negative  $b$ ) with the help of an optimization technique. However, the  $a$ ,  $b$ , and  $c$  values in these equations for each actual hyetograph to be analyzed must be determined first before the  $\gamma$  value can be computed. A computation procedure similar to the one used in the formulation of the rate-duration relationship (Eq. 6) can be set up for each hyetograph to determine the  $a$ ,  $b$ , and  $c$  values.

The values of  $a$ ,  $b$ , and  $c$  for an actual hyetograph are readily determined by first arranging the hyetograph in the order of intensity in a way similar to the formulation of Eq. 6 and then computing the  $a$ ,  $b$ , and  $c$  values by means of the least squares of the expression shown in Eq. 22. On substitution of the  $a$ ,  $b$ , and  $c$  values just obtained from Eq. 22 into Eqs. 12 and 13 (for positive  $b$ ) or Eqs. 18, 19, and 20 (for negative  $b$ ), the  $\gamma$  value is determined by minimizing the following expression. For positive  $b$ ,

$$F(\gamma) = \sum_{j=1}^{n_\gamma} \left[ r^j - \frac{a[(1-c)(t_d - t^j/\gamma) + b]}{[(t_d - t/\gamma) + b]^{1+c}} \right]^2 + \sum_{j=n_\gamma+1}^n \left[ r^j - \frac{a[(1-c)(t^j - \gamma t_d)/(1-\gamma) + b]}{[(t^j - \gamma t_d)/(1-\gamma) + b]^{1+c}} \right]^2 \dots\dots\dots (61)$$

and for negative  $b$ ,

$$F(\gamma) = \sum_{j=1}^{n_{\gamma 1}} \left[ r^j - \frac{a[(1-c)(t_d - t^j/\gamma) - b]}{[(t_d - t/\gamma) - b]^{1+c}} \right]^2 + \sum_{j=n_{\gamma 1}+1}^{n_{\gamma 2}} \left[ r^j - \frac{a}{b^c} \left( \frac{1-c}{1+c} \right)^c \right]^2$$

$$+ \sum_{j=n_{\gamma 2}+1}^n \left[ r^j - \frac{a[(1-c)(t^j - \gamma t_d)/(1-\gamma) - b]}{[(t^j - \gamma t_d)/(1-\gamma) - b]^{1+c}} \right]^2 \dots\dots\dots (62)$$

in which  $n_\gamma$  is the number of measured data points before the peak in the case of positive  $b$ ;  $n$  is the total number of measured data points within  $t_d$ ; and  $n_{\gamma 1}$  and  $n_{\gamma 2}$  are respectively the numbers of measured data points before and after the constant rate around the peak zone as postulated in Eq. 19 for negative  $b$ . An optimization technique similar to that for minimizing the objective function in Eq. 22 can be used to determine the  $\gamma$  value. Note that in the optimization process the numbers of measured data points before and after the peak,  $n_\gamma$  for positive  $b$  (and  $n_{\gamma 1}$  and  $n_{\gamma 2}$  for negative  $b$ ), vary depending on the location of the peak assumed in the hyetograph. It is expected that the best-fitted hyetograph does not necessarily have the theoretical peak fall within the duration of the highest intensity in the actual hyetograph.

The optimization technique described above was developed primarily for evaluating the pattern skewness ( $\gamma$  value) in actual storms. In application of the preceding method, however, one must be aware of all the assumptions made in the optimization process. The most questionable approach in the method is, of course, related to the suitability of the equations and optimization criterion developed in order for the synthetic hyetograph to best fit the recorded hyetograph. For example, if the actual storm under study is double- or triple-peaked or, sometimes even more complicated, multiple-peaked, the hyetograph equations (i.e., Eqs. 12 and 13 for positive  $b$  and Eqs. 18 through 20 for negative  $b$ ) which were derived based on the assumption of a single-peak storm do not seem to be accurate enough to describe the actual hyetographs, as will be seen later from given examples. The numbers of measured data points such as  $n$ ,  $n_\gamma$ ,  $n_{\gamma 1}$ , and  $n_{\gamma 2}$  in Eqs. 55 and 56 could also become another source of errors. Since the accuracy of the result depends greatly on a number of data points used in the curve-fitting process, as a general rule in this simplified "univariate" optimization technique, the more data

points should yield the better result. Unless a multivariate optimization method can be resorted to minimize the expression as shown on the right-hand side of Eq. 61 or 62 in which the "objective" function is now a function not only of  $\gamma$ , but also of  $a$ ,  $b$ , and  $c$ , to equalize the areas under the measured and synthetic hyetographs appears to be a better means and optimization criterion for best fitting the design hyetograph to the recorded hyetograph. The latter optimization techniques should be explored in future study.

The data points used in the present analysis are only limited to those places in a recorded hyetograph where either time or intensity changes in value. Therefore, the limited number of data points may often result in big errors in the estimation of the  $a$ ,  $b$ , and  $c$  values in the recorded hyetograph and hence the  $\gamma$  value.

Major storms for six stations in ARS experimental agricultural watersheds (ARS Black Book Series, 1933-67) as well as those collected by six automatic recording rain gages in each of the two urban highway watersheds in the Salt Lake City area (Fletcher and Chen, 1975) are selected and analyzed. Actual hyetographs of intense bursts may have double peaks, sometimes even more (i.e., multiple peaks), but they are all treated as a single peak and then applied with the equations. One of the most difficult problems encountered in the analysis is the selection of  $t_d$  for the "isolated" burst. Some storms are very distinctively isolated, but others are not, depending upon the intensity of the antecedent and the trailing parts. Especially some prolonged storms with the intensity less than 0.1 in./hr in the trailing part lasted for tens of hours. For maintaining consistence and the range of interest, storm bursts with the duration longer than 24 hours are excluded from this analysis.

#### Major Storms for Selected Stations from ARS Experimental Agricultural Watersheds

In the design of a drainage inlet, criticism may arise if all the significant factors which affect runoff from the urban highway watershed are not taken into account. One such factor is the infiltration capacity that varies due to different species of turf planted on the urban highway sideslopes.

The urban highway watersheds may be classified according to the following six major species of turf planted on the highway sideslopes: Bermuda grass (*Cynodon dactylon*), Crested wheat grass (*Agropyron dactylon*), Fescue grass (*Festuca elation* var *arundinacea*), Kentucky blue grass (*Poa pratensis*), Red top grass (*Agrostis palustris*; *Agrostis alba*) and Rye grass (*Lolium perenne*; *Lolium multiflorum*).

Six grass zones were delineated by Fletcher<sup>1</sup> in accordance with the adaptability of a species of grass for highway sideslopes in an area under study (see Fig. 9). Note that this delineation is not unique because other species may also be planted on the same areas. Unspecified areas in Fig. 9 are either planted with other than the six species of grass or are not taken into consideration in the delineation for lack of available data.

The U.S. Weather Bureau Technical Paper No. 40 was consulted for the selection of most intensive stations, one from each grass zone, from the ARS experimental agricultural watersheds (ARS Black Book Series, 1933-67) at which official records of actual hyetographs have been kept. The six stations representing approximately the points of the most intensive rainfall for any duration and frequency in the respective six grass zones are marked in Fig. 9. Major storm bursts at the six stations were obtained from the ARS Black Book Series and then analyzed, and the storm parameters for each storm were calculated and tabulated in Table 12.

Typical hyetographs for the six stations, one from each grass zone, with their best-fitted counterparts are shown in Figs. 10 through 15 for comparison.

Analysis of the hyetograph equations, Eqs. 24 through 34, has resulted in the derivation of the important dimensionless parameters,  $b/t_d$ ,  $c$ , and  $\gamma$ , for the design storm formation. The values of these parameters were examined in an effort to establish the relationships among them for each station investigated. However, plots of these parameters on linear, semi-log, or log-log paper failed to reveal the existence of such relationships. For example, the computed  $\gamma$  value for each station varies almost independently of any of the other parameters. No attempt was made to calculate the statistical mean  $\gamma$  value of each station for those actual hyetographs analyzed. It would probably require more data points in the analysis in order for any statistical mean  $\gamma$  value to be meaningful.

#### Major Storms for Two Salt Lake City Urban Highway Watersheds

Major storms for two Salt Lake City urban highway watersheds (Fletcher and Chen, 1975) were analyzed in similar ways as for ARS watersheds and the values of the storm parameters calculated accordingly. There were six recording gages for each station and hyetographs measured at the six gages

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<sup>1</sup>Fletcher, J. E., Storm design criteria for highway inlets, Unpublished Interim Report for Federal Highway Administration, Utah Water Res. Lab., Utah State University, Logan, Utah, 1973.

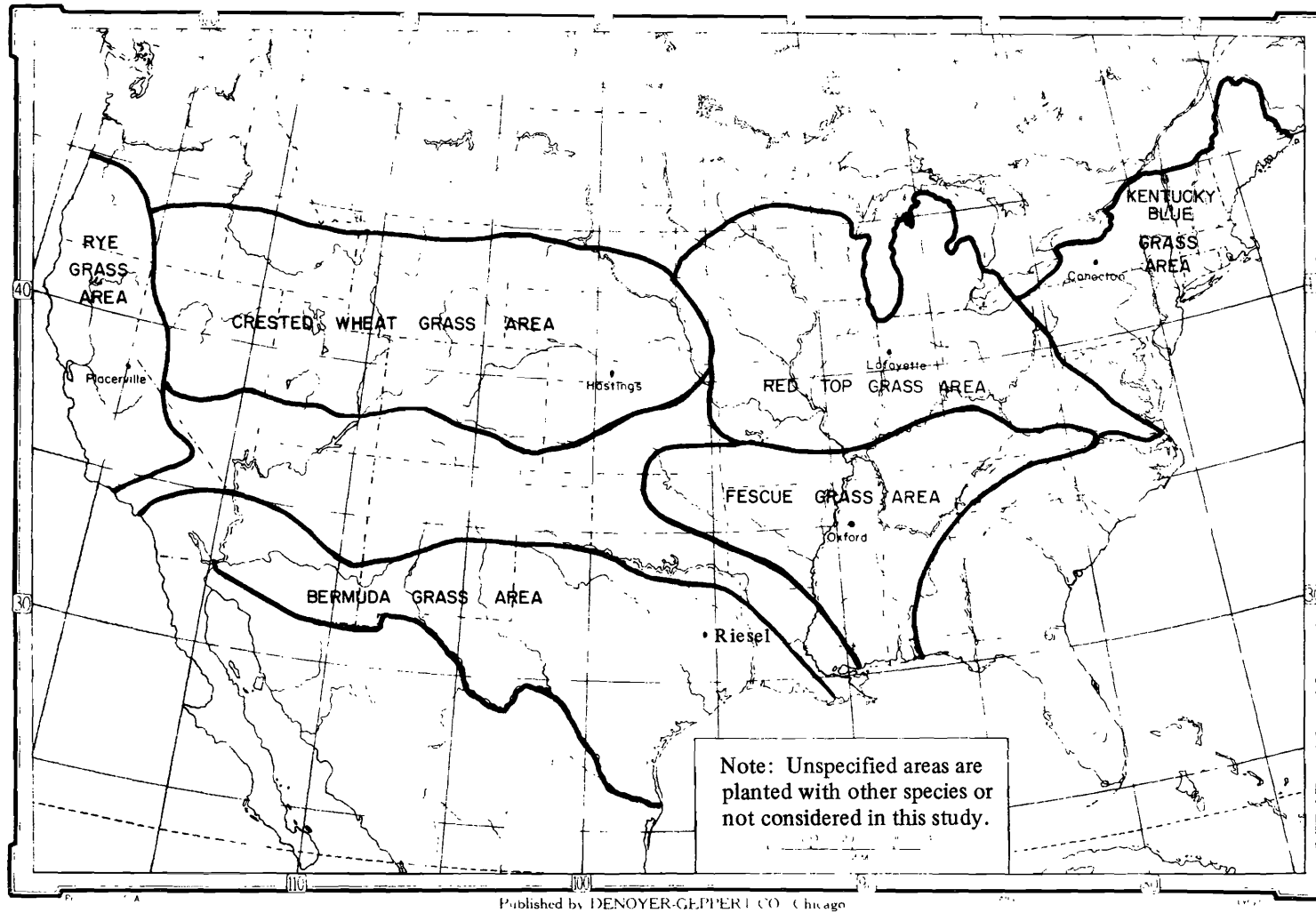


Figure 9. Delineation of six grass zones which are considered to be planted with Bermuda grass, Crested wheat grass, Fescue grass, Kentucky blue grass, Red top grass, and Rye grass on highway sideslopes.

**Table 12. A list of major rainfall events with computed values of storm parameters for six stations selected from ARS experimental agricultural watersheds (ARS Black Book Series, 1933-67).**

Location	Date	$t_d$	a	b	c	$a/b^c$	$b/t_d$	$\gamma$
City, State	M/D/Y	min.		min.		in./hr.		
Riesel, Texas	6/10/41	86	282.18	37.73	1.138	4.54	0.439	0.417
	6/15/42	94	169.38	26.13	1.129	4.25	0.278	0.114
	10/ 8/45	224	529.37	73.44	1.164	3.57	0.328	0.397
	3/12/53	52	98.79	16.05	1.100	4.67	0.309	0.859
	5/ 6/55	18	144.29	10.74	1.086	10.96	0.597	0.231
	7/ 9/61	48	262.61	28.52	1.143	5.70	0.594	0.132
	7/16/61	56	310.72	36.29	1.169	4.66	0.648	0
	7/16/61	48	183.57	24.88	1.121	5.01	0.518	0.352
	7/23/61	28	118.90	16.80	1.111	5.18	0.600	0.785
	6/ 4/62	91	361.54	39.22	1.137	5.57	0.431	0.568
	6/ 9/62	68	130.38	19.26	1.083	5.29	0.283	0.223
	4/26/64	70	293.23	28.55	1.145	6.33	0.408	0.531
	4/26/64	117	233.87	24.49	1.109	6.74	0.209	0.441
	3/29/65	340	971.22	94.37	1.144	5.36	0.278	0.274
	5/10/65	302	167.63	24.88	1.083	5.16	0.082	0.006
	2/ 8/66	175	626.25	71.56	1.176	4.13	0.409	0.927
8/12/66	520	310.04	110.00	1.035	2.39	0.212	0.289	
Hastings, Nebraska	6/20/39	237	97.68	23.87	1.011	3.95	0.101	0.043
	7/10/51	102	333.91	34.30	1.117	6.44	0.336	0.270
	7/10/51	187	404.71	40.94	1.110	6.56	0.219	0.405
	5/15/60	108	316.14	34.22	1.119	6.06	0.317	0.663
	5/15/60	105	378.53	45.55	1.148	4.72	0.434	0.683
	5/15/60	275	1277.80	165.00	1.297	1.70	0.600	0.510
	8/11/61	82	262.85	27.85	1.142	5.89	0.340	0.161
	8/23/64	50	261.57	26.87	1.144	6.07	0.537	0.422
	9/ 9/63	115	220.45	27.15	1.109	5.67	0.236	0.287
	10/17/63	50	58.35	18.95	1.116	2.19	0.379	0.299
	6/21/64	33	103.30	8.87	1.072	9.97	0.269	0
	7/26/64	14	127.95	8.87	1.077	12.20	0.634	0
	5/21/65	100	1332.31	81.25	1.260	5.23	0.813	0
	5/22/65	127	73.63	13.40	1.055	4.76	0.106	0.075
	5/22/65	155	557.15	67.50	1.166	4.10	0.435	0.622
6/ 1/65	65	450.73	56.09	1.223	3.27	0.863	0.186	
6/12/65	65	154.34	18.79	1.111	5.94	0.289	0.137	
6/12/65	115	176.53	51.48	1.205	1.53	0.448	0.326	
Oxford, Mississippi	1/22/57	120	2284.04	255.00	1.593	0.34	2.125	1.000
	4/ 3/58	348	71163.35	615.00	1.895	0.37	1.767	0.189
	9/11/58	470	6669.58	375.00	1.583	0.56	0.798	0.120
	1/17/60	230	4144.07	325.00	1.549	0.53	1.413	0
	3/ 2/60	540	4879.47	380.00	1.517	0.60	0.704	0.148
	8/31/61	135	1402.70	135.62	1.366	1.72	1.005	0.522
	8/31/61	105	228.32	54.37	1.172	2.11	0.518	0.341
	6/11/62	75	1235.92	72.50	1.263	5.53	0.967	0.035
	9/ 4/62	195	7052.05	225.00	1.522	1.86	1.154	0.207
	7/20/63	140	396.45	34.10	1.144	6.99	0.244	0.695

Table 12. Continued.

Location	Date	$t_d$	a	b	c	$a/b^c$	$b/t_d$	$\gamma$
City, State	M/D/Y	min.		min.		in./hr.		
	8/29/63	165	1659.97	118.75	1.299	3.36	0.720	0.218
	3/ 4/64	286	2475.18	171.25	1.384	2.01	0.599	0.780
	4/13/64	217	114.69	30.20	1.066	3.03	0.139	0.135
	3/ 1/65	645	4998.24	505.00	1.511	0.411	0.783	0.543
	7/ 8/65	45	217.51	29.18	1.154	4.44	0.648	1.000
	5/24/66	345	311.88	111.87	1.141	1.43	0.324	0.265
	12/27/66	420	7639.31	430.00	1.562	0.59	1.024	0.382
Lafayette, Indiana	7/ 5/43	63	89.62	10.20	1.060	7.64	0.162	0.356
	6/19/46	25	67.76	13.63	1.096	3.87	0.545	0.445
	6/ 7/47	68	220.22	37.50	1.163	3.26	0.551	0.347
	6/24/50	51	133.91	8.48	1.061	13.87	0.166	0.062
Placerville, California	4/ 1/37	204	122.84	142.50	1.202	0.32	0.699	0.666
	12/ 4/42	200	80.11	58.59	1.065	1.05	0.293	0.856
	12/28/42	212	25.49	28.67	0.930	1.12	0.135	0.030
Cohocton, New York	6/ 7/38	25	52.49	2.81	1.030	18.08	0.112	0.109
	7/21/38	70	525.91	47.19	1.205	5.05	0.674	0.379
	9/12/38	62	274.99	52.73	1.213	2.24	0.850	0.413
	7/17/42	58	122.04	9.02	1.063	11.76	0.156	0.074
	7/18/42	80	356.27	38.52	1.149	5.36	0.482	0.564
	5/26/43	218	173.14	16.09	1.033	9.81	0.074	0.009
	5/26/43	180	105.24	25.00	1.003	4.18	0.139	0.705
	7/23/45	63	113.06	22.34	1.096	3.75	0.355	0.279

somehow show slight variations from each other, even under the same storm. The variations in the measured hyetographs at different gages in a small watershed under an identical storm are not surprisingly unusual, considering extremely high turbulent air stream always accompanying the rainstorm. Despite these variations, however, most of the  $\gamma$  values so computed, as listed in Table 13, are about equal for the six gages under the same storm, except for very few events.

An inspection of Table 13 reveals that the  $\gamma$  values for different storms vary almost randomly. The present analysis thus fails to establish any relationships among the storm parameters investigated.

For illustration, typical hyetographs with their best-fitted counterparts are plotted, as shown in Figs. 16 through 20. These hyetographs with the corresponding storm parameters so computed will be

input into a mathematical model to compute surface runoff from an urban highway watershed. The best-fitted hyetographs developed herein are thus essential to the verification of the mathematical model that was formulated and reported in another phase of the research project (Chen, 1975).

Inadequacy of the present optimization technique for best fitting the parametric hyetograph equations to the recorded hyetograph manifested itself in some unsatisfactory results, as shown in Figs. 14, 17, 18, and 20. As mentioned previously, a single-peak assumption, the limited number of data points in analysis, and deficiency in an univariate optimization method among many other drawbacks in the present method may be attributed to such failures. For lack of a better method presently available in the determination of  $\gamma$  value, the future investigation should be focused on the development of a new method to tackle with these deficiencies and drawbacks.



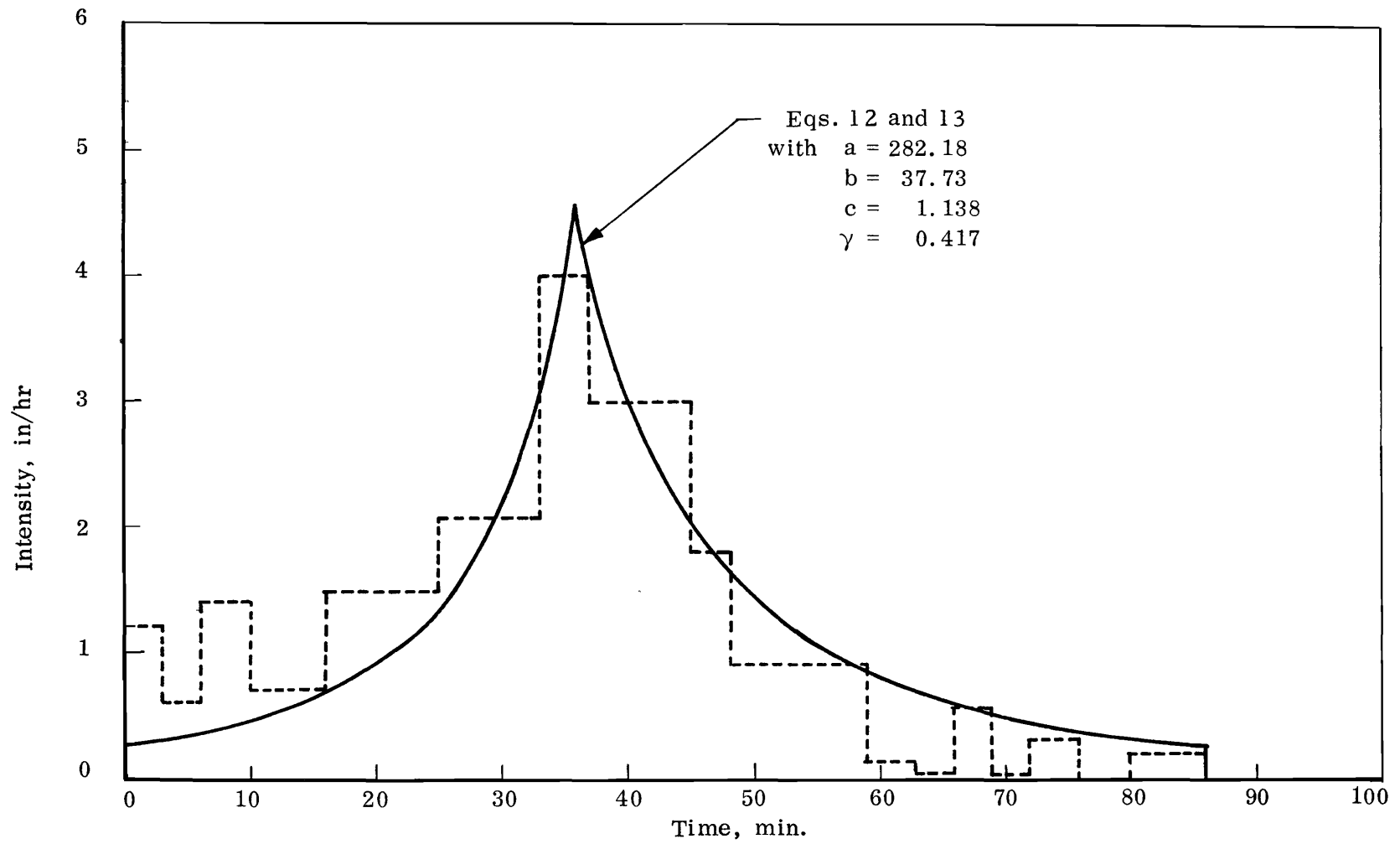


Figure 10. Typical hyetograph occurred on June 10, 1941, at Riesel, Texas, and its best-fitted counterpart.

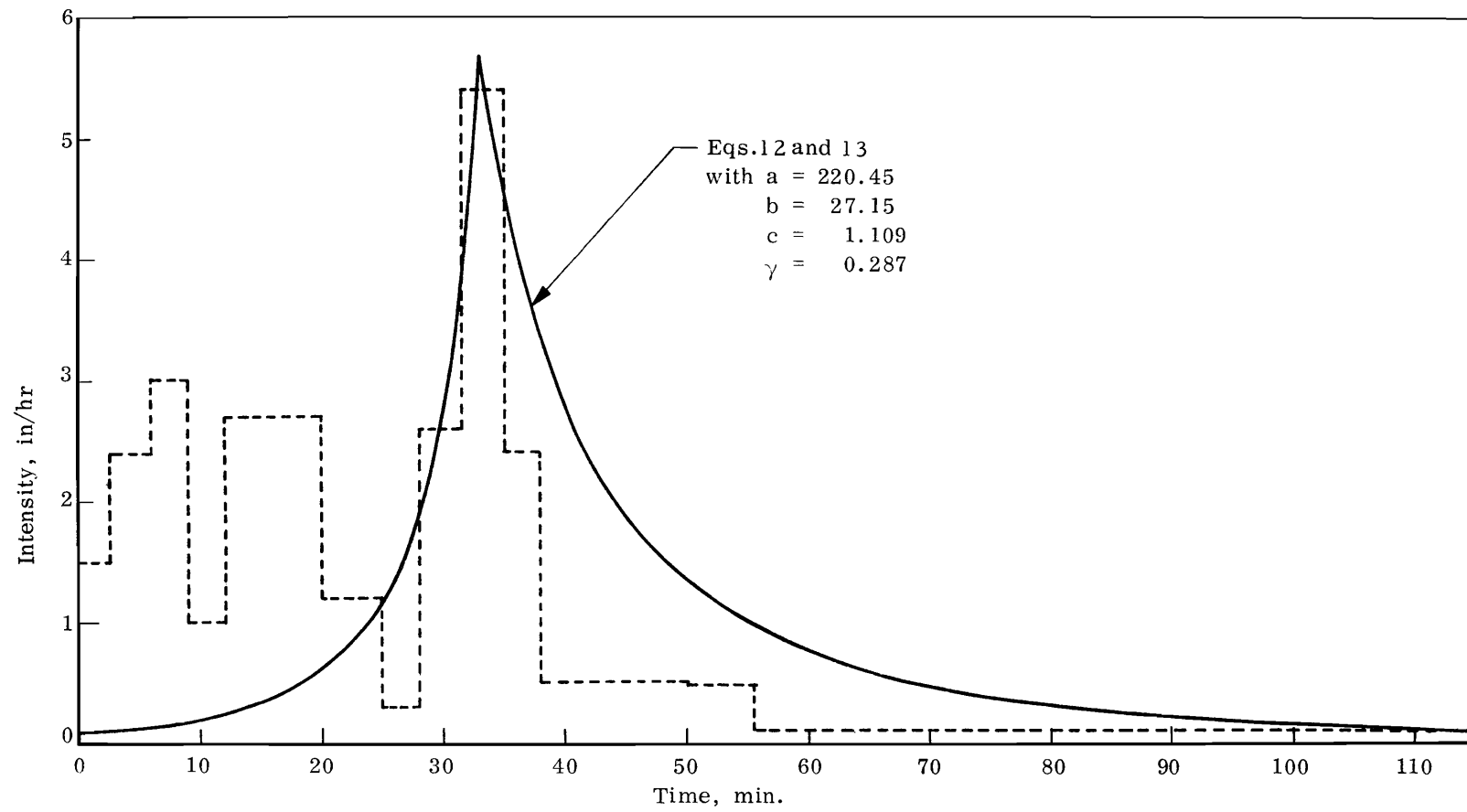


Figure 11. Typical hyetograph occurred on September 9, 1963, at Hastings, Nebraska, and its best-fitted counterpart.

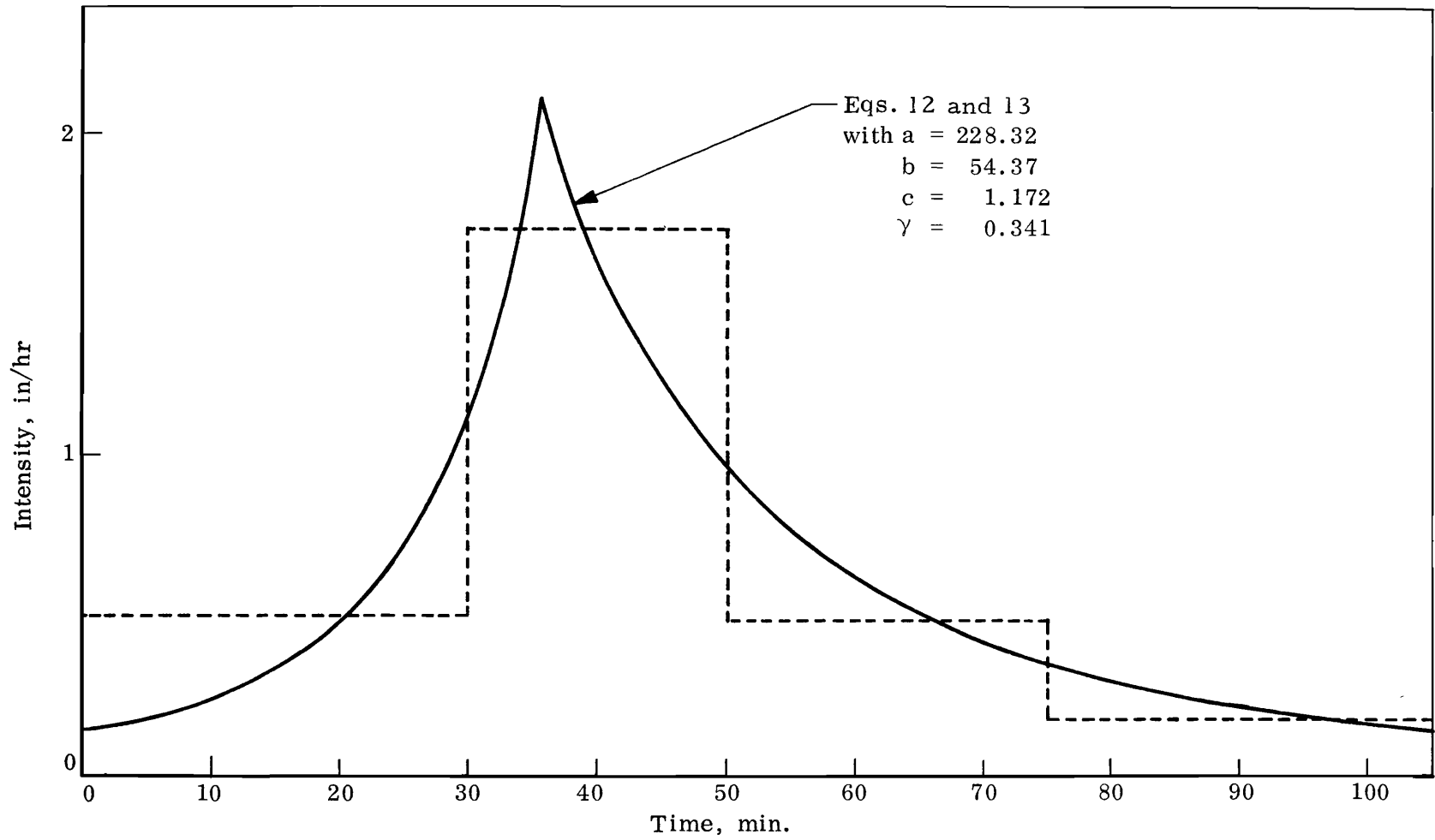


Figure 12. Typical hyetograph occurred on August 31, 1961, at Oxford, Mississippi, and its best-fitted counterpart.

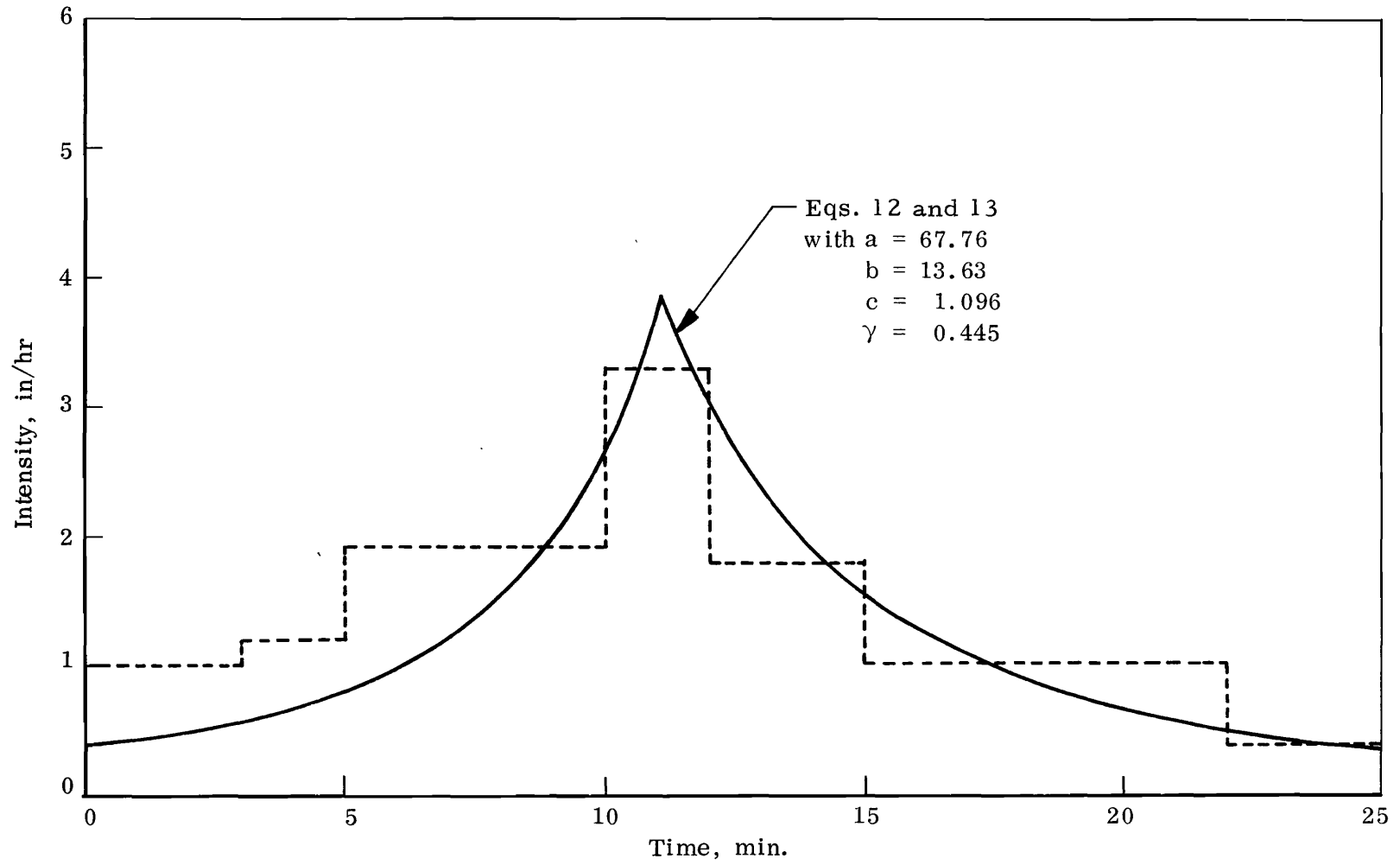


Figure 13. Typical hyetograph occurred on June 19, 1946, at Lafayette, Indiana, and its best-fitted counterpart.

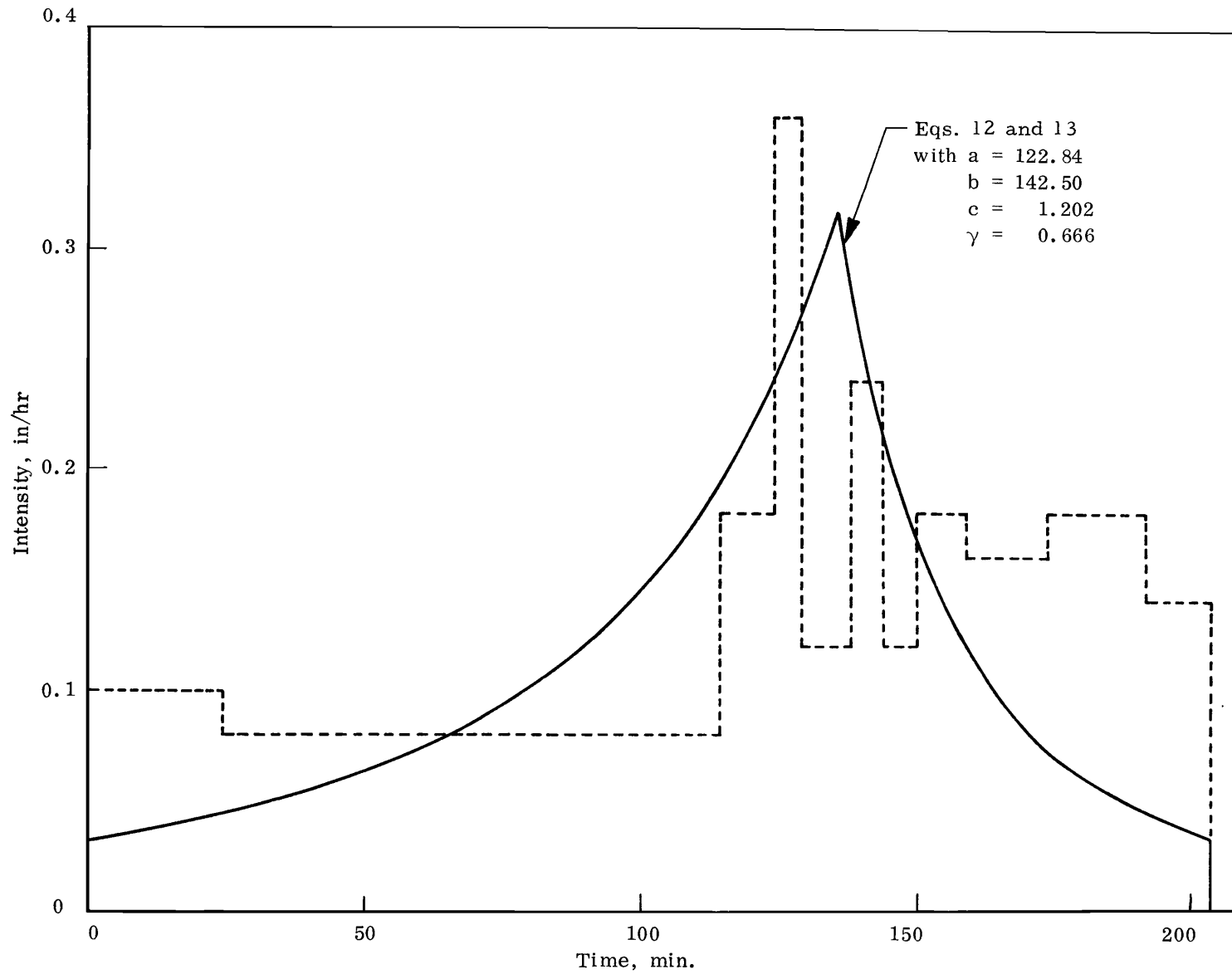


Figure 14. Typical hyetograph occurred on April 1, 1937, at Placerville, California, and its best-fitted counterpart.

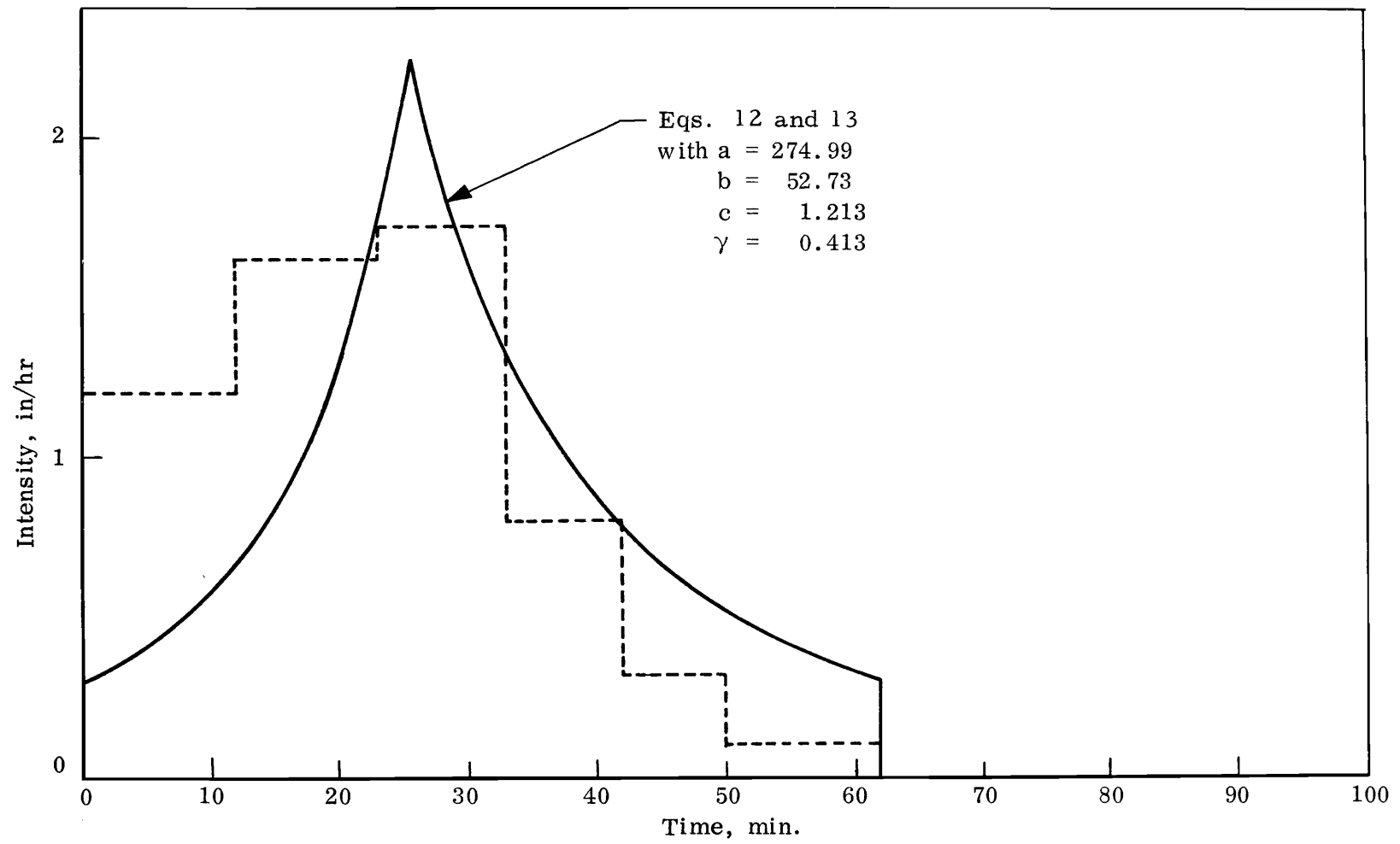


Figure 15. Typical hyetograph occurred on September 12, 1938, at Cohocton, New York, and its best-fitted counterpart.

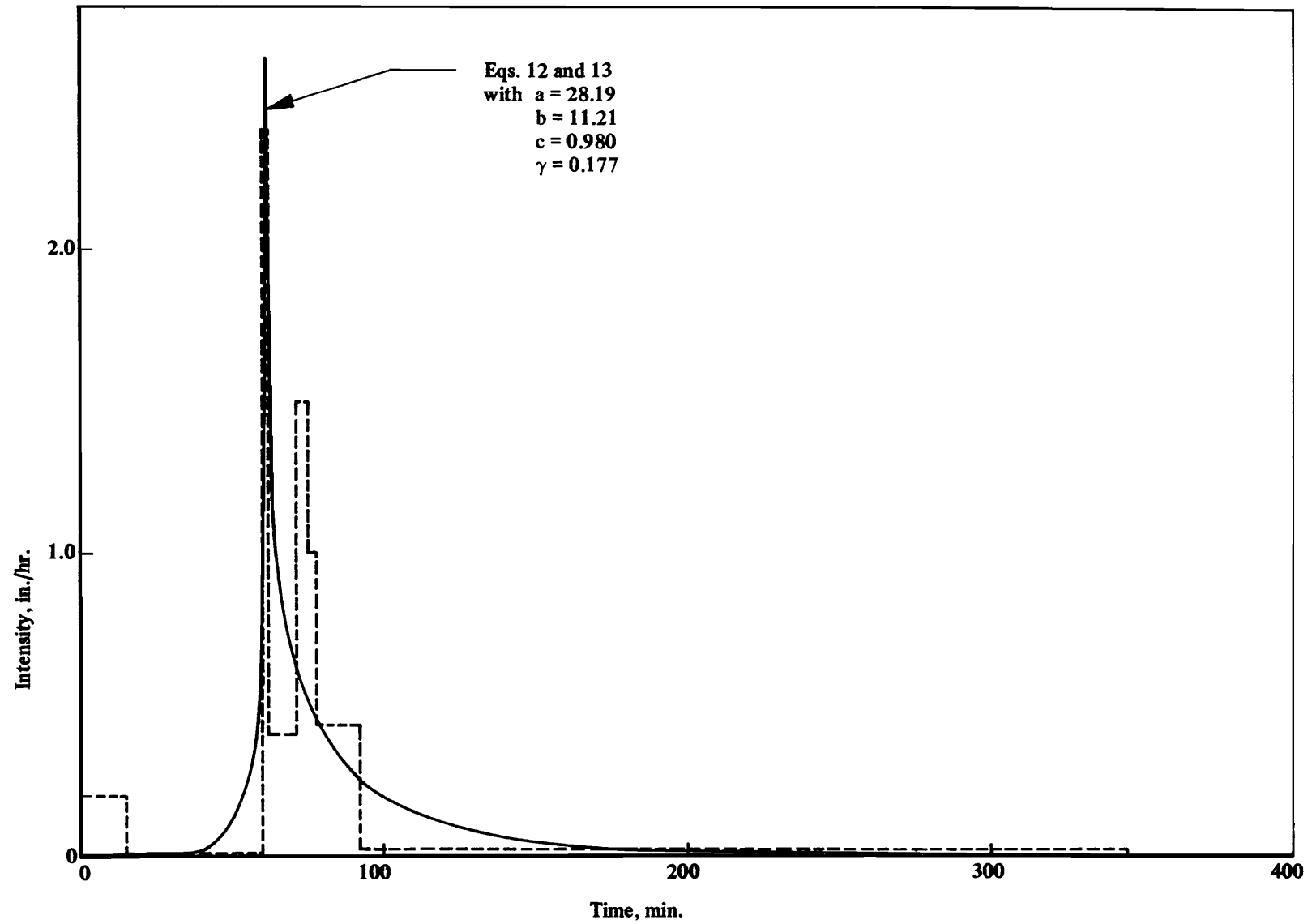


Figure 16. Typical hyetograph occurred on September 5, 1972, at gage L-2 in Layton, Utah, and its best-fitted counterpart.

**Table 13. A list of major rainfall events with computed values of storm parameters for two urban highway watersheds in the Salt Lake City area (Fletcher and Chen, 1975).**

Location City, State	Date M/D/Y	Rain Gage No.	$t_d$ min.	a	b min.	c	$a/b^c$ in./hr.	$b/t_d$	$\gamma$
Layton, Utah	9/ 5/72	L-1	210	51.87	24.80	1.051	1.78	0.118	0.358
	"	L-2	345	28.19	11.21	0.980	2.64	0.032	0.177
	"	L-3	216	75.90	36.95	1.126	1.30	0.171	0.317
	"	L-4	210	56.07	31.56	1.081	1.34	0.150	0.324
	"	L-5	424	33.71	22.89	1.013	1.41	0.054	0.173
	"	L-6	207	67.72	35.23	1.111	1.29	0.170	0.312
	4/17/73	L-1	398	22.87	26.25	0.900	1.21	0.066	0.635
	"	L-2	413	87.76	90.00	1.090	0.65	0.218	0.904
	"	L-3	180	297.93	106.25	1.291	0.72	0.590	0.155
	"	L-4	555	5.58	0.82	0.673	6.37	0.001	0.009
	"	L-5	480	229.20	152.50	1.175	0.63	0.318	0.505
	"	L-6	635	43.83	47.19	0.951	1.12	0.074	0.605
	5/25/73	L-1	10	18.53	6.13	1.067	2.68	0.613	0
	"	L-2	30	23.37	8.87	1.073	2.25	0.296	0.430
	"	L-3	5	--	--	--	--	--	--
	"	L-4	--	--	--	--	--	--	--
	"	L-5	10	12.00	0.00	1.000	0.00	0.000	0.500
	"	L-6	90	18.53	6.13	1.067	2.68	0.613	0
	5/25-26/73	L-1	75	163.84	122.50	1.356	0.24	1.633	0
	"	L-2	65	57.30	65.31	1.217	0.355	1.005	0.894
	"	L-3	75	29.12	47.19	1.145	0.353	0.629	0.481
	"	L-4	--	--	--	--	--	--	--
	"	L-5	60	54.62	40.55	1.156	0.755	0.676	0.322
	"	L-6	75	163.84	122.50	1.356	0.242	1.633	0
7/19/73	L-1	389	16.09	12.54	0.845	1.90	0.032	0.282	
"	L-2	404	42.27	43.44	0.983	1.04	0.108	0.311	
"	L-3	425	44.61	46.41	0.985	1.02	0.109	0.311	
"	L-4	364	28.72	21.21	0.934	1.66	0.058	0.318	
"	L-5	394	39.09	34.69	0.973	1.24	0.088	0.296	
"	L-6	367	18.28	16.80	0.854	1.64	0.046	0.263	
Parleys, Utah	9/ 5/72	P-1	254	15.62	17.66	0.790	1.61	0.070	0.348
	"	P-2	257	56.91	18.09	1.023	2.94	0.070	0.999
	"	P-3	261	59.98	23.20	1.055	2.17	0.089	0.307
	"	P-4	128	57.42	21.37	1.087	2.06	0.167	0.641
	"	P-5	291	33.81	17.27	0.979	2.08	0.059	0.828
	"	P-6	412	56.26	42.97	0.984	1.39	0.104	0.410
	9/19/72	P-1	140	194.86	116.25	1.299	0.41	0.830	0.545
	"	P-2	96	57.31	51.87	1.153	0.60	0.540	0.929
	"	P-3	190	102.72	114.37	1.230	0.30	0.602	0.429
	"	P-4	97	42.15	38.67	1.090	0.784	0.399	0.896
	"	P-5	--	--	--	--	--	--	--
	"	P-6	--	--	--	--	--	--	--
	10/4-5/72	P-1	253	11.37	4.34	0.890	3.08	0.017	0.040
	"	P-2	253	14.91	2.70	0.925	5.96	0.011	0.044
	"	P-3	262	18.31	5.00	0.956	3.93	0.019	0.047
	"	P-4	210	26.92	6.45	1.011	4.09	0.031	0.024
	"	P-5	--	--	--	--	--	--	--
	"	P-6	286	16.43	2.15	0.938	8.01	0.008	0.052



Table 13. Continued.

Location City, State	Date M/D/Y	Rain Gage No.	$t_d$ min.	a	b min.	c	$a/b^c$ in./hr.	$b/t_d$	$\gamma$
	7/19/73	P-1	107	119.69	43.59	1.131	1.68	0.407	0.243
	"	P-2	93	67.03	27.11	1.054	2.07	0.291	0
	"	P-3	145	62.39	19.10	1.027	3.02	0.132	0.216
	"	P-4	90	88.15	38.28	1.105	1.57	0.425	0.209
	"	P-5	89	57.12	23.36	1.014	2.34	0.262	0.157
	"	P-6	115	93.20	37.58	1.101	1.72	0.327	0.281
	8/16/73	P-1	--	--	--	--	--	--	--
	"	P-2	--	--	--	--	--	--	--
	"	P-3	--	--	--	--	--	--	--
	"	P-4	99	29.02	11.05	1.003	2.61	0.112	0.378
	"	P-5	73	27.57	3.01	1.019	8.98	0.041	0.096
	"	P-6	20	31.17	3.24	1.026	9.32	0.162	0.735
	9/ 1/73	P-1	776	9.98	6.29	0.769	2.43	0.008	0.025
	"	P-2	--	--	--	--	--	--	--
	"	P-3	468	30.21	27.50	0.962	1.25	0.059	0.126
	"	P-4	479	48.70	44.37	1.032	0.97	0.093	0.046
	"	P-5	421	36.09	28.79	0.966	1.41	0.068	0.029
	"	P-6	333	80.14	57.97	1.125	0.83	0.174	0.606
	10/ 8/73	P-1	--	--	--	--	--	--	--
	"	P-2	588	105.51	155.00	1.202	0.25	0.264	0.564
	"	P-3	637	107.10	167.50	1.182	0.25	0.263	0.524
	"	P-4	567	28.47	63.12	1.034	0.39	0.111	0.626
	"	P-5	--	--	--	--	--	--	--
	"	P-6	397	806.84	260.00	1.457	0.24	0.655	0.903

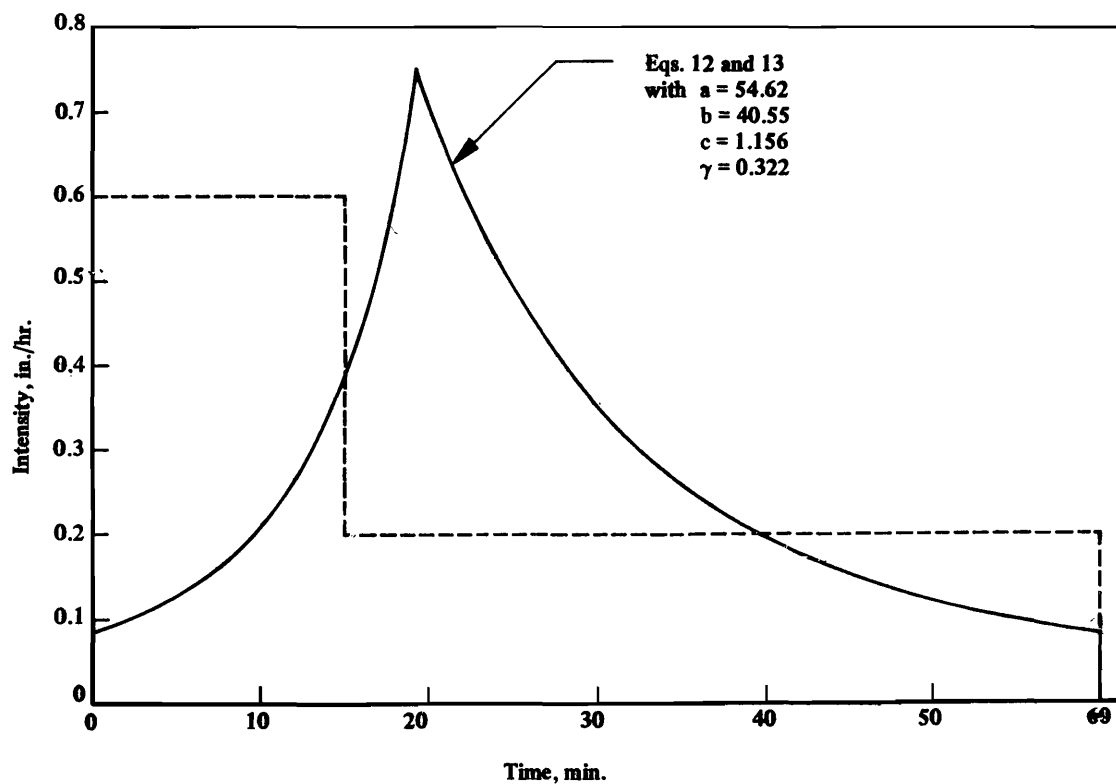


Figure 17. Typical hyetograph occurred on May 25-26, 1973, at gage L-5 in Layton, Utah, and its best-fitted counterpart.

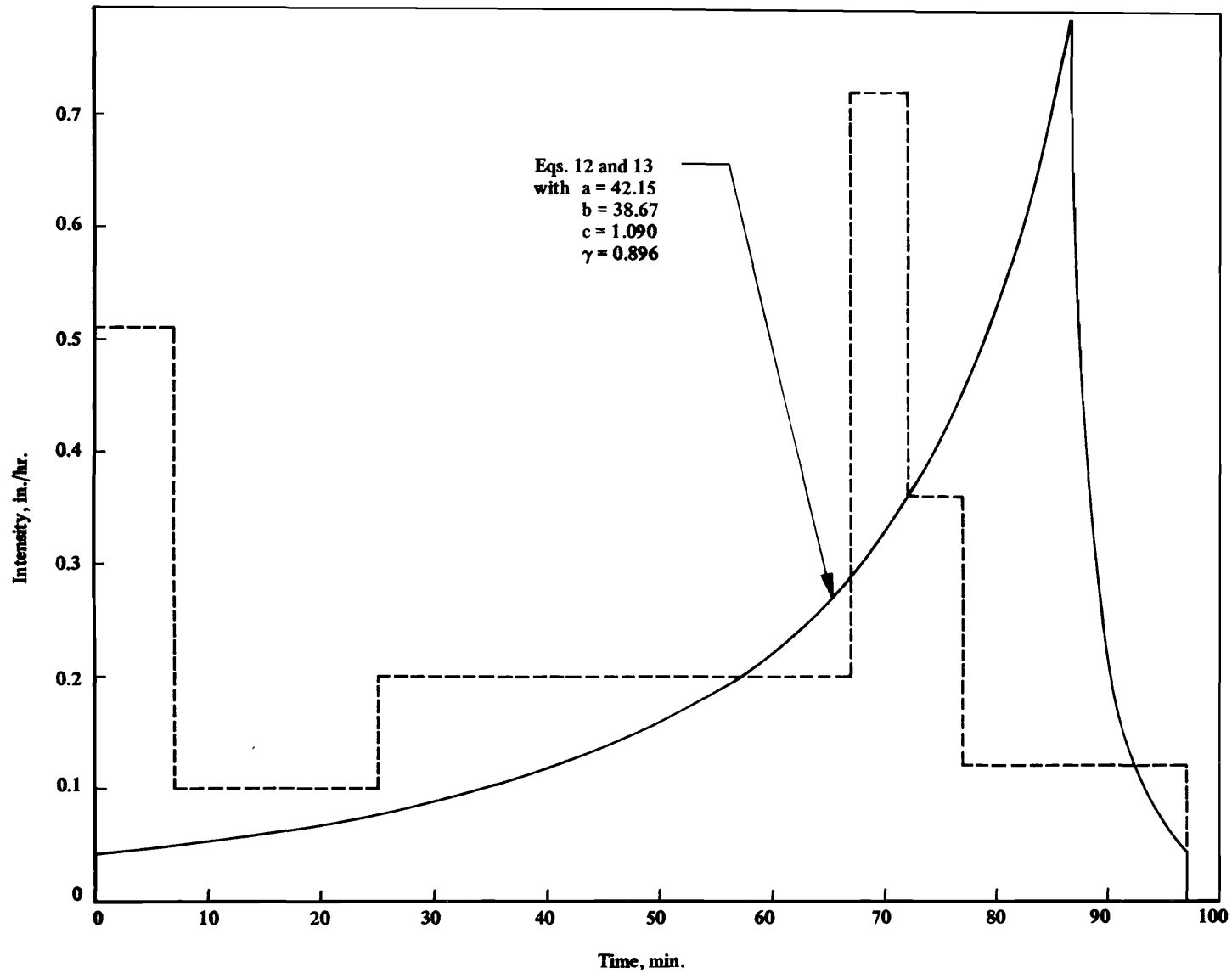


Figure 18. Typical hyetograph occurred on September 19, 1972, at gage P-4 in Parleys, Utah, and its best-fitted counterpart.

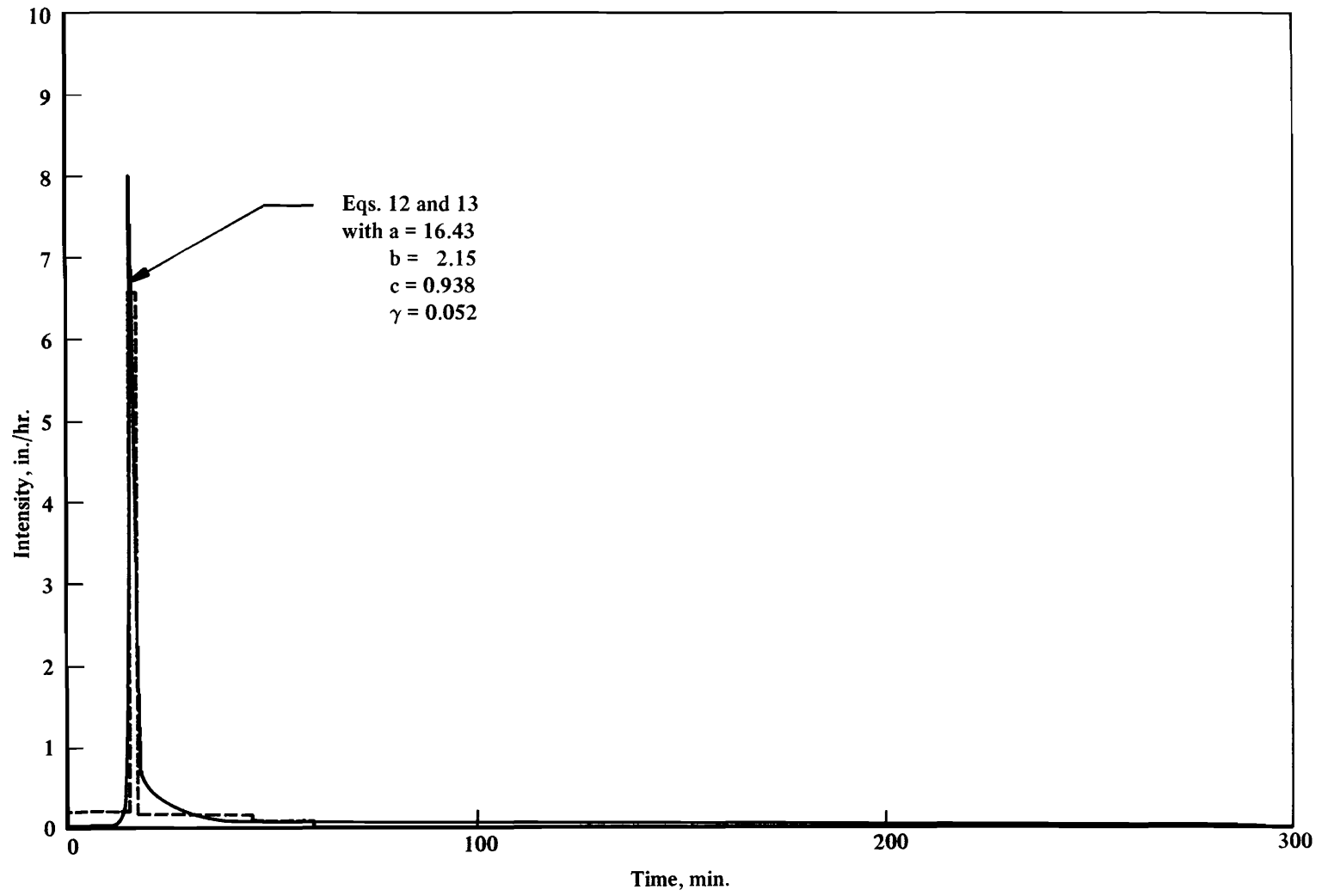


Figure 19. Typical hyetograph occurred on October 4-5, 1972, at gage P-6 in Parleys, Utah, and its best-fitted counterpart.

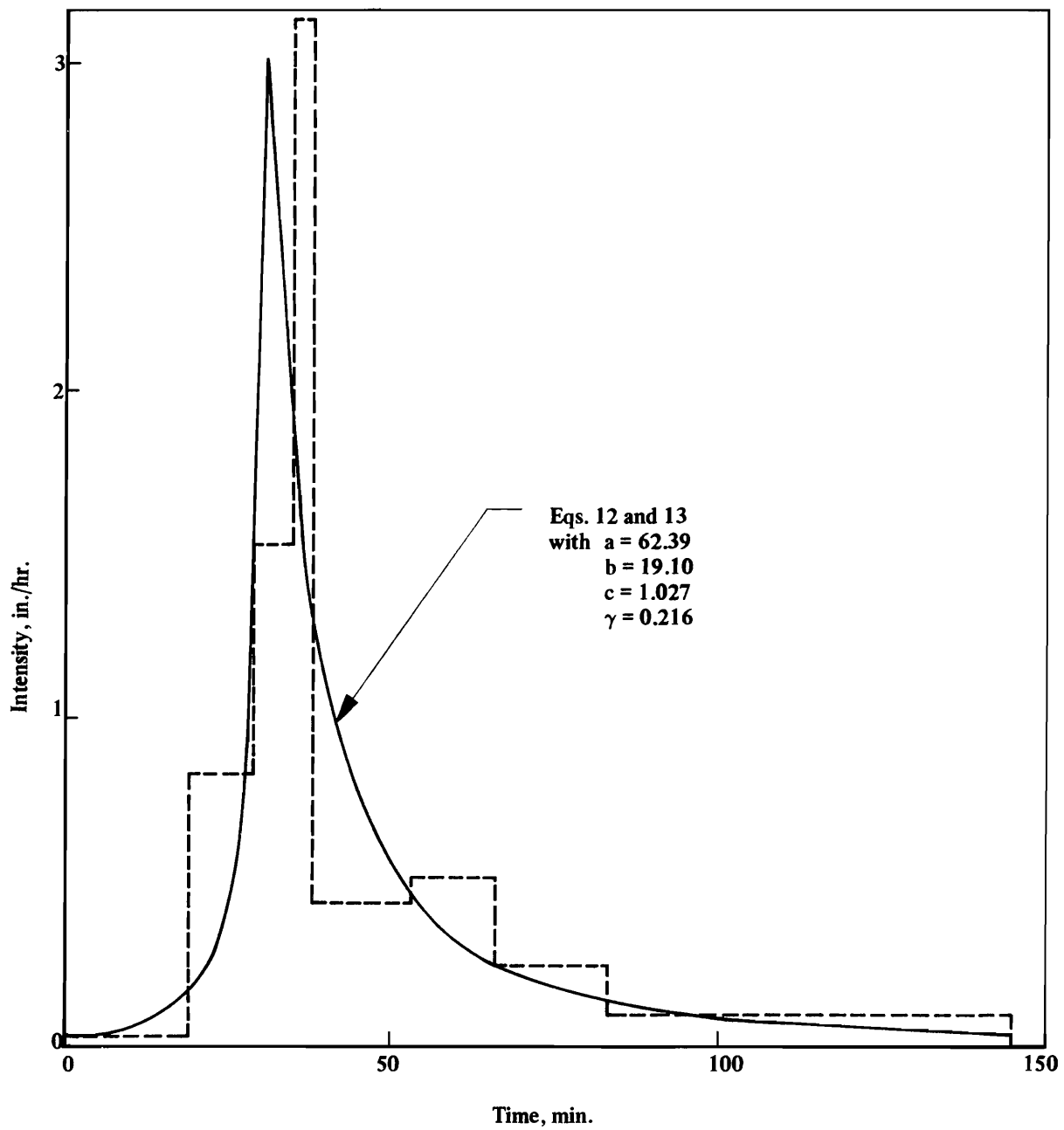


Figure 20. Typical hyetograph occurred on July 19, 1973, at gage P-3 in Parleys, Utah, and its best-fitted counterpart.



## SUMMARY AND CONCLUSIONS

The formulation of a synthetic hyetograph of desired frequency and duration for an urban highway watershed is essential to the successful design of a storm sewer system which drains storm water collected at all drainage inlets. The derived synthetic hyetograph equations that also contain storm frequency and duration can readily be built into the surface runoff model for computing the inlet hydrographs of corresponding frequency and duration. For general use in engineering practice, a simple graphical method was developed to evaluate the storm parameters that characterize the rainfall intensity-duration-frequency relationships at any location in the United States.

The principal conclusions drawn from this study may be summarized as follows:

1. The rainfall intensity-duration-frequency relationships and a unified time-coordinate system have been utilized to develop the generalized synthetic hyetograph equations for all types of storms. Three parameters,  $a$ ,  $b$ , and  $c$ , which describe the intensity-duration-frequency curves also control the time distribution of rainfall in heavy storms. In general, the hyetograph equations so formulated were classified according to whether they are positive or negative  $b$ . A brief analysis of rainfall data obtained from the Weather Bureau Technical Paper Nos. 25 and 40 has indicated that the equation for positive  $b$  mainly applies to a large section of the country—perhaps to the portion east of the Rocky Mountains—while that for negative  $b$  generally applies to the west of the Rocky Mountains.

2. The storm parameters,  $a$ ,  $b$ , and  $c$ , can be evaluated by using the method of least squares and an optimization technique similar to the method of steepest descent for optimizing an unconstrained problem. The rainfall intensity-duration-frequency data obtained from the 49 isopluvial maps in the Weather Bureau Technical Paper No. 40 may be used for this computation.

3. A simple graphical method was developed to evaluate the  $a$ ,  $b$ , and  $c$  values without using all of the 49 isopluvial maps in the Weather Bureau Technical Paper No. 40. The method has been described in

detail in the section under STANDARD INTENSITY-DURATION RELATIONSHIPS. The  $a$ ,  $b$ , and  $c$  values so determined were found to be compatible with those computed directly from the 49 isopluvial maps.

4. Analysis of the Technical Paper No. 40 reveals that the standard storm parameters,  $a_1$ ,  $b_1$  ( $= b$ ), and  $c_1$  ( $= c$ ), vary only with the ratio of 1-hour to corresponding 24-hour rainfall depth which is unique for each location in the United States and independent of frequency. On the other hand, the storm parameter,  $a$ , which can be expressed in terms of  $a_1$ , depends upon return period, as shown in Eq. 45. Therefore, given the ratio of 1-hour to corresponding 24-hour rainfall depth and frequency, the values of the storm parameters,  $a$ ,  $b$ , and  $c$  are already fixed, leaving only pattern skewness ( $\gamma$  value) yet to be determined from other means.

5. Normalization of the derived hyetograph equations reveals that three dimensionless parameters,  $b/t_d$ ,  $c$ , and  $\gamma$ , control the storm pattern. The parameters,  $b$  and  $c$ , are more or less “standardized” for each location in the United States, while the other parameters,  $t_d$  and  $\gamma$ , remain to be evaluated from actual rainfall records. For a storm of uniform intensity,  $t_d$  may take the time of concentration,  $t_c$ , which in actual storms is, of course, trivial.

6. The hyetograph equations so formulated were used to best fit actual hyetographs. The best-fitted  $a$ ,  $b$ , and  $c$  values for an actual hyetograph were determined by first arranging the hyetograph in the order of intensity in a way similar to the formulation of Eq. 6 and then computing the  $a$ ,  $b$ , and  $c$  values by means of the least squares to minimize the objective function as shown in Eq. 22. The  $\gamma$  value was finally determined by minimizing the expression shown in Eq. 61 for positive  $b$  or Eq. 62 for negative  $b$ . An analysis of major storms for six selected ARS experimental watersheds and two Salt Lake City urban highway watersheds revealed that the  $\gamma$  value so determined varied almost randomly for each station studied. The establishment of any relationships between  $\gamma$  and the other storm parameters did not look very promising. The statistical mean  $\gamma$  value for each station could be calculated, but it would be meaningless unless more actual hyetographs for each station are analyzed.



## RECOMMENDATIONS

The results obtained from the present study certainly indicate the need for continuing efforts in pursuit of the formulation of a better expression for design storm patterns. The areas recommended for further investigations are:

1. The present analysis has been based solely on rainfall data obtained from the U.S. Weather Bureau Technical Paper No. 40 that is too old (14 years) to be always reliable. The most recent publication, NOAA Atlas 2, although it provides isopluvial maps for 6- and 24-hour durations for 2-, 5-, 10-, 25-, and 100-year return periods for the 11 western states, cannot be used in the present study because of the difficulty in maintaining the internal consistency between the two sources of data. Updated rainfall data for the whole United States is urgently needed.

2. Maps with iso- $a_1$ , iso- $b_1$ , and iso- $c_1$  lines need to be constructed for the United States. The determination of the  $a_1$ ,  $b_1$ , and  $c_1$  values by means of the proposed graphical method warrants the feasibility of construction of such maps.

3. The storm parameter,  $t_d$ , should be the statistically-determined time duration of local storms, which is independent of the runoff produced by these storms. For the first-order approximation, however, it

may be assumed as the time of concentration,  $t_c$ , at which the maximum runoff occurs under a storm of uniform intensity for a given watershed. Whether or not this assumption is valid needs to be investigated by analyzing all recorded storms.

4. The determination of the statistical mean  $\gamma$  value for any point in the United States appears extremely difficult in view of the intrinsic nature of randomness in highly turbulent air stream that always accompanies the rainstorm. Thousands of actual hyetographs at each station may be required for such determination in order for the statistical mean value to be meaningful.

One alternative for circumventing this difficulty is to determine the  $\gamma$  value on the basis of the design criterion of the maximum runoff. Only a limited number of design storm patterns were tested based on this criterion in another phase of this research project. For lack of a better method presently being available, it is suggested that more design storm patterns with various  $a$ ,  $b$ , and  $c$  values representing various locations in the United States be examined on the basis of the maximum runoff criterion. The  $\gamma$  value so determined would evidently vary with the  $a$ ,  $b$ , and  $c$  values and local  $t_d$  so that the development of an iso- $\gamma$  map without specifying  $t_d$  for an urban highway watershed does not seem to be feasible.





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## APPENDICES



## Appendix A

### Rainfall Depth Tables of 23 Major Cities in the United States and 11 Capitals of the Western States

The 23 major cities and 11 western state capitals selected for this study are:

<u>Table No.</u>	<u>City, State Name</u>	<u>Location</u>
A-1	New York, New York	40.4 <sup>o</sup> N., 74.0 <sup>o</sup> W.
A-2	Los Angeles, California	34.1 <sup>o</sup> N., 118.3 <sup>o</sup> W.
A-3	Chicago, Illinois	41.8 <sup>o</sup> N., 87.7 <sup>o</sup> W.
A-4	Detroit, Michigan	42.4 <sup>o</sup> N., 83.1 <sup>o</sup> W.
A-5	Philadelphia, Pennsylvania	35.9 <sup>o</sup> N., 75.2 <sup>o</sup> W.
A-6	San Francisco, California	37.8 <sup>o</sup> N., 122.5 <sup>o</sup> W.
A-7	Boston, Massachusetts	42.3 <sup>o</sup> N., 71.1 <sup>o</sup> W.
A-8	Washington, D.C.	38.5 <sup>o</sup> N., 77.0 <sup>o</sup> W.
A-9	Cleveland, Ohio	41.5 <sup>o</sup> N., 81.7 <sup>o</sup> W.
A-10	St. Louis, Missouri	40.0 <sup>o</sup> N., 89.6 <sup>o</sup> W.
A-11	Pittsburg, Pennsylvania	40.5 <sup>o</sup> N., 80.0 <sup>o</sup> W.
A-12	Baltimore, Maryland	39.2 <sup>o</sup> N., 76.4 <sup>o</sup> W.
A-13	Minneapolis, Minnesota	45.0 <sup>o</sup> N., 93.2 <sup>o</sup> W.
A-14	Miami, Florida	25.7 <sup>o</sup> N., 80.2 <sup>o</sup> W.
A-15	Houston, Texas	29.5 <sup>o</sup> N., 95.2 <sup>o</sup> W.
A-16	Buffalo, New York	42.5 <sup>o</sup> N., 78.5 <sup>o</sup> W.
A-17	Cincinnati, Ohio	39.1 <sup>o</sup> N., 34.3 <sup>o</sup> W.
A-18	Milwaukee, Wisconsin	43.0 <sup>o</sup> N., 87.5 <sup>o</sup> W.
A-19	San Diego, California	32.4 <sup>o</sup> N., 117.1 <sup>o</sup> W.
A-20	Dallas, Texas	32.4 <sup>o</sup> N., 96.5 <sup>o</sup> W.
A-21	Atlanta, Georgia	33.5 <sup>o</sup> N., 84.2 <sup>o</sup> W.
A-22	Kansas City, Missouri	39.0 <sup>o</sup> N., 94.4 <sup>o</sup> W.
A-23	Seattle, Washington	47.6 <sup>o</sup> N., 122.3 <sup>o</sup> W.
A-24	Helena, Montana	46.7 <sup>o</sup> N., 112.0 <sup>o</sup> W.
A-25	Cheyenne, Wyoming	41.2 <sup>o</sup> N., 104.8 <sup>o</sup> W.
A-26	Denver, Colorado	39.8 <sup>o</sup> N., 105.0 <sup>o</sup> W.
A-27	Santa Fe, New Mexico	35.5 <sup>o</sup> N., 105.9 <sup>o</sup> W.
A-28	Boise, Idaho	43.6 <sup>o</sup> N., 116.3 <sup>o</sup> W.
A-29	Salt Lake City, Utah	40.8 <sup>o</sup> N., 111.9 <sup>o</sup> W.
A-30	Carson City, Nevada	39.1 <sup>o</sup> N., 119.8 <sup>o</sup> W.
A-31	Phoenix, Arizona	33.4 <sup>o</sup> N., 112.1 <sup>o</sup> W.
A-32	Olympia, Washington	47.1 <sup>o</sup> N., 122.9 <sup>o</sup> W.
A-33	Salem, Oregon	44.9 <sup>o</sup> N., 123.0 <sup>o</sup> W.
A-34	Sacramento, California	38.5 <sup>o</sup> N., 121.6 <sup>o</sup> W.

Data are obtained or calculated from U.S. Weather Bureau Technical Paper No. 40 (1961) except for those in parenthesis which are obtained or calculated from NOAA Atlas 2 (Miller, Frederick, and Tracey, 1973).

**Table A-1. Rainfall depth in inches for various duration and frequency at New York.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.34	0.42	0.54	0.63	0.71	0.81	0.89
10 min.	0.52	0.64	0.83	0.97	1.10	1.25	1.37
15 min.	0.66	0.81	1.05	1.22	1.39	1.58	1.73
30 min.	0.91	1.12	1.46	1.70	1.93	2.19	2.40
60 min.	1.23	1.43	1.86	2.15	2.48	2.78	3.11
2 hrs.	1.48	1.77	2.32	2.70	3.15	3.45	3.80
3 hrs.	1.62	1.98	2.55	2.88	3.40	3.82	4.28
6 hrs.	1.97	2.40	3.12	3.65	4.30	4.60	5.38
12 hrs.	2.40	2.88	3.70	4.30	5.08	5.50	6.40
24 hrs.	2.72	3.38	4.40	5.20	5.90	6.52	7.40

**Table A-2. Rainfall depth in inches for various duration and frequency at Los Angeles.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.19	0.22	0.29	0.35	0.43	0.50	0.54
10 min.	0.29	0.34	0.45	0.54	0.66	0.77	0.84
15 min.	0.36	0.42	0.57	0.68	0.83	0.97	1.06
30 min.	0.50	0.63	0.79	0.95	1.15	1.35	1.47
60 min.	0.65	0.78	0.97	1.19	1.45	1.70	1.89
2 hrs.	0.78	0.98	1.40	1.78	2.00	2.35	2.60
3 hrs.	0.95	1.30	1.90	2.20	2.60	2.90	3.30
(6 hrs.)	--	(1.68)	(2.19)	(2.60)	(3.00)	(3.45)	(3.85)
6 hrs.	1.45	1.95	2.85	3.40	4.10	4.50	5.40
12 hrs.	1.80	2.60	3.60	4.70	5.50	6.10	7.00
(24 hrs.)	--	(2.93)	(4.26)	(4.90)	(6.00)	(6.90)	(7.86)
24 hrs.	2.10	3.30	4.50	5.80	6.80	7.70	8.60

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-3. Rainfall depth in inches for various duration and frequency at Chicago**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.37	0.43	0.53	0.60	0.69	0.76	0.84
10 min.	0.58	0.67	0.81	0.93	1.06	1.17	1.29
15 min.	0.73	0.84	1.02	1.17	1.34	1.48	1.63
30 min.	1.01	1.17	1.42	1.63	1.86	2.06	2.26
60 min.	1.22	1.47	1.82	2.03	2.35	2.57	2.85
2 hrs.	1.50	1.72	2.10	2.45	2.78	3.06	3.40
3 hrs.	1.60	1.85	2.33	2.67	3.02	3.38	3.70
6 hrs.	1.87	2.18	2.77	3.10	3.57	4.00	4.35
12 hrs.	2.20	2.59	3.22	3.65	4.18	4.60	5.23
24 hrs.	2.48	2.90	3.65	4.20	4.83	5.47	5.95

**Table A-4. Rainfall depth in inches for various duration and frequency at Detroit**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.30	0.37	0.45	0.53	0.61	0.68	0.74
10 min.	0.46	0.58	0.71	0.82	0.93	1.04	1.15
15 min.	0.58	0.73	0.89	1.03	1.18	1.32	1.45
30 min.	0.81	1.01	1.24	1.43	1.64	1.83	2.01
60 min.	1.05	1.28	1.60	1.81	2.10	2.35	2.60
2 hrs.	1.25	1.50	1.82	2.18	2.46	2.78	3.06
3 hrs.	1.38	1.68	2.02	2.30	2.75	2.97	3.28
6 hrs.	1.63	1.85	2.32	2.78	3.12	3.48	3.82
12 hrs.	1.88	2.25	2.81	3.20	3.65	3.92	4.55
24 hrs.	2.23	2.58	3.22	3.66	4.10	4.65	4.95

**Table A-5. Rainfall depth in inches for various duration and frequency at Philadelphia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.44	0.58	0.71	0.81	0.97	1.10	1.24
10 min.	0.67	0.90	1.10	1.25	1.49	1.69	1.91
15 min.	0.85	1.13	1.39	1.58	1.88	2.14	2.41
30 min.	1.18	1.45	1.93	2.20	2.61	2.97	3.35
60 min.	1.55	2.00	2.42	2.80	3.25	3.66	4.09
2 hrs.	1.94	2.34	3.00	3.49	4.00	4.55	5.22
3 hrs.	2.16	2.55	3.45	4.00	4.70	5.25	6.00
6 hrs.	2.55	3.35	4.30	5.05	6.00	6.75	7.62
12 hrs.	3.38	4.05	5.25	6.25	7.00	8.00	8.98
24 hrs.	4.00	5.00	6.25	7.25	8.25	9.50	10.70

**Table A-6. Rainfall depth in inches for various duration and frequency at San Francisco.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.19	0.22	0.28	0.33	0.36	0.43	0.46
10 min.	0.29	0.34	0.43	0.51	0.56	0.66	0.71
15 min.	0.36	0.43	0.54	0.65	0.71	0.83	0.90
30 min.	0.50	0.59	0.75	0.90	0.98	1.15	1.25
60 min.	0.65	0.70	0.90	1.10	1.25	1.40	1.50
2 hrs.	0.85	1.00	1.30	1.50	1.75	1.85	2.20
3 hrs.	1.05	1.25	1.65	1.80	2.20	2.30	2.70
(6 hrs.)	--	(1.32)	(1.52)	(1.75)	(1.95)	(2.15)	(2.38)
6 hrs.	1.80	1.90	2.50	2.75	3.25	3.50	3.90
12 hrs.	1.90	2.25	3.10	3.50	3.75	4.50	5.00
(24 hrs.)	--	(2.35)	(2.87)	(3.26)	(3.62)	(4.10)	(4.49)
24 hrs.	2.40	3.10	4.00	4.75	5.25	5.75	6.00

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).



**Table A-7. Rainfall depth in inches for various duration and frequency at Boston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.27	0.32	0.44	0.51	0.58	0.65	0.73
10 min.	0.42	0.50	0.67	0.78	0.90	1.01	1.13
15 min.	0.53	0.63	0.85	0.99	1.14	1.27	1.43
30 min.	0.73	0.87	1.18	1.37	1.58	1.77	1.98
60 min.	0.92	1.09	1.46	1.73	1.97	2.27	2.45
2 hrs.	1.18	1.46	1.88	2.27	2.60	2.90	3.26
3 hrs.	1.34	1.72	2.25	2.50	2.87	3.26	3.60
6 hrs.	1.70	2.12	2.76	3.23	3.59	4.00	4.55
12 hrs.	2.12	2.55	3.30	3.80	4.50	4.85	5.50
24 hrs.	2.55	2.93	3.85	4.50	5.10	5.75	6.50

**Table A-8. Rainfall depth in inches for various duration and frequency at Washington, D.C.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.41	0.53	0.65	0.76	0.90	1.02	1.18
10 min.	0.64	0.81	1.00	1.17	1.39	1.57	1.82
15 min.	0.81	1.02	1.27	1.48	1.75	1.99	2.30
30 min.	1.12	1.42	1.76	2.05	2.43	2.76	3.20
60 min.	1.43	1.80	2.23	2.64	3.08	3.47	4.20
2 hrs.	1.66	2.04	2.60	3.10	3.60	4.10	4.60
3 hrs.	1.83	2.12	2.74	3.37	3.87	4.55	5.06
6 hrs.	2.13	2.60	3.26	4.00	4.50	5.20	6.12
12 hrs.	2.41	3.05	3.80	4.62	5.37	6.00	7.20
24 hrs.	2.75	3.30	4.39	5.30	6.00	6.65	8.16

**Table A-9. Rainfall depth in inches for various duration and frequency at Cleveland.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.27	0.34	0.43	0.50	0.57	0.64	0.71
10 min.	0.41	0.52	0.66	0.77	0.88	0.99	1.09
15 min.	0.52	0.66	0.84	0.97	1.11	1.25	1.38
30 min.	0.72	0.92	1.16	1.35	1.54	1.73	1.92
60 min.	0.92	1.12	1.48	1.70	1.96	2.16	2.43
2 hrs.	1.09	1.33	1.68	2.05	2.30	2.63	2.86
3 hrs.	1.27	1.46	1.83	2.20	2.50	2.85	3.18
6 hrs.	1.47	1.70	2.15	2.60	2.90	3.25	3.60
12 hrs.	1.67	2.08	2.68	2.95	3.30	3.68	4.25
24 hrs.	1.81	2.50	2.90	3.37	3.87	4.37	4.80

**Table A-10. Rainfall depth in inches for various duration and frequency at St. Louis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.39	0.46	0.56	0.64	0.73	0.80	0.88
10 min.	0.60	0.70	0.87	0.99	1.12	1.24	1.36
15 min.	0.76	0.89	1.09	1.25	1.41	1.56	1.72
30 min.	1.06	1.23	1.52	1.74	1.96	2.17	2.39
60 min.	1.31	1.54	1.91	2.17	2.49	2.75	3.06
2 hrs.	1.60	1.83	2.28	2.60	2.98	3.33	3.68
3 hrs.	1.74	2.03	2.55	2.93	3.28	3.62	3.95
6 hrs.	2.04	2.44	3.03	3.40	3.93	4.32	4.80
12 hrs.	2.42	2.87	3.55	4.06	4.60	5.06	5.73
24 hrs.	2.75	3.24	4.06	4.65	5.25	5.90	6.49

**Table A-11. Rainfall depth in inches for various duration and frequency at Pittsburg.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.29	0.34	0.46	0.53	0.61	0.69	0.75
10 min.	0.44	0.53	0.70	0.81	0.95	1.06	1.16
15 min.	0.56	0.67	0.89	1.02	1.20	1.34	1.47
30 min.	0.78	0.93	1.23	1.42	1.66	1.86	2.04
60 min.	0.98	1.17	1.58	1.79	2.10	2.36	2.56
2 hrs.	1.20	1.44	1.87	2.24	2.49	2.85	3.12
3 hrs.	1.33	1.65	2.00	2.42	2.81	2.99	3.43
6 hrs.	1.70	1.91	2.42	2.74	3.38	3.62	3.95
12 hrs.	1.87	2.26	2.92	3.35	3.90	4.20	4.85
24 hrs.	2.25	2.65	3.36	3.91	4.48	4.91	5.20

**Table A-12. Rainfall depth in inches for various duration and frequency at Baltimore.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.37	0.46	0.61	0.68	0.81	0.91	1.01
10 min.	0.58	0.71	0.94	1.04	1.25	1.41	1.56
15 min.	0.73	0.89	1.19	1.32	1.58	1.78	1.97
30 min.	1.01	1.24	1.65	1.83	2.20	2.47	2.74
60 min.	1.31	1.60	2.08	2.40	2.72	3.05	3.50
2 hrs.	1.56	1.88	2.40	2.88	3.29	3.56	4.28
3 hrs.	1.71	2.03	2.60	3.10	3.64	4.19	4.60
6 hrs.	2.12	2.43	3.06	3.63	4.12	4.85	5.24
12 hrs.	2.30	2.86	3.62	4.35	5.06	5.60	6.20
24 hrs.	2.63	3.23	4.24	5.10	5.74	6.45	7.18

**Table A-13. Rainfall depth in inches for various duration and frequency at Minneapolis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.33	0.41	0.53	0.62	0.70	0.78	0.89
10 min.	0.51	0.63	0.82	0.95	1.08	1.21	1.37
15 min.	0.65	0.79	1.03	1.20	1.37	1.53	1.73
30 min.	0.90	1.10	1.43	1.67	1.90	2.12	2.40
60 min.	1.15	1.40	1.80	2.10	2.41	2.72	3.00
2 hrs.	1.35	1.65	2.10	2.45	2.70	3.15	3.52
3 hrs.	1.48	1.76	2.26	2.65	3.06	3.41	3.87
6 hrs.	1.70	2.06	2.65	3.10	3.50	4.05	4.42
12 hrs.	1.96	2.43	3.18	3.61	4.20	4.62	5.20
24 hrs.	2.37	2.75	3.55	4.15	4.70	5.30	5.90

**Table A-14. Rainfall depth in inches for various duration and frequency at Miami.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.67	0.78	0.93	1.05	1.18	1.30	1.43
10 min.	1.03	1.20	1.44	1.62	1.82	2.01	2.21
15 min.	1.30	1.51	1.89	2.05	2.30	2.53	2.79
30 min.	1.80	2.10	2.52	2.85	3.20	3.52	3.87
60 min.	2.30	2.60	3.20	3.65	4.10	4.50	4.90
2 hrs.	2.65	3.20	4.00	4.60	5.20	5.80	6.50
3 hrs.	2.88	3.50	4.38	5.25	5.78	6.65	7.30
6 hrs.	3.40	4.20	5.30	6.35	7.40	8.30	8.55
12 hrs.	4.00	4.90	6.50	7.68	9.00	10.00	10.91
24 hrs.	5.52	6.72	7.65	9.30	10.52	12.00	13.45

**Table A-15. Rainfall depth in inches for various duration and frequency at Houston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.58	0.69	0.87	0.98	1.12	1.18	1.35
10 min.	0.90	1.06	1.33	1.50	1.72	1.82	2.08
15 min.	1.14	1.34	1.68	1.89	2.17	2.30	2.63
30 min.	1.58	1.86	2.34	2.63	3.02	3.20	3.65
60 min.	2.02	2.37	2.93	3.40	3.82	4.12	4.63
2 hrs.	2.40	2.87	3.60	4.35	4.94	5.55	6.10
3 hrs.	2.60	3.15	4.04	4.60	5.16	5.43	6.39
6 hrs.	3.02	3.76	4.56	5.10	5.94	6.18	7.20
12 hrs.	3.50	4.45	6.00	7.20	8.00	9.10	10.23
24 hrs.	3.98	5.18	6.50	7.44	8.88	9.60	11.04

**Table A-16. Rainfall depth in inches for various duration and frequency at Buffalo.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.26	0.33	0.41	0.48	0.55	0.63	0.68
10 min.	0.40	0.51	0.64	0.74	0.85	0.96	1.05
15 min.	0.50	0.65	0.81	0.94	1.07	1.22	1.33
30 min.	0.70	0.90	1.12	1.30	1.49	1.69	1.85
60 min.	0.88	1.13	1.40	1.62	1.88	2.09	2.28
2 hrs.	1.08	1.27	1.63	1.93	2.25	2.59	2.79
3 hrs.	1.21	1.43	1.80	2.20	2.51	2.82	3.13
6 hrs.	1.49	1.69	2.25	2.66	3.00	3.40	3.74
12 hrs.	1.72	2.15	2.75	3.12	3.62	3.96	4.48
24 hrs.	2.12	2.48	3.13	3.66	4.20	4.68	4.99

**Table A-17. Rainfall depth in inches for various duration and frequency at Cincinnati.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.33	0.40	0.49	0.57	0.66	0.73	0.81
10 min.	0.50	0.61	0.76	0.88	1.01	1.12	1.24
15 min.	0.63	0.77	0.96	1.12	1.28	1.41	1.57
30 min.	0.88	1.07	1.33	1.55	1.78	1.96	2.18
60 min.	1.11	1.33	1.68	1.96	2.24	2.50	2.73
2 hrs.	1.41	1.62	2.06	2.37	2.67	3.00	3.31
3 hrs.	1.50	1.76	2.20	2.55	2.99	3.24	3.57
6 hrs.	1.83	2.10	2.62	3.06	3.48	3.88	4.13
12 hrs.	2.13	2.55	3.10	3.60	4.10	4.41	5.06
24 hrs.	2.34	2.92	3.61	4.10	4.76	5.13	5.62

**Table A-18. Rainfall depth in inches for various duration and frequency at Milwaukee.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.35	0.41	0.50	0.56	0.64	0.71	0.78
10 min.	0.53	0.63	0.77	0.87	0.98	1.09	1.21
15 min.	0.67	0.79	0.97	1.09	1.24	1.38	1.53
30 min.	0.94	1.10	1.35	1.52	1.72	1.92	2.12
60 min.	1.20	1.40	1.72	1.92	2.21	2.40	2.70
2 hrs.	1.41	1.63	2.02	2.33	2.62	2.88	3.18
3 hrs.	1.55	1.75	2.19	2.49	2.86	3.13	3.50
6 hrs.	1.75	2.00	2.50	2.91	3.35	3.75	4.10
12 hrs.	1.96	2.37	2.97	3.38	3.90	4.26	4.85
24 hrs.	2.33	2.68	3.38	3.93	4.49	5.00	5.50

**Table A-19. Rainfall depth in inches for various duration and frequency at San Diego**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.11	0.17	0.24	0.30	0.36	0.41	0.46
10 min.	0.18	0.26	0.37	0.46	0.55	0.63	0.71
15 min.	0.22	0.33	0.47	0.58	0.70	0.79	0.90
30 min.	0.31	0.46	0.65	0.80	0.97	1.10	1.25
60 min.	0.38	0.56	0.80	0.99	1.18	1.36	1.51
2 hrs.	0.49	0.65	0.94	1.25	1.48	1.65	1.85
3 hrs.	0.57	0.75	1.10	1.40	1.63	1.85	2.20
6 hrs.	0.70	1.00	1.50	1.85	2.20	2.62	3.00
12 hrs.	0.90	1.29	1.75	2.00	2.62	2.95	3.50
24 hrs.	1.00	1.70	2.00	2.72	3.00	3.55	3.78

**Table A-20. Rainfall depth in inches for various duration and frequency at Dallas.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.48	0.58	0.77	0.88	1.01	1.15	1.26
10 min.	0.74	0.89	1.18	1.36	1.56	1.77	1.94
15 min.	0.94	1.13	1.49	1.71	1.97	2.24	2.45
30 min.	1.30	1.57	2.07	2.38	2.78	3.11	3.40
60 min.	1.61	1.94	2.60	2.94	3.43	3.87	4.30
2 hrs.	1.88	2.34	3.10	3.63	4.25	4.76	5.26
3 hrs.	2.05	2.56	3.38	4.00	4.66	5.25	5.83
6 hrs.	2.47	3.05	4.05	4.76	5.63	6.37	7.12
12 hrs.	2.76	3.55	4.78	5.70	6.70	7.55	8.56
24 hrs.	3.30	4.12	5.50	6.60	7.74	8.76	9.76

**Table A-21. Rainfall depth in inches for various duration and frequency at Atlanta.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.48	0.55	0.68	0.76	0.85	0.95	1.04
10 min.	0.74	0.85	1.04	1.17	1.32	1.47	1.60
15 min.	0.93	1.07	1.32	1.48	1.66	1.86	2.02
30 min.	1.29	1.49	1.83	2.06	2.31	2.58	2.80
60 min.	1.64	1.86	2.32	2.63	2.94	3.26	3.60
2 hrs.	1.95	2.28	2.80	3.25	3.73	4.00	4.50
3 hrs.	2.13	2.42	3.10	3.50	3.98	4.41	4.93
6 hrs.	2.42	2.85	3.75	4.27	4.75	5.50	5.89
12 hrs.	2.83	3.35	4.33	4.94	5.70	6.55	7.00
24 hrs.	3.35	3.87	4.98	5.85	6.74	7.80	8.05

**Table A-22. Rainfall depth in inches for various duration and frequency at Kansas City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.44	0.50	0.64	0.74	0.86	0.95	1.07
10 min.	0.67	0.77	0.99	1.15	1.32	1.47	1.64
15 min.	0.85	0.97	1.25	1.45	1.67	1.86	2.07
30 min.	1.18	1.34	1.74	2.01	2.32	2.58	2.88
60 min.	1.49	1.69	2.18	2.55	2.92	3.26	3.62
2 hrs.	1.74	2.08	2.62	3.05	3.50	3.91	4.38
3 hrs.	1.90	2.24	2.92	3.40	3.88	4.35	4.82
6 hrs.	2.23	2.63	3.43	3.98	4.33	5.14	5.75
12 hrs.	2.55	3.13	4.00	4.75	5.40	6.10	6.86
24 hrs.	2.98	3.53	4.65	5.39	6.26	6.99	7.88

**Table A-23. Rainfall depth in inches for various duration and frequency at Seattle.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.11	0.13	0.16	0.19	0.21	0.22	0.28
10 min.	0.17	0.21	0.24	0.29	0.32	0.34	0.43
15 min.	0.22	0.26	0.30	0.37	0.40	0.43	0.54
30 min.	0.30	0.36	0.42	0.51	0.56	0.60	0.75
60 min.	0.36	0.42	0.52	0.60	0.70	0.85	0.98
2 hrs.	0.54	0.65	0.82	0.95	1.10	1.18	1.35
3 hrs.	0.76	0.85	1.15	1.27	1.45	1.60	1.80
6 hrs.	1.10	1.40	1.70	2.00	2.30	2.50	2.80
12 hrs.	1.60	1.80	2.50	2.75	3.00	3.30	3.80
24 hrs.	1.90	2.10	2.90	3.40	3.90	4.20	4.60

**Table A-24. Rainfall depth in inches for various duration and frequency at Helena.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.12	0.16	0.23	0.30	0.32	0.39	0.47
10 min.	0.19	0.25	0.36	0.46	0.52	0.60	0.72
15 min.	0.24	0.32	0.45	0.58	0.66	0.76	0.91
30 min.	0.33	0.44	0.63	0.80	0.92	1.05	1.27
60 min.	0.42	0.60	0.83	1.02	1.23	1.41	1.53
2 hrs.	0.54	0.72	1.03	1.25	1.49	1.70	1.80
3 hrs.	0.64	0.80	1.10	1.35	1.57	1.80	2.15
(6 hrs.)	--	(0.72)	(0.94)	(1.09)	(1.37)	(1.47)	(1.69)
6 hrs.	0.81	1.05	1.37	1.62	1.90	2.20	2.45
12 hrs.	1.05	1.30	1.60	1.95	2.26	2.58	2.85
(24 hrs.)	--	(1.29)	(1.69)	(1.92)	(2.38)	(2.72)	(2.93)
24 hrs.	1.18	1.55	1.88	2.28	2.60	3.00	3.35

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-25. Rainfall depth in inches for various duration and frequency at Cheyenne.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.21	0.26	0.37	0.43	0.53	0.59	0.67
10 min.	0.32	0.40	0.57	0.66	0.82	0.91	1.03
15 min.	0.41	0.50	0.72	0.83	1.03	1.15	1.30
30 min.	0.57	0.70	1.00	1.15	1.43	1.60	1.80
60 min.	0.66	0.90	1.26	1.56	1.83	2.05	2.30
2 hrs.	0.77	1.00	1.39	1.65	2.06	2.27	2.63
3 hrs.	0.87	1.12	1.51	1.80	2.20	2.50	2.77
(6 hrs.)	--	(1.19)	(1.58)	(1.86)	(2.37)	(2.59)	(2.80)
6 hrs.	1.00	1.28	1.75	2.12	2.55	2.82	3.30
12 hrs.	1.19	1.45	2.00	2.40	2.85	3.21	3.68
(24 hrs.)	--	(1.59)	(2.00)	(2.39)	(2.79)	(3.12)	(3.37)
24 hrs.	1.30	1.64	2.28	2.69	3.20	3.65	4.00

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-26. Rainfall depth in inches for various duration and frequency at Denver.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.17	0.23	0.34	0.43	0.51	0.59	0.65
10 min.	0.26	0.36	0.52	0.67	0.78	0.91	0.99
15 min.	0.32	0.45	0.66	0.84	0.99	1.15	1.26
30 min.	0.45	0.63	0.91	1.17	1.37	1.60	1.75
60 min.	0.62	0.82	1.20	1.49	1.72	1.92	2.23
2 hrs.	0.72	1.00	1.38	1.62	1.85	2.25	2.58
3 hrs.	0.82	1.05	1.45	1.81	2.10	2.40	2.75
(6 hrs.)	--	(1.45)	(2.00)	(2.24)	(2.85)	(3.17)	(3.55)
6 hrs.	1.00	1.30	1.70	2.10	2.55	2.75	3.20
12 hrs.	1.15	1.50	1.95	2.30	2.80	3.25	3.62
(24 hrs.)	--	(2.08)	(2.73)	(3.19)	(3.90)	(4.40)	(4.92)
24 hrs.	1.32	1.68	2.25	2.80	3.20	3.62	4.15

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-27. Rainfall depth in inches for various duration and frequency at Santa Fe.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.15	0.22	0.30	0.37	0.45	0.52	0.58
10 min.	0.23	0.34	0.46	0.57	0.69	0.80	0.89
15 min.	0.29	0.42	0.58	0.72	0.87	1.01	1.13
30 min.	0.40	0.59	0.81	1.00	1.21	1.40	1.57
60 min.	0.57	0.80	1.07	1.38	1.60	1.80	1.98
2 hrs.	0.63	0.89	1.31	1.50	1.90	2.07	2.45
3 hrs.	0.72	1.01	1.47	1.74	2.06	2.31	2.56
(6 hrs.)	--	(1.22)	(1.60)	(1.80)	(2.00)	(2.50)	(2.65)
6 hrs.	0.90	1.27	1.62	1.96	2.42	2.68	3.10
12 hrs.	1.06	1.39	1.90	2.30	2.70	3.10	3.49
(24 hrs.)	--	(1.60)	(2.00)	(2.30)	(2.70)	(3.20)	(3.30)
24 hrs.	1.27	1.57	2.23	2.65	3.13	3.50	4.00

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-28. Rainfall depth in inches for various duration and frequency at Boise.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.074	0.089	0.16	0.17	0.20	0.22	0.26
10 min.	0.11	0.14	0.25	0.26	0.31	0.34	0.40
15 min.	0.14	0.17	0.31	0.32	0.40	0.43	0.50
30 min.	0.20	0.24	0.43	0.45	0.55	0.60	0.70
60 min.	0.24	0.33	0.48	0.58	0.68	0.80	0.83
2 hrs.	0.32	0.41	0.62	0.74	0.83	0.90	1.00
3 hrs.	0.41	0.51	0.74	0.80	1.00	1.15	1.37
(6 hrs.)	--	(0.77)	(0.99)	(1.18)	(1.38)	(1.52)	(1.72)
6 hrs.	0.75	0.83	1.10	1.28	1.48	1.55	1.87
12 hrs.	0.90	1.00	1.40	1.62	1.80	2.00	2.23
(24 hrs.)	--	(1.20)	(1.60)	(1.90)	(2.27)	(2.58)	(2.83)
24 hrs.	1.12	1.50	1.70	2.00	2.18	2.45	2.72

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-29. Rainfall depth in inches for various duration and frequency at Salt Lake City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.089	0.13	0.19	0.23	0.27	0.33	0.35
10 min.	0.14	0.19	0.29	0.35	0.42	0.50	0.54
15 min.	0.17	0.24	0.37	0.45	0.53	0.63	0.68
30 min.	0.24	0.34	0.51	0.62	0.73	0.88	0.95
60 min.	0.33	0.42	0.63	0.78	0.92	1.09	1.20
2 hrs.	0.44	0.61	0.81	1.03	1.17	1.55	1.57
3 hrs.	0.60	0.75	1.03	1.10	1.25	1.57	1.63
(6 hrs.)	--	(0.95)	(1.22)	(1.40)	(1.80)	(1.95)	(2.07)
6 hrs.	0.76	0.95	1.20	1.55	2.02	2.20	2.50
12 hrs.	1.01	1.30	1.75	2.05	2.48	2.75	3.00
(24 hrs.)	--	(1.40)	(1.80)	(2.20)	(2.60)	(2.98)	(3.20)
24 hrs.	1.26	1.50	2.05	2.50	2.70	3.05	3.50

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-30. Rainfall depth in inches for various duration and frequency at Carson City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.093	0.13	0.19	0.22	0.26	0.31	0.34
10 min.	0.14	0.20	0.29	0.34	0.40	0.48	0.53
15 min.	0.18	0.25	0.36	0.43	0.50	0.61	0.67
30 min.	0.25	0.35	0.50	0.60	0.70	0.85	0.93
60 min.	0.30	0.40	0.60	0.76	0.81	1.00	1.19
2 hrs.	0.41	0.60	0.80	1.00	1.30	1.38	1.50
3 hrs.	0.57	0.77	1.00	1.22	1.43	1.60	1.77
(6 hrs.)	--	(1.20)	(1.45)	(1.65)	(1.75)	(2.40)	(2.70)
6 hrs.	0.79	1.00	1.35	1.75	2.00	2.48	2.58
12 hrs.	1.10	1.35	1.95	2.38	2.55	2.90	3.00
(24 hrs.)	--	(2.10)	(2.35)	(2.60)	(3.00)	(3.60)	(4.20)
24 hrs.	1.33	1.62	2.25	2.65	2.95	3.20	3.50

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).



**Table A-31. Rainfall depth in inches for various duration and frequency at Phoenix.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.21	0.26	0.36	0.44	0.51	0.59	0.68
10 min.	0.32	0.41	0.55	0.67	0.79	0.91	1.05
15 min.	0.40	0.51	0.69	0.85	1.00	1.15	1.33
30 min.	0.56	0.71	0.96	1.18	1.39	1.60	1.85
60 min.	0.69	0.92	1.25	1.57	1.79	2.01	2.32
2 hrs.	0.86	1.07	1.53	1.80	2.23	2.50	2.80
3 hrs.	0.90	1.23	1.70	2.12	2.38	2.75	3.10
(6 hrs.)	--	(1.19)	(1.68)	(1.98)	(2.50)	(2.85)	(3.20)
6 hrs.	1.06	1.39	1.90	2.30	2.77	3.27	3.70
12 hrs.	1.23	1.64	2.30	2.72	3.21	3.70	4.30
(24 hrs.)	--	(1.39)	(1.98)	(2.40)	(3.00)	(3.70)	(4.25)
24 hrs.	1.38	1.73	2.65	3.20	3.73	4.38	4.90

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-32. Rainfall depth in inches for various duration and frequency at Olympia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.13	0.16	0.19	0.22	0.24	0.26	0.30
10 min.	0.21	0.24	0.29	0.34	0.37	0.40	0.46
15 min.	0.26	0.30	0.36	0.43	0.47	0.50	0.58
30 min.	0.36	0.42	0.50	0.60	0.65	0.70	0.80
60 min.	0.43	0.54	0.64	0.75	0.85	0.93	1.00
2 hrs.	0.67	0.80	0.98	1.12	1.37	1.50	1.75
3 hrs.	0.95	1.00	1.35	1.50	1.75	1.87	2.23
6 hrs.	1.50	1.90	2.40	2.77	2.90	3.00	3.85
12 hrs.	2.25	2.78	3.00	3.75	4.00	4.45	5.00
24 hrs.	2.80	3.00	3.85	4.00	4.40	4.89	6.00

**Table A-33. Rainfall depth in inches for various duration and frequency at Salem.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.13	0.16	0.21	0.26	0.30	0.34	0.38
10 min.	0.19	0.25	0.32	0.40	0.46	0.52	0.59
15 min.	0.24	0.32	0.40	0.50	0.58	0.66	0.75
30 min.	0.37	0.48	0.56	0.70	0.80	0.91	1.04
60 min.	0.42	0.55	0.72	0.88	1.02	1.18	1.28
2 hrs.	0.60	0.90	1.00	1.33	1.50	1.70	1.86
3 hrs.	0.92	1.11	1.40	1.80	1.92	2.30	2.42
(6 hrs.)	--	(1.13)	(1.40)	(1.60)	(1.82)	(2.00)	(2.20)
6 hrs.	1.39	1.85	2.60	2.78	3.00	3.70	3.95
12 hrs.	1.90	2.62	2.90	3.72	3.90	4.75	4.90
(24 hrs.)	--	(2.58)	(3.08)	(3.48)	(3.90)	(4.25)	(4.60)
24 hrs.	2.68	2.80	3.75	5.25	5.50	5.80	6.00

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table A-34. Rainfall depth in inches for various duration and frequency at Sacramento.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.15	0.19	0.23	0.27	0.30	0.34	0.38
10 min.	0.23	0.30	0.35	0.42	0.47	0.53	0.59
15 min.	0.29	0.37	0.44	0.53	0.59	0.67	0.74
30 min.	0.40	0.52	0.61	0.73	0.82	0.93	1.03
60 min.	0.49	0.60	0.73	0.92	1.05	1.21	1.29
2 hrs.	0.70	0.80	1.00	1.25	1.40	1.48	1.75
3 hrs.	0.80	1.00	1.25	1.50	1.75	1.90	2.00
(6 hrs.)	--	(1.16)	(1.50)	(1.68)	(2.00)	(2.25)	(2.50)
6 hrs.	1.30	1.50	1.90	2.25	2.60	3.00	3.10
12 hrs.	1.62	2.00	2.55	3.00	3.50	3.80	4.00
(24 hrs.)	--	(1.97)	(2.40)	(2.80)	(3.35)	(3.75)	(4.20)
24 hrs.	2.25	2.60	3.25	3.77	4.00	5.10	5.50

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).



## Appendix B

### Rainfall Intensity Tables of 23 Major Cities in the United States and 11 Capitals of the Western States

The 23 major cities and 11 western state capitals selected for this study are:

<u>Table No.</u>	<u>City, State Name</u>	<u>Location</u>
B-1	New York, New York	40.4 <sup>o</sup> N., 74.0 <sup>o</sup> W.
B-2	Los Angeles, California	34.1 <sup>o</sup> N., 118.3 <sup>o</sup> W.
B-3	Chicago, Illinois	41.8 <sup>o</sup> N., 87.7 <sup>o</sup> W.
B-4	Detroit, Michigan	42.4 <sup>o</sup> N., 83.1 <sup>o</sup> W.
B-5	Philadelphia, Pennsylvania	35.9 <sup>o</sup> N., 75.2 <sup>o</sup> W.
B-6	San Francisco, California	37.8 <sup>o</sup> N., 122.5 <sup>o</sup> W.
B-7	Boston, Massachusetts	42.3 <sup>o</sup> N., 71.1 <sup>o</sup> W.
B-8	Washington, D.C.	38.5 <sup>o</sup> N., 77.0 <sup>o</sup> W.
B-9	Cleveland, Ohio	41.5 <sup>o</sup> N., 81.7 <sup>o</sup> W.
B-10	St. Louis, Missouri	40.0 <sup>o</sup> N., 89.6 <sup>o</sup> W.
B-11	Pittsburg, Pennsylvania	40.5 <sup>o</sup> N., 80.0 <sup>o</sup> W.
B-12	Baltimore, Maryland	39.2 <sup>o</sup> N., 76.4 <sup>o</sup> W.
B-13	Minneapolis, Minnesota	45.0 <sup>o</sup> N., 93.2 <sup>o</sup> W.
B-14	Miami, Florida	25.7 <sup>o</sup> N., 80.2 <sup>o</sup> W.
B-15	Houston, Texas	29.5 <sup>o</sup> N., 95.2 <sup>o</sup> W.
B-16	Buffalo, New York	42.5 <sup>o</sup> N., 78.5 <sup>o</sup> W.
B-17	Cincinnati, Ohio	39.1 <sup>o</sup> N., 84.3 <sup>o</sup> W.
B-18	Milwaukee, Wisconsin	43.0 <sup>o</sup> N., 87.5 <sup>o</sup> W.
B-19	San Diego, California	32.4 <sup>o</sup> N., 117.1 <sup>o</sup> W.
B-20	Dallas, Texas	32.4 <sup>o</sup> N., 96.5 <sup>o</sup> W.
B-21	Atlanta, Georgia	33.5 <sup>o</sup> N., 84.2 <sup>o</sup> W.
B-22	Kansas City, Missouri	39.0 <sup>o</sup> N., 94.4 <sup>o</sup> W.
B-23	Seattle, Washington	47.6 <sup>o</sup> N., 122.3 <sup>o</sup> W.
B-24	Helena, Montana	46.7 <sup>o</sup> N., 112.0 <sup>o</sup> W.
B-25	Cheyenne, Wyoming	41.2 <sup>o</sup> N., 104.8 <sup>o</sup> W.
B-26	Denver, Colorado	39.8 <sup>o</sup> N., 105.0 <sup>o</sup> W.
B-27	Santa Fe, New Mexico	35.5 <sup>o</sup> N., 105.9 <sup>o</sup> W.
B-28	Boise, Idaho	43.6 <sup>o</sup> N., 116.3 <sup>o</sup> W.
B-29	Salt Lake City, Utah	40.8 <sup>o</sup> N., 111.9 <sup>o</sup> W.
B-30	Carson City, Nevada	39.1 <sup>o</sup> N., 119.8 <sup>o</sup> W.
B-31	Phoenix, Arizona	33.4 <sup>o</sup> N., 112.1 <sup>o</sup> W.
B-32	Olympia, Washington	47.1 <sup>o</sup> N., 122.9 <sup>o</sup> W.
B-33	Salem, Oregon	44.9 <sup>o</sup> N., 123.0 <sup>o</sup> W.
B-34	Sacramento, California	38.5 <sup>o</sup> N., 121.6 <sup>o</sup> W.

Data are obtained or calculated from U.S. Weather Bureau Technical Paper No. 40 (1961) except for those in parenthesis which are obtained or calculated from NOAA Atlas 2 (Miller, Frederick, and Tracey, 1973).

**Table B-1. Rainfall intensity in inches per hour for various duration and frequency at New York.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.08	5.04	6.48	7.56	8.52	9.72	10.68
10 min.	3.12	3.84	4.98	5.82	6.60	7.50	8.22
15 min.	2.64	3.24	4.20	4.88	5.56	6.32	6.92
30 min.	1.82	2.24	2.92	3.40	3.86	4.38	4.80
60 min.	1.23	1.43	1.86	2.15	2.48	2.78	3.11
2 hrs.	0.74	0.89	1.16	1.35	1.58	1.73	1.90
3 hrs.	0.54	0.66	0.85	0.96	1.13	1.27	1.43
6 hrs.	0.33	0.40	0.52	0.61	0.72	0.77	0.90
12 hrs.	0.20	0.24	0.31	0.36	0.42	0.46	0.53
24 hrs.	0.11	0.14	0.18	0.22	0.25	0.27	0.31

**Table B-2. Rainfall intensity in inches per hour for various duration and frequency at Los Angeles.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	2.28	2.64	3.48	4.20	5.16	6.00	6.48
10 min.	1.74	2.04	2.70	3.24	3.96	4.62	5.04
15 min.	1.44	1.68	2.28	2.72	3.32	3.88	4.24
30 min.	1.00	1.26	1.58	1.90	2.30	2.70	2.94
60 min.	0.65	0.78	0.97	1.19	1.45	1.70	1.89
2 hrs.	0.39	0.49	0.70	0.89	1.00	1.18	1.30
3 hrs.	0.32	0.43	0.63	0.73	0.87	0.97	1.10
(6 hrs.)	--	(0.28)	(0.37)	(0.43)	(0.50)	(0.58)	(0.64)
6 hrs.	0.24	0.33	0.48	0.57	0.68	0.75	0.90
12 hrs.	0.15	0.22	0.30	0.39	0.46	0.51	0.58
(24 hrs.)	--	(0.12)	(0.18)	(0.20)	(0.25)	(0.29)	(0.33)
24 hrs.	0.087	0.14	0.19	0.24	0.28	0.32	0.36

**Table B-3. Rainfall intensity in inches per hour for various duration and frequency at Chicago.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.44	5.16	6.36	7.20	8.28	9.12	10.08
10 min.	3.48	4.02	4.86	5.58	6.36	7.02	7.74
15 min.	2.92	3.36	4.08	4.68	5.36	5.92	6.52
30 min.	2.02	2.34	2.84	3.26	3.72	4.12	4.52
60 min.	1.22	1.47	1.82	2.03	2.35	2.57	2.85
2 hrs.	0.75	0.86	1.05	1.23	1.39	1.53	1.70
3 hrs.	0.53	0.62	0.78	0.89	1.01	1.13	1.23
6 hrs.	0.31	0.36	0.46	0.52	0.60	0.67	0.73
12 hrs.	0.18	0.22	0.27	0.30	0.35	0.38	0.44
24 hrs.	0.10	0.12	0.15	0.18	0.20	0.23	0.25

**Table B-4. Rainfall intensity in inches per hour for various duration and frequency at Detroit.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.60	4.44	5.40	6.36	7.32	8.16	8.88
10 min.	2.76	3.48	4.26	4.92	5.58	6.24	6.90
15 min.	2.32	2.92	3.56	4.12	4.72	5.28	5.80
30 min.	1.62	2.02	2.48	2.86	3.28	3.66	4.02
60 min.	1.05	1.28	1.60	1.81	2.10	2.35	2.60
2 hrs.	0.63	0.75	0.91	1.09	1.23	1.38	1.53
3 hrs.	0.46	0.56	0.67	0.77	0.92	0.99	1.09
6 hrs.	0.27	0.31	0.39	0.46	0.52	0.58	0.64
12 hrs.	0.16	0.18	0.23	0.27	0.30	0.33	0.38
24 hrs.	0.093	0.11	0.13	0.15	0.17	0.19	0.21

**Table B-5. Rainfall intensity in inches per hour for various duration and frequency at Philadelphia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	5.28	6.90	8.52	9.72	11.64	13.20	14.88
10 min.	4.02	5.40	6.60	7.50	8.94	10.14	11.46
15 min.	3.40	4.16	5.56	6.32	7.52	8.56	9.64
30 min.	2.36	2.90	3.86	4.40	5.22	5.94	6.70
60 min.	1.55	2.00	2.42	2.80	3.25	3.66	4.09
2 hrs.	0.97	1.17	1.50	1.75	2.00	2.28	2.61
3 hrs.	0.72	0.85	1.15	1.33	1.57	1.75	2.00
6 hrs.	0.42	0.56	0.72	0.84	1.00	1.13	1.27
12 hrs.	0.28	0.34	0.44	0.52	0.58	0.67	0.74
24 hrs.	0.17	0.21	0.26	0.30	0.34	0.40	0.45

**Table B-6. Rainfall intensity in inches per hour for various duration and frequency at San Francisco.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	2.22	2.62	3.33	4.00	4.35	5.11	5.55
10 min.	1.71	2.02	2.57	3.08	3.35	3.93	4.28
15 min.	1.44	1.70	2.16	2.59	2.82	3.31	3.60
30 min.	1.00	1.18	1.50	1.80	1.96	2.30	2.50
60 min.	0.65	0.70	0.90	1.10	1.25	1.40	1.50
2 hrs.	0.43	0.50	0.65	0.75	0.88	0.93	1.10
3 hrs.	0.35	0.42	0.55	0.60	0.73	0.77	0.90
(6 hrs.)	--	(0.22)	(0.25)	(0.29)	(0.33)	(0.36)	(0.40)
6 hrs.	0.30	0.32	0.42	0.46	0.54	0.58	0.65
12 hrs.	0.16	0.19	0.26	0.29	0.31	0.38	0.42
(24 hrs.)	--	(0.098)	(0.12)	(0.14)	(0.15)	(0.17)	(0.19)
24 hrs.	0.10	0.13	0.17	0.20	0.22	0.24	0.25

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-7. Rainfall intensity in inches per hour for various duration and frequency at Boston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.24	3.84	5.28	6.21	6.96	7.80	8.76
10 min.	2.52	3.00	4.02	4.68	5.40	6.06	6.78
15 min.	2.12	2.52	3.40	3.99	4.56	5.08	5.72
30 min.	1.46	1.74	2.36	2.74	3.16	3.54	3.96
60 min.	0.92	1.09	1.46	1.73	1.97	2.27	2.45
2 hrs.	0.59	0.73	0.94	1.14	1.30	1.45	1.63
3 hrs.	0.45	0.57	0.75	0.83	0.96	1.09	1.20
6 hrs.	0.28	0.35	0.46	0.54	0.60	0.67	0.76
12 hrs.	0.18	0.21	0.28	0.32	0.38	0.40	0.46
24 hrs.	0.11	0.12	0.16	0.19	0.21	0.24	0.27

**Table B-8. Rainfall intensity in inches per hour for various duration and frequency at Washington, D. C.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.92	6.36	7.80	9.12	10.80	12.24	14.16
10 min.	3.84	4.86	6.00	7.02	8.34	9.42	10.92
15 min.	3.24	4.08	5.08	5.92	7.00	7.96	9.20
30 min.	2.25	2.84	3.52	4.10	4.86	5.51	6.40
60 min.	1.43	1.80	2.23	2.64	3.08	3.47	4.00
2 hrs.	0.83	1.02	1.30	1.55	1.80	2.05	2.30
3 hrs.	0.61	0.71	0.91	1.12	1.29	1.52	1.69
6 hrs.	0.35	0.43	0.54	0.67	0.75	0.87	1.02
12 hrs.	0.20	0.25	0.32	0.39	0.45	0.50	0.60
24 hrs.	0.11	0.14	0.18	0.22	0.25	0.28	0.34

**Table B-9. Rainfall intensity in inches per hour for various duration and frequency at Cleveland.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.24	4.08	5.16	6.00	6.84	7.68	8.52
10 min.	2.46	3.12	3.96	4.62	5.28	5.94	6.54
15 min.	2.08	2.64	3.36	3.88	4.44	5.00	5.52
30 min.	1.44	1.84	2.32	2.70	3.08	3.46	3.84
60 min.	0.92	1.12	1.48	1.70	1.96	2.16	2.43
2 hrs.	0.55	0.67	0.84	1.03	1.15	1.32	1.43
3 hrs.	0.42	0.49	0.61	0.73	0.83	0.95	1.06
6 hrs.	0.24	0.28	0.36	0.43	0.48	0.54	0.60
12 hrs.	0.14	0.17	0.22	0.25	0.28	0.31	0.35
24 hrs.	0.075	0.10	0.12	0.14	0.16	0.18	0.20

**Table B-10. Rainfall intensity in inches per hour for various duration and frequency at St. Louis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.68	5.52	6.72	7.68	8.76	9.60	10.56
10 min.	3.60	4.20	5.22	5.94	6.72	7.44	8.16
15 min.	3.04	3.56	4.36	5.00	5.64	6.24	6.88
30 min.	2.12	2.46	3.04	3.48	3.92	4.34	4.78
60 min.	1.31	1.54	1.91	2.17	2.49	2.75	3.06
2 hrs.	0.80	0.92	1.14	1.30	1.49	1.67	1.84
3 hrs.	0.58	0.68	0.85	0.98	1.09	1.21	1.32
6 hrs.	0.34	0.41	0.51	0.57	0.66	0.72	0.80
12 hrs.	0.20	0.24	0.30	0.34	0.38	0.42	0.48
24 hrs.	0.11	0.14	0.17	0.19	0.22	0.24	0.27

**Table B-11. Rainfall intensity in inches per hour for various duration and frequency at Pittsburg.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.48	4.08	5.52	6.36	7.32	8.28	9.00
10 min.	2.64	3.18	4.20	4.86	5.70	6.36	6.96
15 min.	2.24	2.68	3.56	4.08	4.80	5.36	5.88
30 min.	1.56	1.85	2.46	2.83	3.32	3.72	4.07
60 min.	0.98	1.17	1.58	1.79	2.10	2.36	2.56
2 hrs.	0.60	0.72	0.94	1.12	1.23	1.43	1.56
3 hrs.	0.44	0.55	0.67	0.81	0.94	1.00	1.14
6 hrs.	0.28	0.33	0.40	0.46	0.56	0.60	0.66
12 hrs.	0.16	0.19	0.24	0.28	0.33	0.35	0.40
24 hrs.	0.094	0.11	0.14	0.16	0.19	0.20	0.22

**Table B-12. Rainfall intensity in inches per hour for various duration and frequency at Baltimore.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.44	5.52	7.32	8.16	9.72	10.92	12.12
10 min.	3.48	4.26	5.64	6.24	7.50	8.46	9.36
15 min.	2.92	3.56	4.76	5.28	6.32	7.12	7.88
30 min.	2.02	2.48	3.30	3.66	4.40	4.94	5.48
60 min.	1.31	1.60	2.08	2.40	2.72	3.05	3.50
2 hrs.	0.78	0.94	1.20	1.44	1.65	2.10	2.30
3 hrs.	0.57	0.68	0.87	1.03	1.21	1.40	1.53
6 hrs.	0.35	0.41	0.51	0.61	0.69	0.81	0.87
12 hrs.	0.19	0.24	0.30	0.36	0.42	0.47	0.52
24 hrs.	0.11	0.13	0.18	0.21	0.24	0.27	0.30



**Table B-13. Rainfall intensity in inches per hour for various duration and frequency at Minneapolis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.00	4.92	6.36	7.44	8.40	9.36	10.68
10 min.	3.06	3.78	4.92	5.70	6.46	7.26	8.22
15 min.	2.60	3.16	4.12	4.80	5.48	6.12	6.92
30 min.	1.80	2.20	2.86	3.34	3.80	4.24	4.80
60 min.	1.15	1.40	1.80	2.10	2.41	2.72	3.00
2 hrs.	0.68	0.83	1.05	1.23	1.35	1.58	1.76
3 hrs.	0.49	0.59	0.75	0.88	1.02	1.14	1.29
6 hrs.	0.28	0.34	0.44	0.52	0.58	0.68	0.74
12 hrs.	0.16	0.20	0.27	0.30	0.35	0.39	0.43
24 hrs.	0.099	0.11	0.15	0.17	0.20	0.22	0.25

**Table B-14. Rainfall intensity in inches per hour for various duration and frequency at Miami.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	8.04	9.36	11.16	12.60	14.16	15.60	17.16
10 min.	6.18	7.20	8.64	9.72	10.92	12.06	13.26
15 min.	5.20	6.04	7.56	8.20	9.20	10.12	11.16
30 min.	3.60	4.20	5.04	5.70	6.40	7.04	7.74
60 min.	2.30	2.60	3.20	3.65	4.10	4.50	4.90
2 hrs.	1.33	1.60	2.00	2.30	2.60	2.90	3.25
3 hrs.	0.96	1.17	1.46	1.75	1.93	2.22	2.43
6 hrs.	0.57	0.70	0.88	1.06	1.23	1.38	1.51
12 hrs.	0.33	0.41	0.54	0.64	0.75	0.83	0.91
24 hrs.	0.23	0.28	0.32	0.39	0.44	0.50	0.56

**Table B-15. Rainfall intensity in inches per hour for various duration and frequency at Houston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	6.96	8.28	10.44	11.80	13.44	14.16	16.20
10 min.	5.40	6.36	7.98	9.00	10.32	10.92	12.48
15 min.	4.56	5.36	6.72	7.56	8.68	9.20	10.52
30 min.	3.16	3.72	4.68	5.26	6.04	6.40	7.30
60 min.	2.02	2.37	2.93	3.40	3.82	4.12	4.63
2 hrs.	1.20	1.52	1.88	2.18	2.47	2.78	3.05
3 hrs.	0.87	1.05	1.35	1.53	1.72	1.81	2.13
6 hrs.	0.50	0.63	0.76	0.85	0.99	1.03	1.20
12 hrs.	0.29	0.37	0.50	0.60	0.67	0.76	0.85
24 hrs.	0.17	0.22	0.27	0.31	0.37	0.40	0.46

**Table B-16. Rainfall intensity in inches per hour for various duration and frequency at Buffalo.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.12	3.96	4.92	5.76	6.60	7.56	8.16
10 min.	2.40	3.06	3.84	4.44	5.10	5.76	6.30
15 min.	2.00	2.60	3.24	3.76	4.28	4.88	5.32
30 min.	1.40	1.80	2.24	2.60	2.98	3.38	3.70
60 min.	0.88	1.13	1.40	1.62	1.88	2.09	2.28
2 hrs.	0.54	0.64	0.82	0.97	1.13	1.30	1.40
3 hrs.	0.40	0.48	0.60	0.73	0.84	0.94	1.04
6 hrs.	0.25	0.28	0.38	0.44	0.50	0.57	0.62
12 hrs.	0.14	0.18	0.23	0.26	0.30	0.33	0.37
24 hrs.	0.088	0.10	0.13	0.15	0.18	0.20	0.21

**Table B-17. Rainfall intensity in inches per hour for various duration and frequency at Cincinnati.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.96	4.80	5.88	6.84	7.92	8.76	9.72
10 min.	3.00	3.66	4.56	5.26	6.06	6.72	7.44
15 min.	2.52	3.08	3.84	4.48	5.12	5.64	6.28
30 min.	1.76	2.14	2.66	3.10	3.56	3.92	4.36
60 min.	1.11	1.33	1.68	1.96	2.24	2.50	2.73
2 hrs.	0.71	0.81	1.03	1.19	1.34	1.50	1.66
3 hrs.	0.50	0.59	0.73	0.85	1.00	1.08	1.19
6 hrs.	0.30	0.35	0.44	0.51	0.58	0.65	0.69
12 hrs.	0.18	0.21	0.26	0.30	0.34	0.37	0.42
24 hrs.	0.098	0.12	0.15	0.17	0.20	0.21	0.23

**Table B-18. Rainfall intensity in inches per hour for various duration and frequency at Milwaukee.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	4.20	4.92	6.00	6.72	7.68	8.52	9.36
10 min.	3.18	3.78	4.62	5.22	5.88	6.54	7.26
15 min.	2.68	3.16	3.88	4.36	4.96	5.52	6.12
30 min.	1.87	2.20	2.70	3.04	3.44	3.84	4.24
60 min.	1.20	1.40	1.72	1.92	2.21	2.40	2.70
2 hrs.	0.71	0.82	1.01	1.17	1.31	1.44	1.59
3 hrs.	0.52	0.58	0.73	0.83	0.95	1.04	1.17
6 hrs.	0.29	0.33	0.42	0.49	0.56	0.63	0.68
12 hrs.	0.16	0.20	0.25	0.28	0.33	0.36	0.40
24 hrs.	0.097	0.11	0.14	0.16	0.19	0.21	0.23

**Table B-19. Rainfall intensity in inches per hour for various duration and frequency at San Diego.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.38	2.04	2.89	3.60	4.32	4.92	5.52
10 min.	1.08	1.56	2.22	2.76	3.30	3.78	4.26
15 min.	0.88	1.32	1.88	2.32	2.80	3.16	3.60
30 min.	0.62	0.91	1.30	1.60	1.94	2.20	2.50
60 min.	0.38	0.56	0.80	0.99	1.18	1.36	1.51
2 hrs.	0.25	0.33	0.47	0.63	0.74	0.83	0.93
3 hrs.	0.19	0.25	0.37	0.47	0.54	0.62	0.73
6 hrs.	0.12	0.17	0.25	0.31	0.37	0.44	0.50
12 hrs.	0.075	0.11	0.15	0.17	0.22	0.25	0.29
24 hrs.	0.042	0.071	0.083	0.11	0.13	0.15	0.16

**Table B-20. Rainfall intensity in inches per hour for various duration and frequency at Dallas.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	5.76	6.96	9.24	10.56	12.12	13.80	15.12
10 min.	4.44	5.34	7.08	8.16	9.36	10.62	11.64
15 min.	3.76	4.52	5.96	6.84	7.88	8.96	9.80
30 min.	2.60	3.14	4.14	4.76	5.56	6.22	6.80
60 min.	1.61	1.94	2.60	2.94	3.43	3.87	4.30
2 hrs.	0.94	1.17	1.55	1.82	2.13	2.38	2.63
3 hrs.	0.68	0.85	1.13	1.33	1.55	1.75	1.94
6 hrs.	0.41	0.51	0.68	0.79	0.94	1.06	1.19
12 hrs.	0.23	0.30	0.40	0.48	0.56	0.63	0.71
24 hrs.	0.14	0.17	0.23	0.28	0.32	0.37	0.41

**Table B-21. Rainfall intensity in inches per hour for various duration and frequency at Atlanta.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	5.76	6.60	8.16	9.12	10.20	11.40	12.48
10 min.	4.44	5.10	6.24	7.02	7.92	8.82	9.60
15 min.	3.72	4.28	5.28	5.92	6.64	7.44	8.08
30 min.	2.58	2.98	3.66	4.12	4.62	5.16	5.60
60 min.	1.64	1.86	2.32	2.63	2.94	3.26	3.60
2 hrs.	0.98	1.14	1.40	1.63	1.87	2.00	2.25
3 hrs.	0.71	0.81	1.03	1.17	1.33	1.47	1.64
6 hrs.	0.40	0.48	0.63	0.71	0.79	0.92	0.98
12 hrs.	0.24	0.28	0.36	0.41	0.48	0.55	0.58
24 hrs.	0.14	0.16	0.21	0.24	0.28	0.33	0.34

**Table B-22. Rainfall intensity in inches per hour for various duration and frequency at Kansas City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	5.28	6.00	7.68	8.88	10.32	11.40	12.84
10 min.	4.02	4.62	5.94	6.90	7.92	8.82	9.84
15 min.	3.40	3.88	5.00	5.80	6.68	7.44	8.28
30 min.	2.35	2.69	3.48	4.02	4.64	5.16	5.76
60 min.	1.49	1.69	2.18	2.55	2.92	3.26	3.62
2 hrs.	0.87	1.04	1.31	1.53	1.75	1.96	2.19
3 hrs.	0.63	0.75	0.97	1.13	1.29	1.45	1.61
6 hrs.	0.37	0.44	0.57	0.66	0.72	0.86	0.96
12 hrs.	0.21	0.26	0.33	0.40	0.45	0.51	0.57
24 hrs.	0.12	0.15	0.19	0.22	0.26	0.29	0.33

**Table B-23. Rainfall intensity in inches per hour for various duration and frequency at Seattle.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.32	1.56	1.92	2.28	2.52	2.64	3.36
10 min.	1.02	1.26	1.44	1.74	1.92	2.04	2.58
15 min.	0.88	1.04	1.20	1.48	1.60	1.72	2.16
30 min.	0.60	0.72	0.84	1.02	1.12	1.20	1.50
60 min.	0.36	0.42	0.52	0.60	0.70	0.85	0.98
2 hrs.	0.27	0.33	0.41	0.48	0.55	0.59	0.68
3 hrs.	0.25	0.28	0.38	0.42	0.48	0.53	0.60
6 hrs.	0.18	0.23	0.28	0.33	0.38	0.42	0.47
12 hrs.	0.13	0.15	0.21	0.23	0.25	0.28	0.32
24 hrs.	0.079	0.087	0.12	0.14	0.16	0.18	0.19

**Table B-24. Rainfall intensity in inches per hour for various duration and frequency at Helena.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.44	1.92	2.76	3.60	3.84	4.68	5.64
10 min.	1.14	1.50	2.16	2.76	3.12	3.60	4.32
15 min.	0.96	1.28	1.80	2.32	2.64	3.04	3.64
30 min.	0.66	0.88	1.26	1.60	1.84	2.10	2.54
60 min.	0.42	0.60	0.83	1.02	1.23	1.41	1.53
2 hrs.	0.27	0.36	0.52	0.63	0.75	0.85	0.90
3 hrs.	0.21	0.27	0.37	0.45	0.52	0.60	0.72
(6 hrs.)	--	(0.12)	(0.16)	(0.18)	(0.23)	(0.25)	(0.28)
6 hrs.	0.13	0.18	0.23	0.27	0.32	0.37	0.41
12 hrs.	0.088	0.11	0.13	0.16	0.19	0.22	0.24
(24 hrs.)	--	(0.054)	(0.070)	(0.080)	(0.099)	(0.11)	(0.12)
24 hrs.	0.049	0.065	0.078	0.095	0.11	0.13	0.14

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-25. Rainfall intensity in inches per hour for various duration and frequency at Cheyenne.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	2.52	3.12	4.44	5.16	6.36	7.08	8.04
10 min.	1.92	2.40	3.42	3.96	4.92	5.46	6.18
15 min.	1.64	2.00	2.88	3.32	4.12	4.60	5.20
30 min.	1.14	1.40	2.00	2.30	2.83	3.20	3.60
60 min.	0.66	0.90	1.26	1.56	1.83	2.05	2.30
2 hrs.	0.39	0.50	0.70	0.83	1.03	1.14	1.32
3 hrs.	0.29	0.37	0.50	0.60	0.73	0.83	0.92
(6 hrs.)	--	(0.20)	(0.26)	(0.31)	(0.40)	(0.43)	(0.47)
6 hrs.	0.17	0.21	0.29	0.35	0.43	0.47	0.55
12 hrs.	0.099	0.12	0.17	0.20	0.24	0.27	0.31
(24 hrs.)	--	(0.066)	(0.083)	(0.099)	(0.12)	(0.13)	(0.14)
24 hrs.	0.054	0.068	0.095	0.11	0.13	0.15	0.17

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-26. Rainfall intensity in inches per hour for various duration and frequency at Denver**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	2.04	2.76	4.08	5.16	6.12	7.08	7.80
10 min.	1.56	2.16	3.12	4.02	4.68	5.46	5.94
15 min.	1.28	1.80	2.64	3.36	3.96	4.60	5.04
30 min.	0.90	1.26	1.82	2.34	2.74	3.20	3.50
60 min.	0.62	0.82	1.20	1.49	1.72	1.92	2.23
2 hrs.	0.36	0.50	0.69	0.81	0.93	1.13	1.29
3 hrs.	0.27	0.35	0.48	0.60	0.70	0.80	0.92
(6 hrs.)	--	(0.24)	(0.33)	(0.37)	(0.48)	(0.53)	(0.59)
6 hrs.	0.17	0.22	0.28	0.35	0.43	0.46	0.53
12 hrs.	0.096	0.13	0.16	0.19	0.23	0.27	0.31
(24 hrs.)	--	(0.087)	(0.11)	(0.13)	(0.16)	(0.18)	(0.21)
24 hrs.	0.055	0.070	0.094	0.12	0.13	0.15	0.17

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-27. Rainfall intensity in inches per hour for various duration and frequency at Santa Fe.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.80	2.64	3.60	4.44	5.40	6.24	6.96
10 min.	1.38	2.04	2.76	3.42	4.14	4.80	5.34
15 min.	1.16	1.68	2.32	2.88	3.48	4.04	4.52
30 min.	0.80	1.18	1.62	2.00	2.42	2.80	3.14
60 min.	0.57	0.80	1.07	1.38	1.60	1.80	1.98
2 hrs.	0.32	0.45	0.66	0.75	0.95	1.03	1.23
3 hrs.	0.24	0.34	0.49	0.58	0.69	0.77	0.85
(6 hrs.)	--	(0.20)	(0.27)	(0.30)	(0.33)	(0.42)	(0.44)
6 hrs.	0.15	0.21	0.27	0.33	0.40	0.45	0.52
12 hrs.	0.088	0.12	0.16	0.19	0.23	0.26	0.29
(24 hrs.)	--	(0.067)	(0.083)	(0.096)	(0.11)	(0.13)	(0.14)
24 hrs.	0.053	0.065	0.093	0.11	0.13	0.15	0.17

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-28. Rainfall intensity in inches per hour for various duration and frequency at Boise.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.89	1.07	1.92	2.04	2.40	2.64	3.12
10 min.	0.66	0.84	1.50	1.56	1.86	2.04	2.40
15 min.	0.56	0.68	1.24	1.28	1.60	1.72	2.00
30 min.	0.40	0.48	0.86	0.90	1.10	1.20	1.40
60 min.	0.24	0.33	0.48	0.58	0.68	0.80	0.83
2 hrs.	0.16	0.21	0.31	0.37	0.42	0.45	0.50
3 hrs.	0.14	0.17	0.25	0.27	0.33	0.38	0.46
(6 hrs.)	--	(0.13)	(0.17)	(0.20)	(0.23)	(0.25)	(0.29)
6 hrs.	0.13	0.14	0.18	0.21	0.25	0.26	0.31
12 hrs.	0.075	0.083	0.12	0.14	0.15	0.17	0.19
(24 hrs.)	--	(0.049)	(0.067)	(0.079)	(0.095)	(0.11)	(0.12)
24 hrs.	0.047	0.063	0.071	0.083	0.091	0.10	0.11

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-29. Rainfall intensity in inches per hour for various duration and frequency at Salt Lake City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.07	1.56	2.28	2.76	3.24	3.96	4.20
10 min.	0.84	1.14	1.74	2.10	2.52	3.00	3.24
15 min.	0.68	0.96	1.48	1.80	2.12	2.52	2.72
30 min.	0.48	0.68	1.02	1.24	1.46	1.76	1.90
60 min.	0.33	0.42	0.63	0.78	0.92	1.09	1.20
2 hrs.	0.22	0.31	0.41	0.52	0.59	0.78	0.79
3 hrs.	0.20	0.25	0.34	0.37	0.42	0.52	0.54
(6 hrs.)	--	(0.16)	(0.20)	(0.23)	(0.30)	(0.33)	(0.35)
6 hrs.	0.13	0.16	0.20	0.26	0.34	0.37	0.42
12 hrs.	0.084	0.11	0.15	0.17	0.21	0.23	0.25
(24 hrs.)	--	(0.058)	(0.075)	(0.092)	(0.11)	(0.12)	(0.13)
24 hrs.	0.052	0.063	0.085	0.10	0.11	0.13	0.15

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-30. Rainfall intensity in inches per hour for various duration and frequency at Carson City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.12	1.56	2.28	2.64	3.12	3.72	4.08
10 min.	0.84	1.20	1.74	2.04	2.40	2.88	3.18
15 min.	0.72	1.00	1.44	1.72	2.00	2.44	2.68
30 min.	0.50	0.70	1.00	1.20	1.40	1.70	1.86
60 min.	0.30	0.40	0.60	0.76	0.81	1.00	1.19
2 hrs.	0.21	0.30	0.40	0.50	0.65	0.69	0.75
3 hrs.	0.19	0.26	0.33	0.41	0.48	0.53	0.59
(6 hrs.)	--	(0.20)	(0.24)	(0.28)	(0.29)	(0.40)	(0.45)
6 hrs.	0.13	0.17	0.23	0.29	0.33	0.41	0.43
12 hrs.	0.092	0.11	0.16	0.20	0.21	0.24	0.25
(24 hrs.)	--	(0.087)	(0.098)	(0.11)	(0.13)	(0.15)	(0.18)
24 hrs.	0.055	0.068	0.094	0.11	0.12	0.13	0.15

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-31. Rainfall intensity in inches per hour for various duration and frequency at Phoenix.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	2.52	3.12	4.32	5.28	6.12	7.08	8.16
10 min.	1.92	2.46	3.30	4.02	4.74	5.46	6.30
15 min.	1.60	2.04	2.76	3.40	4.00	4.60	5.32
30 min.	1.12	1.42	1.92	2.36	2.78	3.20	3.70
60 min.	0.69	0.92	1.25	1.57	1.79	2.01	2.32
2 hrs.	0.43	0.54	0.77	0.90	1.12	1.25	1.40
3 hrs.	0.30	0.41	0.57	0.71	0.79	0.92	1.03
(6 hrs.)	--	(0.20)	(0.28)	(0.33)	(0.42)	(0.48)	(0.53)
6 hrs.	0.18	0.23	0.32	0.38	0.46	0.55	0.62
12 hrs.	0.10	0.14	0.19	0.23	0.27	0.31	0.36
(24 hrs.)	--	(0.058)	(0.083)	(0.11)	(0.13)	(0.15)	(0.18)
24 hrs.	0.057	0.072	0.11	0.13	0.16	0.18	0.20

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-32. Rainfall intensity in inches per hour for various duration and frequency at Olympia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.56	1.92	2.28	2.64	2.88	3.12	3.60
10 min.	1.26	1.44	1.74	2.04	2.22	2.40	2.76
15 min.	1.04	1.20	1.44	1.72	1.88	2.00	2.32
30 min.	0.72	0.84	1.00	1.20	1.30	1.40	1.60
60 min.	0.43	0.54	0.64	0.75	0.85	0.93	1.00
2 hrs.	0.34	0.40	0.49	0.56	0.69	0.75	0.88
3 hrs.	0.32	0.33	0.45	0.50	0.58	0.62	0.74
6 hrs.	0.25	0.32	0.40	0.46	0.48	0.50	0.64
12 hrs.	0.20	0.23	0.25	0.31	0.33	0.37	0.42
24 hrs.	0.12	0.13	0.16	0.17	0.18	0.20	0.25

**Table B-33. Rainfall intensity in inches per hour for various duration and frequency at Salem.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.51	1.96	2.52	3.12	3.60	4.08	4.56
10 min.	1.15	1.50	1.92	2.40	2.76	3.12	3.54
15 min.	0.95	1.27	1.60	2.00	2.32	2.64	3.00
30 min.	0.74	0.96	1.12	1.40	1.60	1.82	2.08
60 min.	0.42	0.55	0.72	0.88	1.02	1.18	1.28
2 hrs.	0.30	0.45	0.50	0.67	0.75	0.85	0.93
3 hrs.	0.31	0.37	0.47	0.60	0.64	0.77	0.81
(6 hrs.)	--	(0.19)	(0.23)	(0.27)	(0.30)	(0.33)	(0.37)
6 hrs.	0.23	0.31	0.43	0.46	0.50	0.62	0.66
12 hrs.	0.16	0.22	0.24	0.31	0.33	0.40	0.41
(24 hrs.)	--	(0.11)	(0.13)	(0.15)	(0.16)	(0.18)	(0.19)
24 hrs.	0.11	0.12	0.16	0.22	0.23	0.24	0.25

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table B-34. Rainfall intensity in inches per hour for various duration and frequency at Sacramento.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	1.80	2.28	2.76	3.24	3.60	4.08	4.56
10 min.	1.38	1.80	2.10	2.52	2.82	3.18	3.54
15 min.	1.16	1.48	1.76	2.12	2.36	2.68	2.96
30 min.	0.80	1.04	1.22	1.46	1.64	1.86	2.06
60 min.	0.49	0.60	0.73	0.92	1.05	1.21	1.29
2 hrs.	0.35	0.40	0.50	0.63	0.70	0.74	0.88
3 hrs.	0.27	0.33	0.42	0.50	0.58	0.63	0.67
(6 hrs.)	--	(0.19)	(0.25)	(0.28)	(0.33)	(0.38)	(0.42)
6 hrs.	0.22	0.25	0.32	0.38	0.43	0.50	0.52
12 hrs.	0.14	0.17	0.21	0.25	0.29	0.32	0.33
(24 hrs.)	--	(0.082)	(0.10)	(0.12)	(0.14)	(0.16)	(0.18)
24 hrs.	0.094	0.11	0.14	0.16	0.17	0.21	0.23

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).





## Appendix C

### Relationships Between Various-Duration Rainfall Intensities and 60-Minute Intensity for the Same Frequency in 23 Major Cities and 11 Western State Capitals

The 23 major cities and 11 western state capitals selected for this study are:

<u>Table No.</u>	<u>City, State Name</u>	<u>Location</u>
C-1	New York, New York	40.4°N., 74.0°W.
C-2	Los Angeles, California	34.1°N., 118.3°W.
C-3	Chicago, Illinois	41.8°N., 87.7°W.
C-4	Detroit, Michigan	42.4°N., 83.1°W.
C-5	Philadelphia, Pennsylvania	35.9°N., 75.2°W.
C-6	San Francisco, California	37.8°N., 122.5°W.
C-7	Boston, Massachusetts	42.3°N., 71.1°W.
C-8	Washington, D.C.	38.5°N., 77.0°W.
C-9	Cleveland, Ohio	41.5°N., 81.7°W.
C-10	St. Louis, Missouri	40.0°N., 89.6°W.
C-11	Pittsburg, Pennsylvania	40.5°N., 80.0°W.
C-12	Baltimore, Maryland	39.2°N., 76.4°W.
C-13	Minneapolis, Minnesota	45.0°N., 93.2°W.
C-14	Miami, Florida	25.7°N., 80.2°W.
C-15	Houston, Texas	29.5°N., 95.2°W.
C-16	Buffalo, New York	42.5°N., 78.5°W.
C-17	Cincinnati, Ohio	39.1°N., 34.3°W.
C-18	Milwaukee, Wisconsin	43.0°N., 87.5°W.
C-19	San Diego, California	32.4°N., 117.1°W.
C-20	Dallas, Texas	32.4°N., 96.5°W.
C-21	Atlanta, Georgia	33.5°N., 84.2°W.
C-22	Kansas City, Missouri	39.0°N., 94.4°W.
C-23	Seattle, Washington	47.6°N., 122.3°W.
C-24	Helena, Montana	46.7°N., 112.0°W.
C-25	Cheyenne, Wyoming	41.2°N., 104.8°W.
C-26	Denver, Colorado	39.8°N., 105.0°W.
C-27	Santa Fe, New Mexico	35.5°N., 105.9°W.
C-28	Boise, Idaho	43.6°N., 116.3°W.
C-29	Salt Lake City, Utah	40.8°N., 111.9°W.
C-30	Carson City, Nevada	39.1°N., 119.8°W.
C-31	Phoenix, Arizona	33.4°N., 112.1°W.
C-32	Olympia, Washington	47.1°N., 122.9°W.
C-33	Salem, Oregon	44.9°N., 123.0°W.
C-34	Sacramento, California	38.5°N., 121.6°W.

Data are obtained or calculated from U.S. Weather Bureau Technical Paper No. 40 (1961) except for those in parenthesis which are obtained or calculated from NOAA Atlas 2 (Miller, Frederick, and Tracey, 1973).

**Table C-1. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at New York.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.32	3.52	3.48	3.52	3.44	3.50	3.43
10 min.	2.54	2.68	2.68	2.71	2.66	2.70	2.64
15 min.	2.15	2.27	2.26	2.27	2.24	2.27	2.23
30 min.	1.48	1.57	1.57	1.58	1.56	1.58	1.54
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.60	0.62	0.62	0.63	0.64	0.62	0.61
3 hrs.	0.44	0.46	0.46	0.45	0.46	0.46	0.46
6 hrs.	0.27	0.28	0.28	0.28	0.29	0.28	0.29
12 hrs.	0.16	0.17	0.17	0.17	0.17	0.17	0.17
24 hrs.	0.089	0.098	0.097	0.10	0.10	0.097	0.10

**Table C-2. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Los Angeles.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.51	3.38	3.59	3.53	3.56	3.53	3.43
10 min.	2.68	2.62	2.78	2.72	2.73	2.72	2.67
15 min.	2.22	2.15	2.35	2.29	2.29	2.28	2.24
30 min.	1.54	1.62	1.63	1.60	1.59	1.59	1.56
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.60	0.63	0.72	0.75	0.69	0.69	0.69
3 hrs.	0.49	0.55	0.65	0.61	0.60	0.57	0.58
(6 hrs.)	--	(0.36)	(0.38)	(0.36)	(0.34)	(0.34)	(0.34)
6 hrs.	0.37	0.42	0.49	0.48	0.47	0.44	0.48
12 hrs.	0.23	0.28	0.31	0.33	0.32	0.30	0.31
(24 hrs.)	--	(0.15)	(0.19)	(0.17)	(0.17)	(0.17)	(0.19)
24 hrs.	0.13	0.18	0.20	0.20	0.19	0.19	0.19

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-3. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Chicago.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.64	3.51	3.49	3.55	3.52	3.55	3.54
10 min.	2.85	2.73	2.67	2.75	2.71	2.73	2.72
15 min.	2.39	2.29	2.24	2.31	2.28	2.30	2.29
30 min.	1.66	1.59	1.56	1.61	1.58	1.60	1.59
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.61	0.59	0.58	0.61	0.59	0.60	0.60
3 hrs.	0.43	0.42	0.43	0.44	0.43	0.44	0.43
6 hrs.	0.25	0.24	0.25	0.26	0.26	0.26	0.26
12 hrs.	0.15	0.15	0.15	0.15	0.15	0.15	0.15
24 hrs.	0.082	0.082	0.082	0.089	0.085	0.089	0.088

**Table C-4. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Detroit.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.42	3.47	3.38	3.51	3.49	3.47	3.42
10 min.	2.63	2.72	2.67	2.72	2.66	2.66	2.65
15 min.	2.21	2.28	2.23	2.28	2.25	2.25	2.23
30 min.	1.54	1.58	1.55	1.58	1.56	1.56	1.55
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.60	0.59	0.57	0.60	0.59	0.59	0.59
3 hrs.	0.44	0.44	0.42	0.43	0.44	0.42	0.42
6 hrs.	0.26	0.24	0.24	0.25	0.25	0.25	0.25
12 hrs.	0.15	0.14	0.14	0.15	0.14	0.14	0.15
24 hrs.	0.089	0.086	0.081	0.083	0.081	0.081	0.081

**Table C-5. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Philadelphia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.41	3.45	3.52	3.47	3.58	3.61	3.64
10 min.	2.59	2.70	2.73	2.68	2.75	2.77	2.80
15 min.	2.19	2.25	2.30	2.26	2.31	2.34	2.36
30 min.	1.52	1.45	1.60	1.57	1.61	1.62	1.64
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.63	0.59	0.62	0.63	0.62	0.62	0.64
3 hrs.	0.46	0.43	0.48	0.48	0.48	0.48	0.49
6 hrs.	0.27	0.28	0.30	0.30	0.31	0.31	0.31
12 hrs.	0.18	0.17	0.18	0.19	0.18	0.18	0.18
24 hrs.	0.11	0.11	0.11	0.11	0.10	0.11	0.11

**Table C-6. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at San Francisco.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.42	3.74	3.70	3.64	3.48	3.65	3.70
10 min.	2.63	2.89	2.86	2.80	2.68	2.81	2.85
15 min.	2.22	2.43	2.40	2.35	2.26	2.36	2.40
30 min.	1.54	1.69	1.67	1.64	1.57	1.64	1.67
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.66	0.71	0.72	0.68	0.70	0.66	0.73
3 hrs.	0.54	0.60	0.61	0.55	0.58	0.55	0.60
(6 hrs.)	--	(0.31)	(0.28)	(0.26)	(0.26)	(0.26)	(0.27)
6 hrs.	0.46	0.46	0.47	0.42	0.43	0.41	0.43
12 hrs.	0.25	0.27	0.29	0.26	0.25	0.27	0.28
(24 hrs.)	--	(0.14)	(0.13)	(0.13)	(0.12)	(0.12)	(0.13)
24 hrs.	0.15	0.19	0.19	0.18	0.18	0.17	0.17

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-7. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Boston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.52	3.52	3.61	3.59	3.53	3.44	3.58
10 min.	2.74	2.75	2.75	2.71	2.74	2.67	2.77
15 min.	2.30	2.31	2.33	2.31	2.31	2.24	2.33
30 min.	1.59	1.60	1.62	1.58	1.60	1.56	1.62
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.64	0.67	0.64	0.66	0.66	0.64	0.67
3 hrs.	0.49	0.52	0.51	0.48	0.49	0.48	0.49
6 hrs.	0.30	0.32	0.32	0.31	0.30	0.30	0.31
12 hrs.	0.20	0.19	0.19	0.18	0.19	0.18	0.19
24 hrs.	0.12	0.11	0.11	0.11	0.11	0.11	0.11

**Table C-8. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Washington, D. C.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.44	3.53	3.50	3.45	3.51	3.53	3.54
10 min.	2.64	2.70	2.69	2.66	2.71	2.71	2.73
15 min.	2.27	2.27	2.28	2.24	2.27	2.29	2.30
30 min.	1.57	1.58	1.58	1.55	1.58	1.59	1.60
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.58	0.57	0.58	0.59	0.58	0.59	0.59
3 hrs.	0.43	0.39	0.41	0.42	0.42	0.44	0.42
6 hrs.	0.24	0.24	0.24	0.25	0.24	0.25	0.26
12 hrs.	0.14	0.14	0.14	0.15	0.15	0.14	0.15
24 hrs.	0.077	0.077	0.081	0.083	0.081	0.081	0.085

**Table C-9. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Cleveland.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.52	3.64	3.49	3.53	3.49	3.56	3.51
10 min.	2.67	2.79	2.68	2.72	2.69	2.75	2.69
15 min.	2.26	2.36	2.27	2.28	2.27	2.31	2.27
30 min.	1.57	1.64	1.57	1.59	1.57	1.60	1.58
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.60	0.60	0.57	0.61	0.59	0.61	0.59
3 hrs.	0.46	0.44	0.41	0.43	0.42	0.44	0.44
6 hrs.	0.26	0.25	0.24	0.25	0.24	0.25	0.25
12 hrs.	0.15	0.15	0.15	0.15	0.14	0.14	0.14
24 hrs.	0.082	0.089	0.081	0.082	0.082	0.083	0.083

**Table C-10. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at St. Louis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.57	3.58	3.52	3.54	3.52	3.49	3.45
10 min.	2.75	2.73	2.73	2.74	2.70	2.71	2.67
15 min.	2.32	2.31	2.28	2.30	2.27	2.27	2.25
30 min.	1.62	1.60	1.59	1.60	1.57	1.58	1.56
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.61	0.60	0.60	0.60	0.60	0.61	0.60
3 hrs.	0.44	0.44	0.45	0.45	0.44	0.44	0.43
6 hrs.	0.26	0.27	0.27	0.26	0.27	0.26	0.26
12 hrs.	0.15	0.16	0.16	0.16	0.15	0.15	0.16
24 hrs.	0.084	0.091	0.089	0.088	0.088	0.087	0.088

**Table C-11. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Pittsburg.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.55	3.49	3.49	3.55	3.49	3.51	3.52
10 min.	2.69	2.72	2.66	2.72	2.71	2.69	2.72
15 min.	2.29	2.29	2.25	2.28	2.29	2.27	2.30
30 min.	1.59	1.58	1.56	1.58	1.58	1.58	1.59
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.61	0.62	0.59	0.63	0.59	0.61	0.61
3 hrs.	0.45	0.47	0.42	0.45	0.45	0.42	0.45
6 hrs.	0.29	0.28	0.25	0.26	0.27	0.25	0.26
12 hrs.	0.16	0.16	0.15	0.16	0.16	0.15	0.16
24 hrs.	0.096	0.094	0.089	0.089	0.090	0.085	0.086

**Table C-12. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Baltimore.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.39	3.45	3.52	3.40	3.57	3.58	3.46
10 min.	2.66	2.66	2.71	2.60	2.76	2.77	2.67
15 min.	2.23	2.23	2.29	2.20	2.32	2.33	2.25
30 min.	1.54	1.55	1.59	1.53	1.62	1.62	1.57
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.60	0.59	0.58	0.60	0.61	0.69	0.66
3 hrs.	0.44	0.43	0.42	0.43	0.44	0.46	0.44
6 hrs.	0.27	0.26	0.25	0.25	0.25	0.27	0.25
12 hrs.	0.15	0.15	0.14	0.15	0.15	0.15	0.15
24 hrs.	0.084	0.081	0.087	0.088	0.088	0.089	0.086

**Table C-13. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Minneapolis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.48	3.51	3.53	3.54	3.49	3.44	3.56
10 min.	2.66	2.70	2.73	2.71	2.69	2.67	2.74
15 min.	2.26	2.26	2.29	2.29	2.27	2.25	2.31
30 min.	1.57	1.57	1.59	1.59	1.58	1.56	1.60
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.59	0.59	0.58	0.59	0.56	0.58	0.59
3 hrs.	0.43	0.42	0.42	0.42	0.42	0.42	0.43
6 hrs.	0.24	0.24	0.24	0.25	0.24	0.25	0.25
12 hrs.	0.14	0.14	0.15	0.14	0.15	0.14	0.14
24 hrs.	0.086	0.079	0.083	0.081	0.083	0.081	0.083

**Table C-14. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Miami.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.50	3.60	3.49	3.45	3.45	3.47	3.50
10 min.	2.69	2.77	2.70	2.66	2.66	2.68	2.71
15 min.	2.26	2.32	2.36	2.25	2.24	2.25	2.28
30 min.	1.57	1.62	1.58	1.56	1.56	1.56	1.58
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.58	0.62	0.63	0.63	0.63	0.64	0.66
3 hrs.	0.42	0.45	0.46	0.48	0.47	0.49	0.50
6 hrs.	0.25	0.27	0.28	0.29	0.30	0.31	0.32
12 hrs.	0.14	0.16	0.17	0.18	0.18	0.18	0.19
24 hrs.	0.10	0.11	0.10	0.11	0.11	0.11	0.11

**Table C-15. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Houston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.45	3.49	3.47	3.42	3.52	3.44	3.50
10 min.	2.67	2.68	2.72	2.65	2.70	2.65	2.70
15 min.	2.26	2.26	2.29	2.22	2.27	2.23	2.27
30 min.	1.56	1.57	1.60	1.55	1.58	1.55	1.58
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.59	0.64	0.64	0.64	0.65	0.67	0.66
3 hrs.	0.43	0.44	0.46	0.45	0.45	0.44	0.46
6 hrs.	0.25	0.27	0.26	0.25	0.26	0.25	0.26
12 hrs.	0.14	0.16	0.17	0.18	0.18	0.18	0.18
24 hrs.	0.082	0.093	0.092	0.092	0.097	0.096	0.099

**Table C-16. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Buffalo.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.55	3.50	3.51	3.56	3.51	3.62	3.58
10 min.	2.73	2.71	2.74	2.74	2.71	2.76	2.76
15 min.	2.27	2.30	2.31	2.32	2.28	2.33	2.33
30 min.	1.59	1.60	1.60	1.60	1.59	1.62	1.62
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.61	0.57	0.59	0.60	0.60	0.62	0.61
3 hrs.	0.45	0.42	0.43	0.45	0.45	0.45	0.46
6 hrs.	0.28	0.25	0.27	0.27	0.27	0.27	0.27
12 hrs.	0.16	0.16	0.16	0.16	0.16	0.16	0.16
24 hrs.	0.10	0.088	0.093	0.093	0.096	0.096	0.092

**Table C-17. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Cincinnati.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.57	3.60	3.50	3.49	3.54	3.50	3.56
10 min.	2.70	2.75	2.71	2.68	2.71	2.67	2.73
15 min.	2.27	2.32	2.29	2.29	2.29	2.26	2.30
30 min.	1.59	1.61	1.58	1.58	1.59	1.57	1.60
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.64	0.61	0.61	0.61	0.60	0.60	0.61
3 hrs.	0.45	0.44	0.43	0.43	0.45	0.43	0.44
6 hrs.	0.27	0.26	0.26	0.26	0.26	0.26	0.25
12 hrs.	0.16	0.16	0.15	0.15	0.15	0.15	0.15
24 hrs.	0.088	0.090	0.089	0.087	0.089	0.084	0.084

**Table C-18. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Milwaukee.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.50	3.51	3.49	3.50	3.48	3.55	3.47
10 min.	2.65	2.70	2.69	2.72	2.66	2.73	2.69
15 min.	2.23	2.26	2.26	2.27	2.24	2.30	2.27
30 min.	1.56	1.57	1.57	1.58	1.56	1.60	1.57
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.59	0.59	0.59	0.61	0.59	0.60	0.59
3 hrs.	0.43	0.41	0.42	0.43	0.43	0.43	0.43
6 hrs.	0.24	0.24	0.24	0.26	0.25	0.26	0.25
12 hrs.	0.13	0.14	0.15	0.15	0.15	0.15	0.15
24 hrs.	0.081	0.079	0.081	0.083	0.086	0.088	0.085



**Table C-19. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at San Diego.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.62	3.64	3.61	3.64	3.66	3.62	3.66
10 min.	2.84	2.79	2.78	2.79	2.80	2.78	2.82
15 min.	2.32	2.36	2.35	2.34	2.37	2.32	2.38
30 min.	1.63	1.62	1.62	1.62	1.64	1.62	1.66
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.66	0.59	0.59	0.64	0.63	0.61	0.62
3 hrs.	0.50	0.45	0.46	0.47	0.46	0.46	0.48
6 hrs.	0.32	0.30	0.31	0.31	0.31	0.32	0.33
12 hrs.	0.20	0.20	0.19	0.17	0.19	0.18	0.19
24 hrs.	0.11	0.13	0.10	0.11	0.11	0.11	0.11

**Table C-20. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Dallas.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.58	3.59	3.56	3.59	3.53	3.57	3.52
10 min.	2.76	2.75	2.72	2.78	2.73	2.74	2.71
15 min.	2.34	2.33	2.29	2.33	2.30	2.32	2.28
30 min.	1.61	1.62	1.59	1.62	1.62	1.61	1.58
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.58	0.60	0.60	0.62	0.62	0.61	0.61
3 hrs.	0.42	0.44	0.43	0.45	0.45	0.45	0.45
6 hrs.	0.25	0.26	0.26	0.27	0.27	0.27	0.28
12 hrs.	0.14	0.15	0.15	0.16	0.16	0.16	0.17
24 hrs.	0.087	0.088	0.088	0.095	0.093	0.096	0.095

**Table C-21. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Atlanta.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.51	3.55	3.52	3.47	3.47	3.50	3.47
10 min.	2.71	2.74	2.69	2.67	2.69	2.71	2.67
15 min.	2.27	2.30	2.28	2.25	2.26	2.28	2.24
30 min.	1.57	1.60	1.58	1.57	1.57	1.58	1.56
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.60	0.61	0.60	0.62	0.64	0.61	0.63
3 hrs.	0.43	0.44	0.44	0.44	0.45	0.45	0.46
6 hrs.	0.24	0.26	0.27	0.27	0.27	0.28	0.27
12 hrs.	0.15	0.15	0.16	0.16	0.16	0.17	0.16
24 hrs.	0.085	0.086	0.091	0.091	0.095	0.10	0.094

**Table C-22. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Kansas City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.54	3.55	3.52	3.48	3.53	3.50	3.55
10 min.	2.70	2.73	2.72	2.71	2.71	2.71	2.72
15 min.	2.28	2.30	2.29	2.27	2.29	2.28	2.29
30 min.	1.58	1.59	1.60	1.58	1.59	1.58	1.59
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.58	0.62	0.60	0.60	0.60	0.60	0.60
3 hrs.	0.42	0.44	0.44	0.44	0.44	0.44	0.44
6 hrs.	0.25	0.26	0.26	0.26	0.25	0.26	0.27
12 hrs.	0.14	0.15	0.15	0.16	0.15	0.16	0.16
24 hrs.	0.081	0.089	0.087	0.086	0.089	0.089	0.091

**Table C-23. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Seattle.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.67	3.71	3.69	3.80	3.60	3.11	3.43
10 min.	2.83	3.00	2.77	2.90	2.74	2.40	2.63
15 min.	2.44	2.48	2.31	2.47	2.29	2.02	2.20
30 min.	1.67	1.71	1.62	1.70	1.60	1.41	1.53
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.75	0.79	0.79	0.80	0.79	0.69	0.69
3 hrs.	0.69	0.67	0.73	0.70	0.69	0.62	0.61
6 hrs.	0.50	0.55	0.54	0.55	0.54	0.49	0.48
12 hrs.	0.36	0.36	0.40	0.38	0.36	0.33	0.33
24 hrs.	0.20	0.21	0.23	0.23	0.23	0.21	0.19

**Table C-24. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Helena.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.43	3.20	3.33	3.53	3.13	3.32	3.68
10 min.	2.71	2.50	2.60	2.71	2.54	2.55	2.82
15 min.	2.29	2.13	2.17	2.27	2.15	2.16	2.38
30 min.	1.57	1.47	1.52	1.57	1.50	1.49	1.66
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.64	0.60	0.63	0.62	0.61	0.62	0.59
3 hrs.	0.50	0.45	0.45	0.44	0.43	0.43	0.47
(6 hrs.)	--	(0.20)	(0.19)	(0.18)	(0.19)	(0.18)	(0.18)
6 hrs.	0.31	0.30	0.28	0.26	0.26	0.26	0.27
12 hrs.	0.21	0.18	0.16	0.16	0.15	0.16	0.16
(24 hrs.)	--	(0.090)	(0.084)	(0.078)	(0.080)	(0.078)	(0.078)
24 hrs.	0.12	0.11	0.094	0.093	0.089	0.092	0.092

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-25. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Cheyenne.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.82	3.47	3.52	3.31	3.48	3.45	3.50
10 min.	2.91	2.67	2.71	2.54	2.69	2.66	2.69
15 min.	2.48	2.22	2.29	2.13	2.25	2.24	2.26
30 min.	1.73	1.56	1.59	1.47	1.55	1.56	1.57
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.59	0.56	0.56	0.53	0.56	0.56	0.57
3 hrs.	0.44	0.41	0.40	0.38	0.40	0.40	0.40
(6 hrs.)	--	(0.22)	(0.21)	(0.20)	(0.22)	(0.21)	(0.20)
6 hrs.	0.26	0.23	0.23	0.22	0.23	0.23	0.24
12 hrs.	0.15	0.13	0.13	0.13	0.13	0.13	0.14
(24 hrs.)	--	(0.073)	(0.066)	(0.063)	(0.066)	(0.063)	(0.061)
24 hrs.	0.082	0.076	0.075	0.071	0.071	0.073	0.074

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-26. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Denver.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.29	3.37	3.40	3.46	3.56	3.69	3.50
10 min.	2.51	2.63	2.60	2.70	2.72	2.84	2.66
15 min.	2.06	2.20	2.20	2.26	2.30	2.40	2.26
30 min.	1.45	1.54	1.52	1.57	1.59	1.67	1.57
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.58	0.61	0.58	0.54	0.66	0.59	0.58
3 hrs.	0.44	0.43	0.40	0.40	0.41	0.42	0.41
(6 hrs.)	--	(0.29)	(0.28)	(0.25)	(0.28)	(0.27)	(0.26)
6 hrs.	0.27	0.27	0.23	0.23	0.25	0.24	0.24
12 hrs.	0.15	0.16	0.13	0.13	0.13	0.14	0.14
(24 hrs.)	--	(0.11)	(0.092)	(0.087)	(0.093)	(0.094)	(0.094)
24 hrs.	0.089	0.085	0.078	0.081	0.076	0.078	0.076

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-27. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Santa Fe.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.16	3.30	3.36	3.22	3.38	3.47	3.51
10 min.	2.42	2.55	2.58	2.48	2.59	2.67	2.70
15 min.	2.04	2.10	2.17	2.09	2.18	2.24	2.28
30 min.	1.40	1.48	1.51	1.45	1.51	1.56	1.59
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.56	0.56	0.62	0.54	0.59	0.57	0.62
3 hrs.	0.42	0.43	0.46	0.42	0.43	0.43	0.43
(6 hrs.)	--	(0.25)	(0.25)	(0.22)	(0.21)	(0.23)	(0.22)
6 hrs.	0.26	0.26	0.25	0.24	0.25	0.25	0.26
12 hrs.	0.15	0.15	0.15	0.14	0.14	0.14	0.15
(24 hrs.)	--	(0.084)	(0.078)	(0.070)	(0.069)	(0.072)	(0.071)
24 hrs.	0.093	0.081	0.087	0.080	0.081	0.083	0.086

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-28. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Boise.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.77	3.23	4.17	3.52	3.53	3.30	3.76
10 min.	2.74	2.55	3.26	2.69	2.24	2.55	2.89
15 min.	2.33	2.06	2.69	2.21	2.35	2.15	2.41
30 min.	1.67	1.46	1.87	1.55	1.62	1.50	1.69
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.67	0.64	0.67	0.64	0.62	0.56	0.60
3 hrs.	0.58	0.52	0.54	0.47	0.49	0.48	0.55
(6 hrs.)	--	(0.39)	(0.35)	(0.34)	(0.34)	(0.31)	(0.35)
6 hrs.	0.54	0.42	0.39	0.36	0.37	0.33	0.37
12 hrs.	0.31	0.25	0.26	0.24	0.22	0.21	0.23
(24 hrs.)	--	(0.15)	(0.14)	(0.14)	(0.14)	(0.14)	(0.14)
24 hrs.	0.20	0.19	0.15	0.14	0.13	0.13	0.13

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-29. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Salt Lake City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.24	3.70	3.62	3.54	3.52	3.63	3.50
10 min.	2.55	2.71	2.76	2.69	2.74	2.75	2.70
15 min.	2.06	2.29	2.35	2.31	2.30	2.31	2.27
30 min.	1.45	1.62	1.62	1.59	1.59	1.61	1.58
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.67	0.74	0.65	0.67	0.64	0.72	0.66
3 hrs.	0.61	0.60	0.54	0.47	0.46	0.48	0.45
(6 hrs.)	--	(0.38)	(0.32)	(0.29)	(0.33)	(0.30)	(0.29)
6 hrs.	0.39	0.38	0.32	0.33	0.37	0.34	0.35
12 hrs.	0.25	0.26	0.24	0.22	0.23	0.21	0.21
(24 hrs.)	--	(0.14)	(0.12)	(0.12)	(0.12)	(0.11)	(0.11)
24 hrs.	0.16	0.15	0.13	0.13	0.12	0.12	0.13

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-30. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Carson City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.73	3.90	3.80	3.47	3.85	3.72	3.43
10 min.	2.80	3.00	2.90	2.68	2.96	2.88	2.67
15 min.	2.40	2.50	2.40	2.26	2.47	2.44	2.25
30 min.	1.67	1.75	1.67	1.58	1.73	1.70	1.56
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.70	0.75	0.67	0.66	0.80	0.69	0.63
3 hrs.	0.63	0.65	0.55	0.54	0.59	0.53	0.50
(6 hrs.)	--	(0.50)	(0.39)	(0.37)	(0.36)	(0.40)	(0.38)
6 hrs.	0.43	0.43	0.38	0.38	0.41	0.41	0.36
12 hrs.	0.31	0.28	0.27	0.26	0.26	0.24	0.21
(24 hrs.)	--	(0.22)	(0.16)	(0.14)	(0.16)	(0.15)	(0.15)
24 hrs.	0.18	0.17	0.16	0.14	0.15	0.13	0.13

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-31. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Phoenix.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.65	3.39	3.46	3.36	3.42	3.52	3.52
10 min.	2.78	2.67	2.64	2.56	2.65	2.72	2.72
15 min.	2.32	2.22	2.21	2.17	2.23	2.29	2.29
30 min.	1.62	1.54	1.54	1.50	1.55	1.59	1.59
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.62	0.59	0.62	0.57	0.63	0.62	0.60
3 hrs.	0.43	0.45	0.46	0.45	0.44	0.46	0.44
(6 hrs.)	--	(0.22)	(0.22)	(0.21)	(0.23)	(0.24)	(0.23)
6 hrs.	0.26	0.25	0.26	0.24	0.26	0.27	0.27
12 hrs.	0.14	0.15	0.15	0.15	0.15	0.15	0.16
(24 hrs.)	--	(0.063)	(0.067)	(0.070)	(0.073)	(0.075)	(0.078)
24 hrs.	0.083	0.078	0.088	0.083	0.089	0.089	0.086

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-32. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Olympia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.63	3.56	3.56	3.52	3.39	3.35	3.60
10 min.	2.93	2.67	2.72	2.72	2.61	2.58	2.75
15 min.	2.42	2.22	2.25	2.29	2.21	2.15	2.32
30 min.	1.67	1.56	1.56	1.60	1.53	1.51	1.60
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.79	0.74	0.77	0.75	0.81	0.81	0.88
3 hrs.	0.74	0.61	0.70	0.67	0.68	0.67	0.74
6 hrs.	0.58	0.59	0.63	0.61	0.56	0.54	0.64
12 hrs.	0.47	0.43	0.39	0.41	0.39	0.40	0.42
24 hrs.	0.28	0.24	0.25	0.23	0.27	0.26	0.25

**Table C-33. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Salem.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.60	3.57	3.50	3.55	3.53	3.46	3.56
10 min.	2.73	2.70	2.67	2.73	2.71	2.64	2.77
15 min.	2.25	2.30	2.22	2.27	2.27	2.24	2.34
30 min.	1.76	1.75	1.56	1.59	1.57	1.54	1.63
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.72	0.81	0.70	0.76	0.74	0.72	0.73
3 hrs.	0.74	0.67	0.65	0.68	0.63	0.65	0.63
(6 hrs.)	--	(0.35)	(0.32)	(0.31)	(0.29)	(0.28)	(0.29)
6 hrs.	0.55	0.56	0.60	0.52	0.49	0.53	0.52
12 hrs.	0.38	0.40	0.33	0.35	0.32	0.34	0.32
(24 hrs.)	--	(0.20)	(0.18)	(0.17)	(0.16)	(0.15)	(0.15)
24 hrs.	0.26	0.22	0.22	0.25	0.23	0.20	0.20

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table C-34. Ratios of various-duration rainfall intensities to 60-minute intensity for the same frequency at Sacramento.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	3.67	3.79	3.78	3.52	3.43	3.37	3.53
10 min.	2.82	3.00	2.88	2.74	2.69	2.63	2.74
15 min.	2.37	2.47	2.41	2.30	2.25	2.21	2.29
30 min.	1.63	1.73	1.67	1.59	1.56	1.54	1.60
60 min.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2 hrs.	0.71	0.67	0.68	0.68	0.67	0.61	0.68
3 hrs.	0.55	0.55	0.58	0.54	0.55	0.52	0.52
(6 hrs.)	--	(0.32)	(0.34)	(0.38)	(0.31)	(0.31)	(0.33)
6 hrs.	0.45	0.42	0.44	0.41	0.41	0.41	0.40
12 hrs.	0.29	0.28	0.29	0.27	0.28	0.26	0.26
(24 hrs.)	--	(0.14)	(0.14)	(0.16)	(0.15)	(0.13)	(0.14)
24 hrs.	0.19	0.18	0.19	0.17	0.16	0.17	0.18

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).



## Appendix D

### Relationships Between Various-Frequency Rainfall Intensities and 10-Year Intensity for the Same Duration in 23 Major Cities and 11 Western State Capitals

The 23 major cities and 11 western state capitals selected for this study are:

<u>Table No.</u>	<u>City, State Name</u>	<u>Location</u>
D-1	New York, New York	40.4 <sup>o</sup> N., 74.0 <sup>o</sup> W.
D-2	Los Angeles, California	34.1 <sup>o</sup> N., 118.3 <sup>o</sup> W.
D-3	Chicago, Illinois	41.8 <sup>o</sup> N., 87.7 <sup>o</sup> W.
D-4	Detroit, Michigan	42.4 <sup>o</sup> N., 83.1 <sup>o</sup> W.
D-5	Philadelphia, Pennsylvania	35.9 <sup>o</sup> N., 75.2 <sup>o</sup> W.
D-6	San Francisco, California	37.8 <sup>o</sup> N., 122.5 <sup>o</sup> W.
D-7	Boston, Massachusetts	42.3 <sup>o</sup> N., 71.1 <sup>o</sup> W.
D-8	Washington, D.C.	38.5 <sup>o</sup> N., 77.0 <sup>o</sup> W.
D-9	Cleveland, Ohio	41.5 <sup>o</sup> N., 81.7 <sup>o</sup> W.
D-10	St. Louis, Missouri	40.0 <sup>o</sup> N., 89.6 <sup>o</sup> W.
D-11	Pittsburg, Pennsylvania	40.5 <sup>o</sup> N., 80.0 <sup>o</sup> W.
D-12	Baltimore, Maryland	39.2 <sup>o</sup> N., 76.4 <sup>o</sup> W.
D-13	Minneapolis, Minnesota	45.0 <sup>o</sup> N., 93.2 <sup>o</sup> W.
D-14	Miami, Florida	25.7 <sup>o</sup> N., 80.2 <sup>o</sup> W.
D-15	Houston, Texas	29.5 <sup>o</sup> N., 95.2 <sup>o</sup> W.
D-16	Buffalo, New York	42.5 <sup>o</sup> N., 78.5 <sup>o</sup> W.
D-17	Cincinnati, Ohio	39.1 <sup>o</sup> N., 34.3 <sup>o</sup> W.
D-18	Milwaukee, Wisconsin	43.0 <sup>o</sup> N., 87.5 <sup>o</sup> W.
D-19	San Diego, California	32.4 <sup>o</sup> N., 117.1 <sup>o</sup> W.
D-20	Dallas, Texas	32.4 <sup>o</sup> N., 96.5 <sup>o</sup> W.
D-21	Atlanta, Georgia	33.5 <sup>o</sup> N., 84.2 <sup>o</sup> W.
D-22	Kansas City, Missouri	39.0 <sup>o</sup> N., 94.4 <sup>o</sup> W.
D-23	Seattle, Washington	47.6 <sup>o</sup> N., 122.3 <sup>o</sup> W.
D-24	Helena, Montana	46.7 <sup>o</sup> N., 112.0 <sup>o</sup> W.
D-25	Cheyenne, Wyoming	41.2 <sup>o</sup> N., 104.8 <sup>o</sup> W.
D-26	Denver, Colorado	39.8 <sup>o</sup> N., 105.0 <sup>o</sup> W.
D-27	Santa Fe, New Mexico	35.5 <sup>o</sup> N., 105.9 <sup>o</sup> W.
D-28	Boise, Idaho	43.6 <sup>o</sup> N., 116.3 <sup>o</sup> W.
D-29	Salt Lake City, Utah	40.8 <sup>o</sup> N., 111.9 <sup>o</sup> W.
D-30	Carson City, Nevada	39.1 <sup>o</sup> N., 119.8 <sup>o</sup> W.
D-31	Phoenix, Arizona	33.4 <sup>o</sup> N., 112.1 <sup>o</sup> W.
D-32	Olympia, Washington	47.1 <sup>o</sup> N., 122.9 <sup>o</sup> W.
D-33	Salem, Oregon	44.9 <sup>o</sup> N., 123.0 <sup>o</sup> W.
D-34	Sacramento, California	38.5 <sup>o</sup> N., 121.6 <sup>o</sup> W.

Data are obtained or calculated from U.S. Weather Bureau Technical Paper No. 40 (1961) except for those in parenthesis which are obtained or calculated from NOAA Atlas 2 (Miller, Frederick, and Tracey, 1973).



**Table D-1. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at New York.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.67	0.86	1.00	1.13	1.29	1.41
10 min.	0.54	0.66	0.86	1.00	1.13	1.29	1.41
15 min.	0.54	0.66	0.86	1.00	1.14	1.30	1.42
30 min.	0.54	0.66	0.86	1.00	1.14	1.29	1.41
60 min.	0.57	0.67	0.87	1.00	1.15	1.29	1.45
2 hrs.	0.55	0.66	0.86	1.00	1.17	1.28	1.41
3 hrs.	0.56	0.68	0.89	1.00	1.18	1.32	1.49
6 hrs.	0.54	0.66	0.85	1.00	1.18	1.26	1.48
12 hrs.	0.56	0.67	0.86	1.00	1.17	1.28	1.47
24 hrs.	0.50	0.64	0.82	1.00	1.14	1.23	1.41

**Table D-2. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Los Angeles.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.63	0.83	1.00	1.23	1.43	1.54
10 min.	0.54	0.63	0.83	1.00	1.22	1.43	1.56
15 min.	0.53	0.62	0.84	1.00	1.22	1.43	1.56
30 min.	0.53	0.66	0.83	1.00	1.21	1.42	1.55
60 min.	0.55	0.66	0.82	1.00	1.22	1.43	1.59
2 hrs.	0.44	0.55	0.79	1.00	1.12	1.33	1.46
3 hrs.	0.44	0.59	0.86	1.00	1.19	1.33	1.51
(6 hrs.)	--	(0.65)	(0.86)	(1.00)	(1.16)	(1.35)	(1.49)
6 hrs.	0.42	0.58	0.84	1.00	1.19	1.32	1.58
12 hrs.	0.38	0.56	0.77	1.00	1.18	1.31	1.49
(24 hrs.)	--	(0.60)	(0.90)	(1.00)	(1.25)	(1.45)	(1.65)
24 hrs.	0.36	0.58	0.79	1.00	1.17	1.33	1.50

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-3. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Chicago.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.62	0.72	0.88	1.00	1.15	1.27	1.40
10 min.	0.62	0.72	0.87	1.00	1.14	1.26	1.39
15 min.	0.62	0.72	0.87	1.00	1.15	1.26	1.39
30 min.	0.62	0.72	0.87	1.00	1.14	1.26	1.39
60 min.	0.60	0.72	0.90	1.00	1.16	1.27	1.40
2 hrs.	0.61	0.70	0.85	1.00	1.13	1.24	1.38
3 hrs.	0.60	0.70	0.88	1.00	1.13	1.27	1.38
6 hrs.	0.60	0.69	0.88	1.00	1.15	1.29	1.40
12 hrs.	0.60	0.73	0.90	1.00	1.17	1.27	1.47
24 hrs.	0.55	0.67	0.83	1.00	1.11	1.28	1.39

**Table D-4. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Detroit.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.57	0.70	0.85	1.00	1.15	1.28	1.40
10 min.	0.56	0.71	0.87	1.00	1.13	1.27	1.40
15 min.	0.56	0.71	0.86	1.00	1.15	1.28	1.41
30 min.	0.57	0.71	0.87	1.00	1.15	1.28	1.41
60 min.	0.58	0.71	0.88	1.00	1.16	1.30	1.44
2 hrs.	0.58	0.69	0.83	1.00	1.13	1.27	1.40
3 hrs.	0.60	0.73	0.87	1.00	1.19	1.29	1.42
6 hrs.	0.59	0.67	0.85	1.00	1.13	1.26	1.39
12 hrs.	0.59	0.67	0.85	1.00	1.11	1.22	1.41
24 hrs.	0.62	0.73	0.87	1.00	1.13	1.27	1.40

**Table D-5. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Philadelphia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.71	0.88	1.00	1.20	1.36	1.53
10 min.	0.54	0.72	0.88	1.00	1.19	1.35	1.53
15 min.	0.54	0.66	0.88	1.00	1.19	1.35	1.53
30 min.	0.54	0.68	0.88	1.00	1.19	1.35	1.52
60 min.	0.55	0.71	0.86	1.00	1.16	1.31	1.46
2 hrs.	0.55	0.67	0.86	1.00	1.14	1.30	1.49
3 hrs.	0.54	0.64	0.86	1.00	1.18	1.32	1.50
6 hrs.	0.50	0.67	0.86	1.00	1.19	1.35	1.51
12 hrs.	0.54	0.65	0.85	1.00	1.12	1.29	1.42
24 hrs.	0.57	0.70	0.87	1.00	1.13	1.33	1.50

**Table D-6. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at San Francisco.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.56	0.66	0.83	1.00	1.09	1.28	1.39
10 min.	0.56	0.66	0.83	1.00	1.09	1.28	1.39
15 min.	0.56	0.66	0.83	1.00	1.09	1.28	1.39
30 min.	0.56	0.66	0.83	1.00	1.09	1.28	1.39
60 min.	0.59	0.64	0.82	1.00	1.14	1.27	1.36
2 hrs.	0.57	0.67	0.87	1.00	1.17	1.24	1.47
3 hrs.	0.58	0.70	0.92	1.00	1.22	1.28	1.50
(6 hrs.)	--	(0.76)	(0.86)	(1.00)	(1.14)	(1.24)	(1.38)
6 hrs.	0.65	0.70	0.91	1.00	1.17	1.26	1.41
12 hrs.	0.55	0.66	0.90	1.00	1.07	1.31	1.45
(24 hrs.)	--	(0.70)	(0.86)	(1.00)	(1.07)	(1.21)	(1.36)
24 hrs.	0.50	0.65	0.85	1.00	1.10	1.20	1.25

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-7. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Boston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.52	0.62	0.85	1.00	1.12	1.26	1.41
10 min.	0.54	0.64	0.86	1.00	1.15	1.29	1.45
15 min.	0.53	0.63	0.85	1.00	1.14	1.27	1.43
30 min.	0.53	0.64	0.86	1.00	1.15	1.29	1.45
60 min.	0.53	0.63	0.84	1.00	1.14	1.31	1.42
2 hrs.	0.52	0.64	0.82	1.00	1.14	1.27	1.43
3 hrs.	0.54	0.69	0.90	1.00	1.16	1.31	1.45
6 hrs.	0.52	0.65	0.85	1.00	1.11	1.24	1.41
12 hrs.	0.56	0.66	0.88	1.00	1.19	1.25	1.44
24 hrs.	0.58	0.63	0.84	1.00	1.11	1.26	1.42

**Table D-8. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Washington, D. C.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.70	0.86	1.00	1.18	1.34	1.55
10 min.	0.55	0.69	0.85	1.00	1.19	1.34	1.56
15 min.	0.55	0.69	0.86	1.00	1.18	1.34	1.55
30 min.	0.55	0.69	0.86	1.00	1.19	1.34	1.56
60 min.	0.54	0.68	0.84	1.00	1.17	1.31	1.52
2 hrs.	0.54	0.66	0.84	1.00	1.16	1.32	1.52
3 hrs.	0.54	0.63	0.81	1.00	1.15	1.36	1.51
6 hrs.	0.52	0.69	0.81	1.00	1.12	1.30	1.52
12 hrs.	0.51	0.64	0.82	1.00	1.15	1.28	1.54
24 hrs.	0.50	0.64	0.82	1.00	1.14	1.27	1.55

**Table D-9. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Cleveland.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.68	0.86	1.00	1.14	1.28	1.42
10 min.	0.53	0.68	0.86	1.00	1.14	1.29	1.42
15 min.	0.54	0.68	0.87	1.00	1.14	1.29	1.42
30 min.	0.53	0.68	0.86	1.00	1.14	1.28	1.42
60 min.	0.54	0.66	0.87	1.00	1.15	1.27	1.43
2 hrs.	0.53	0.65	0.82	1.00	1.12	1.28	1.39
3 hrs.	0.58	0.67	0.84	1.00	1.14	1.30	1.45
6 hrs.	0.56	0.65	0.84	1.00	1.12	1.26	1.40
12 hrs.	0.56	0.68	0.88	1.00	1.12	1.24	1.40
24 hrs.	0.54	0.71	0.86	1.00	1.14	1.29	1.43

**Table D-10. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at St. Louis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.61	0.72	0.88	1.00	1.14	1.25	1.38
10 min.	0.61	0.71	0.88	1.00	1.13	1.25	1.37
15 min.	0.61	0.71	0.87	1.00	1.13	1.25	1.38
30 min.	0.61	0.71	0.87	1.00	1.13	1.25	1.37
60 min.	0.60	0.71	0.88	1.00	1.15	1.27	1.41
2 hrs.	0.62	0.71	0.88	1.00	1.15	1.28	1.42
3 hrs.	0.59	0.69	0.87	1.00	1.11	1.23	1.35
6 hrs.	0.60	0.72	0.89	1.00	1.16	1.26	1.40
12 hrs.	0.59	0.71	0.88	1.00	1.12	1.24	1.41
24 hrs.	0.58	0.74	0.89	1.00	1.16	1.26	1.42

**Table D-11. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Pittsburg.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.55	0.64	0.87	1.00	1.15	1.30	1.42
10 min.	0.54	0.65	0.86	1.00	1.17	1.31	1.43
15 min.	0.55	0.66	0.87	1.00	1.18	1.31	1.44
30 min.	0.55	0.65	0.87	1.00	1.17	1.31	1.44
60 min.	0.55	0.65	0.88	1.00	1.17	1.32	1.43
2 hrs.	0.54	0.64	0.84	1.00	1.10	1.28	1.39
3 hrs.	0.54	0.68	0.83	1.00	1.16	1.23	1.41
6 hrs.	0.61	0.72	0.87	1.00	1.22	1.30	1.43
12 hrs.	0.57	0.68	0.86	1.00	1.18	1.25	1.43
24 hrs.	0.59	0.69	0.88	1.00	1.19	1.25	1.38

**Table D-12. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Baltimore.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.68	0.90	1.00	1.19	1.34	1.49
10 min.	0.56	0.68	0.90	1.00	1.20	1.36	1.50
15 min.	0.55	0.67	0.90	1.00	1.20	1.35	1.49
30 min.	0.55	0.68	0.90	1.00	1.20	1.35	1.50
60 min.	0.55	0.67	0.87	1.00	1.13	1.27	1.46
2 hrs.	0.54	0.65	0.83	1.00	1.15	1.45	1.60
3 hrs.	0.55	0.66	0.84	1.00	1.17	1.36	1.49
6 hrs.	0.57	0.67	0.84	1.00	1.13	1.33	1.43
12 hrs.	0.53	0.67	0.83	1.00	1.17	1.31	1.44
24 hrs.	0.52	0.62	0.86	1.00	1.14	1.29	1.43

**Table D-13. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Minneapolis.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.66	0.85	1.00	1.13	1.26	1.44
10 min.	0.54	0.66	0.86	1.00	1.14	1.27	1.44
15 min.	0.54	0.66	0.86	1.00	1.14	1.28	1.44
30 min.	0.54	0.66	0.86	1.00	1.14	1.27	1.44
60 min.	0.55	0.67	0.86	1.00	1.15	1.30	1.43
2 hrs.	0.55	0.67	0.85	1.00	1.10	1.28	1.43
3 hrs.	0.56	0.67	0.85	1.00	1.16	1.30	1.47
6 hrs.	0.54	0.65	0.85	1.00	1.12	1.31	1.42
12 hrs.	0.53	0.67	0.90	1.00	1.17	1.30	1.43
24 hrs.	0.58	0.65	0.88	1.00	1.18	1.29	1.47

**Table D-14. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Miami.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.64	0.74	0.89	1.00	1.12	1.24	1.36
10 min.	0.64	0.74	0.89	1.00	1.12	1.24	1.36
15 min.	0.63	0.74	0.92	1.00	1.12	1.23	1.36
30 min.	0.63	0.74	0.88	1.00	1.12	1.24	1.36
60 min.	0.63	0.71	0.88	1.00	1.12	1.23	1.34
2 hrs.	0.58	0.70	0.87	1.00	1.13	1.26	1.41
3 hrs.	0.55	0.67	0.83	1.00	1.10	1.27	1.39
6 hrs.	0.54	0.66	0.83	1.00	1.16	1.30	1.42
12 hrs.	0.52	0.64	0.84	1.00	1.17	1.30	1.42
24 hrs.	0.59	0.71	0.82	1.00	1.13	1.28	1.44

**Table D-15. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Houston.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.59	0.70	0.88	1.00	1.14	1.20	1.37
10 min.	0.60	0.71	0.89	1.00	1.15	1.21	1.39
15 min.	0.60	0.71	0.89	1.00	1.15	1.22	1.39
30 min.	0.60	0.71	0.89	1.00	1.15	1.22	1.39
60 min.	0.59	0.70	0.86	1.00	1.12	1.21	1.36
2 hrs.	0.58	0.70	0.86	1.00	1.13	1.27	1.40
3 hrs.	0.57	0.69	0.88	1.00	1.12	1.18	1.39
6 hrs.	0.51	0.64	0.89	1.00	1.16	1.21	1.41
12 hrs.	0.48	0.62	0.83	1.00	1.12	1.27	1.42
24 hrs.	0.55	0.71	0.87	1.00	1.19	1.29	1.48

**Table D-16. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Buffalo.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.54	0.69	0.85	1.00	1.15	1.31	1.42
10 min.	0.54	0.69	0.86	1.00	1.15	1.30	1.42
15 min.	0.53	0.69	0.86	1.00	1.14	1.30	1.41
30 min.	0.54	0.69	0.86	1.00	1.15	1.30	1.42
60 min.	0.54	0.70	0.86	1.00	1.16	1.29	1.41
2 hrs.	0.56	0.66	0.85	1.00	1.16	1.34	1.44
3 hrs.	0.55	0.66	0.82	1.00	1.15	1.29	1.42
6 hrs.	0.57	0.64	0.86	1.00	1.14	1.30	1.41
12 hrs.	0.54	0.69	0.88	1.00	1.15	1.30	1.42
24 hrs.	0.59	0.67	0.87	1.00	1.20	1.33	1.40

**Table D-17. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Cincinnati.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.58	0.70	0.86	1.00	1.16	1.28	1.42
10 min.	0.57	0.70	0.87	1.00	1.15	1.27	1.41
15 min.	0.56	0.69	0.86	1.00	1.14	1.26	1.40
30 min.	0.57	0.69	0.86	1.00	1.15	1.26	1.41
60 min.	0.57	0.68	0.86	1.00	1.14	1.28	1.39
2 hrs.	0.60	0.68	0.87	1.00	1.13	1.26	1.39
3 hrs.	0.59	0.69	0.86	1.00	1.18	1.27	1.40
6 hrs.	0.59	0.69	0.86	1.00	1.14	1.27	1.35
12 hrs.	0.60	0.70	0.87	1.00	1.13	1.23	1.40
24 hrs.	0.58	0.71	0.88	1.00	1.18	1.24	1.35

**Table D-18. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Milwaukee.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.63	0.73	0.89	1.00	1.14	1.27	1.39
10 min.	0.61	0.72	0.89	1.00	1.13	1.25	1.39
15 min.	0.61	0.72	0.89	1.00	1.14	1.27	1.40
30 min.	0.62	0.72	0.89	1.00	1.13	1.26	1.39
60 min.	0.63	0.73	0.90	1.00	1.15	1.25	1.41
2 hrs.	0.61	0.70	0.86	1.00	1.12	1.23	1.36
3 hrs.	0.63	0.70	0.88	1.00	1.14	1.25	1.41
6 hrs.	0.59	0.67	0.86	1.00	1.14	1.29	1.39
12 hrs.	0.57	0.71	0.89	1.00	1.17	1.29	1.43
24 hrs.	0.61	0.69	0.88	1.00	1.18	1.31	1.43

**Table D-19. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at San Diego.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.38	0.57	0.80	1.00	1.20	1.37	1.53
10 min.	0.39	0.57	0.80	1.00	1.20	1.37	1.54
15 min.	0.38	0.57	0.81	1.00	1.21	1.36	1.55
30 min.	0.39	0.57	0.81	1.00	1.21	1.38	1.56
60 min.	0.38	0.57	0.81	1.00	1.19	1.37	1.53
2 hrs.	0.40	0.52	0.75	1.00	1.17	1.32	1.48
3 hrs.	0.40	0.53	0.79	1.00	1.15	1.32	1.55
6 hrs.	0.39	0.55	0.81	1.00	1.19	1.42	1.61
12 hrs.	0.44	0.65	0.88	1.00	1.29	1.47	1.70
24 hrs.	0.38	0.65	0.75	1.00	1.18	1.36	1.45

**Table D-20. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Dallas.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.55	0.66	0.88	1.00	1.15	1.31	1.43
10 min.	0.54	0.65	0.87	1.00	1.15	1.30	1.43
15 min.	0.55	0.66	0.87	1.00	1.15	1.31	1.43
30 min.	0.55	0.66	0.87	1.00	1.17	1.31	1.43
60 min.	0.55	0.66	0.88	1.00	1.17	1.32	1.46
2 hrs.	0.52	0.64	0.85	1.00	1.17	1.31	1.45
3 hrs.	0.51	0.64	0.85	1.00	1.17	1.32	1.46
6 hrs.	0.52	0.65	0.86	1.00	1.19	1.34	1.51
12 hrs.	0.48	0.63	0.83	1.00	1.17	1.31	1.48
24 hrs.	0.50	0.61	0.82	1.00	1.14	1.32	1.46

**Table D-21. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Atlanta.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.63	0.72	0.89	1.00	1.12	1.25	1.37
10 min.	0.63	0.73	0.89	1.00	1.13	1.26	1.37
15 min.	0.63	0.72	0.89	1.00	1.12	1.26	1.36
30 min.	0.63	0.72	0.89	1.00	1.12	1.25	1.36
60 min.	0.62	0.71	0.88	1.00	1.12	1.24	1.37
2 hrs.	0.60	0.70	0.86	1.00	1.15	1.23	1.38
3 hrs.	0.61	0.69	0.88	1.00	1.14	1.26	1.40
6 hrs.	0.56	0.68	0.89	1.00	1.11	1.30	1.38
12 hrs.	0.59	0.68	0.88	1.00	1.17	1.34	1.41
24 hrs.	0.58	0.67	0.88	1.00	1.17	1.38	1.42

**Table D-22. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Kansas City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.59	0.68	0.86	1.00	1.16	1.28	1.45
10 min.	0.58	0.67	0.86	1.00	1.15	1.28	1.43
15 min.	0.59	0.67	0.86	1.00	1.15	1.28	1.43
30 min.	0.58	0.67	0.87	1.00	1.15	1.28	1.43
60 min.	0.58	0.66	0.85	1.00	1.15	1.28	1.42
2 hrs.	0.57	0.68	0.86	1.00	1.14	1.28	1.43
3 hrs.	0.56	0.66	0.86	1.00	1.14	1.28	1.42
6 hrs.	0.56	0.67	0.86	1.00	1.09	1.30	1.45
12 hrs.	0.53	0.65	0.83	1.00	1.13	1.28	1.43
24 hrs.	0.55	0.68	0.86	1.00	1.18	1.32	1.50

**Table D-23. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Seattle.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.58	0.68	0.84	1.00	1.11	1.16	1.47
10 min.	0.59	0.72	0.83	1.00	1.10	1.17	1.48
15 min.	0.59	0.70	0.81	1.00	1.08	1.16	1.46
30 min.	0.59	0.71	0.82	1.00	1.10	1.18	1.47
60 min.	0.60	0.70	0.87	1.00	1.17	1.42	1.63
2 hrs.	0.56	0.69	0.85	1.00	1.15	1.23	1.42
3 hrs.	0.60	0.67	0.90	1.00	1.14	1.26	1.43
6 hrs.	0.55	0.70	0.85	1.00	1.15	1.27	1.42
12 hrs.	0.57	0.65	0.91	1.00	1.09	1.22	1.39
24 hrs.	0.56	0.62	0.86	1.00	1.14	1.29	1.36

**Table D-24. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Helena.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.40	0.53	0.77	1.00	1.07	1.30	1.57
10 min.	0.41	0.54	0.78	1.00	1.13	1.30	1.57
15 min.	0.41	0.55	0.78	1.00	1.14	1.31	1.57
30 min.	0.41	0.55	0.79	1.00	1.15	1.31	1.59
60 min.	0.41	0.59	0.81	1.00	1.21	1.38	1.50
2 hrs.	0.43	0.57	0.83	1.00	1.19	1.35	1.43
3 hrs.	0.47	0.60	0.82	1.00	1.16	1.33	1.60
(6 hrs.)	--	(0.67)	(0.89)	(1.00)	(1.28)	(1.39)	(1.56)
6 hrs.	0.48	0.67	0.85	1.00	1.19	1.37	1.52
12 hrs.	0.55	0.69	0.81	1.00	1.19	1.38	1.50
(24 hrs.)	--	(0.68)	(0.88)	(1.00)	(1.24)	(1.38)	(1.50)
24 hrs.	0.52	0.68	0.82	1.00	1.16	1.37	1.47

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).



**Table D-25. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Cheyenne.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.49	0.60	0.86	1.00	1.23	1.37	1.56
10 min.	0.48	0.61	0.86	1.00	1.24	1.38	1.56
15 min.	0.49	0.60	0.87	1.00	1.24	1.39	1.57
30 min.	0.50	0.61	0.87	1.00	1.23	1.39	1.57
60 min.	0.42	0.58	0.81	1.00	1.17	1.31	1.47
2 hrs.	0.47	0.60	0.84	1.00	1.24	1.37	1.59
3 hrs.	0.48	0.62	0.83	1.00	1.22	1.38	1.53
(6 hrs.)	--	(0.65)	(0.84)	(1.00)	(1.29)	(1.39)	(1.52)
6 hrs.	0.49	0.60	0.83	1.00	1.23	1.34	1.57
12 hrs.	0.50	0.60	0.85	1.00	1.20	1.35	1.55
(24 hrs.)	--	(0.67)	(0.84)	(1.00)	(1.21)	(1.31)	(1.42)
24 hrs.	0.49	0.62	0.86	1.00	1.18	1.36	1.55

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-26. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Denver.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.40	0.53	0.79	1.00	1.19	1.37	1.51
10 min.	0.39	0.54	0.78	1.00	1.16	1.36	1.48
15 min.	0.38	0.54	0.79	1.00	1.19	1.37	1.50
30 min.	0.38	0.54	0.78	1.00	1.17	1.37	1.50
60 min.	0.42	0.55	0.81	1.00	1.15	1.29	1.50
2 hrs.	0.44	0.62	0.85	1.00	1.15	1.40	1.59
3 hrs.	0.45	0.58	0.80	1.00	1.17	1.33	1.53
(6 hrs.)	--	(0.65)	(0.89)	(1.00)	(1.30)	(1.43)	(1.59)
6 hrs.	0.49	0.63	0.80	1.00	1.23	1.31	1.51
12 hrs.	0.51	0.68	0.84	1.00	1.21	1.42	1.63
(24 hrs.)	--	(0.67)	(0.85)	(1.00)	(1.23)	(1.38)	(1.62)
24 hrs.	0.46	0.58	0.78	1.00	1.08	1.25	1.42

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-27. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Santa Fe.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.41	0.59	0.81	1.00	1.22	1.41	1.57
10 min.	0.40	0.60	0.81	1.00	1.21	1.40	1.56
15 min.	0.40	0.58	0.81	1.00	1.21	1.40	1.57
30 min.	0.40	0.59	0.81	1.00	1.21	1.40	1.57
60 min.	0.41	0.58	0.78	1.00	1.16	1.30	1.43
2 hrs.	0.43	0.60	0.88	1.00	1.27	1.37	1.64
3 hrs.	0.41	0.59	0.84	1.00	1.19	1.33	1.47
(6 hrs.)	--	(0.67)	(0.90)	(1.00)	(1.10)	(1.40)	(1.47)
6 hrs.	0.45	0.64	0.82	1.00	1.21	1.36	1.58
12 hrs.	0.46	0.63	0.84	1.00	1.21	1.37	1.53
(24 hrs.)	--	(0.70)	(0.86)	(1.00)	(1.15)	(1.35)	(1.46)
24 hrs.	0.48	0.59	0.85	1.00	1.18	1.36	1.55

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-28. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Boise.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.44	0.52	0.94	1.00	1.18	1.29	1.53
10 min.	0.42	0.54	0.96	1.00	1.19	1.31	1.54
15 min.	0.44	0.53	0.97	1.00	1.25	1.34	1.56
30 min.	0.44	0.53	0.95	1.00	1.22	1.33	1.55
60 min.	0.41	0.57	0.83	1.00	1.17	1.38	1.43
2 hrs.	0.43	0.57	0.84	1.00	1.14	1.22	1.35
3 hrs.	0.52	0.63	0.93	1.00	1.22	1.41	1.70
(6 hrs.)	--	(0.65)	(0.85)	(1.00)	(1.15)	(1.25)	(1.45)
6 hrs.	0.62	0.67	0.86	1.00	1.19	1.24	1.48
12 hrs.	0.54	0.59	0.86	1.00	1.07	1.21	1.36
(24 hrs.)	--	(0.62)	(0.85)	(1.00)	(1.20)	(1.39)	(1.52)
24 hrs.	0.57	0.76	0.86	1.00	1.10	1.20	1.33

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-29. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Salt Lake City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.39	0.57	0.83	1.00	1.17	1.43	1.52
10 min.	0.40	0.54	0.83	1.00	1.20	1.43	1.54
15 min.	0.38	0.53	0.82	1.00	1.18	1.40	1.51
30 min.	0.39	0.55	0.82	1.00	1.18	1.42	1.53
60 min.	0.42	0.54	0.81	1.00	1.18	1.40	1.54
2 hrs.	0.42	0.60	0.79	1.00	1.13	1.50	1.52
3 hrs.	0.54	0.66	0.92	1.00	1.14	1.41	1.46
(6 hrs.)	--	(0.70)	(0.87)	(1.00)	(1.30)	(1.43)	(1.52)
6 hrs.	0.50	0.62	0.77	1.00	1.31	1.42	1.62
12 hrs.	0.49	0.65	0.88	1.00	1.24	1.35	1.47
(24 hrs.)	--	(0.63)	(0.82)	(1.00)	(1.20)	(1.30)	(1.41)
24 hrs.	0.52	0.63	0.85	1.00	1.10	1.30	1.50

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-30. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Carson City.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.42	0.59	0.86	1.00	1.18	1.41	1.55
10 min.	0.41	0.59	0.85	1.00	1.18	1.41	1.56
15 min.	0.42	0.58	0.84	1.00	1.16	1.42	1.56
30 min.	0.42	0.58	0.83	1.00	1.17	1.42	1.55
60 min.	0.39	0.53	0.79	1.00	1.07	1.32	1.57
2 hrs.	0.42	0.60	0.80	1.00	1.30	1.38	1.50
3 hrs.	0.46	0.63	0.80	1.00	1.17	1.29	1.44
(6 hrs.)	--	(0.71)	(0.86)	(1.00)	(1.04)	(1.43)	(1.61)
6 hrs.	0.45	0.59	0.79	1.00	1.14	1.41	1.48
12 hrs.	0.46	0.55	0.80	1.00	1.05	1.20	1.25
(24 hrs.)	--	(0.79)	(0.89)	(1.00)	(1.18)	(1.36)	(1.64)
24 hrs.	0.50	0.62	0.85	1.00	1.09	1.18	1.36

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-31. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Phoenix.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.48	0.59	0.82	1.00	1.16	1.34	1.55
10 min.	0.48	0.62	0.82	1.00	1.18	1.36	1.57
15 min.	0.47	0.60	0.81	1.00	1.18	1.35	1.56
30 min.	0.47	0.60	0.81	1.00	1.18	1.36	1.57
60 min.	0.44	0.59	0.80	1.00	1.14	1.28	1.48
2 hrs.	0.48	0.60	0.86	1.00	1.24	1.39	1.56
3 hrs.	0.42	0.58	0.80	1.00	1.11	1.30	1.45
(6 hrs.)	--	(0.61)	(0.85)	(1.00)	(1.27)	(1.45)	(1.61)
6 hrs.	0.47	0.61	0.84	1.00	1.21	1.45	1.63
12 hrs.	0.43	0.61	0.83	1.00	1.17	1.35	1.57
(24 hrs.)	--	(0.53)	(0.75)	(1.00)	(1.18)	(1.36)	(1.64)
24 hrs.	0.44	0.55	0.85	1.00	1.23	1.38	1.54

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-32. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Olympia.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.59	0.73	0.86	1.00	1.09	1.18	1.36
10 min.	0.62	0.71	0.85	1.00	1.09	1.18	1.35
15 min.	0.60	0.70	0.84	1.00	1.09	1.16	1.35
30 min.	0.60	0.70	0.83	1.00	1.08	1.17	1.33
60 min.	0.57	0.72	0.85	1.00	1.13	1.24	1.33
2 hrs.	0.61	0.71	0.88	1.00	1.23	1.34	1.57
3 hrs.	0.64	0.66	0.90	1.00	1.16	1.24	1.48
6 hrs.	0.54	0.70	0.87	1.00	1.04	1.09	1.39
12 hrs.	0.65	0.74	0.81	1.00	1.06	1.19	1.35
24 hrs.	0.71	0.76	0.94	1.00	1.08	1.41	1.47

**Table D-33. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Salem.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.48	0.63	0.81	1.00	1.15	1.31	1.46
10 min.	0.48	0.63	0.80	1.00	1.15	1.30	1.48
15 min.	0.48	0.64	0.80	1.00	1.16	1.32	1.50
30 min.	0.53	0.68	0.80	1.00	1.14	1.30	1.49
60 min.	0.48	0.63	0.82	1.00	1.16	1.34	1.45
2 hrs.	0.45	0.67	0.75	1.00	1.12	1.27	1.39
3 hrs.	0.52	0.62	0.78	1.00	1.07	1.28	1.35
(6 hrs.)	--	(0.70)	(0.85)	(1.00)	(1.11)	(1.22)	(1.37)
6 hrs.	0.50	0.67	0.93	1.00	1.09	1.35	1.43
12 hrs.	0.52	0.71	0.77	1.00	1.07	1.29	1.33
(24 hrs.)	--	(0.73)	(0.87)	(1.00)	(1.07)	(1.20)	(1.27)
24 hrs.	0.50	0.55	0.73	1.00	1.05	1.10	1.15

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).

**Table D-34. Ratios of various-frequency rainfall intensities to 10-year intensity for the same duration at Sacramento.**

Duration	Return Period (Years)						
	1	2	5	10	25	50	100
5 min.	0.56	0.70	0.85	1.00	1.11	1.26	1.41
10 min.	0.55	0.71	0.83	1.00	1.12	1.26	1.40
15 min.	0.55	0.70	0.83	1.00	1.11	1.26	1.40
30 min.	0.55	0.71	0.84	1.00	1.12	1.27	1.41
60 min.	0.53	0.65	0.79	1.00	1.14	1.31	1.40
2 hrs.	0.56	0.63	0.79	1.00	1.11	1.17	1.40
3 hrs.	0.54	0.66	0.84	1.00	1.16	1.26	1.34
(6 hrs.)	--	(0.68)	(0.89)	(1.00)	(1.18)	(1.36)	(1.50)
6 hrs.	0.58	0.66	0.84	1.00	1.13	1.32	1.37
12 hrs.	0.56	0.68	0.84	1.00	1.16	1.28	1.32
(24 hrs.)	--	(0.68)	(0.83)	(1.00)	(1.17)	(1.33)	(1.50)
24 hrs.	0.59	0.69	0.88	1.00	1.06	1.31	1.44

Note: Numbers in parentheses are obtained from NOAA Atlas 2 (Miller et al., 1973).



## Appendix E

### Standard Rainstorm Parameters of 23 Major Cities in the United States and 11 Capitals of the Western States

The 23 major cities and 11 western state capitals selected for this study are:

<u>Table No.</u>	<u>City, State Name</u>	<u>Location</u>
E-1	New York, New York	40.4°N., 74.0°W.
E-2	Los Angeles, California	34.1°N., 118.3°W.
E-3	Chicago, Illinois	41.8°N., 87.7°W.
E-4	Detroit, Michigan	42.4°N., 83.1°W.
E-5	Philadelphia, Pennsylvania	35.9°N., 75.2°W.
E-6	San Francisco, California	37.8°N., 122.5°W.
E-7	Boston, Massachusetts	42.3°N., 71.1°W.
E-8	Washington, D.C.	38.5°N., 77.0°W.
E-9	Cleveland, Ohio	41.5°N., 81.7°W.
E-10	St. Louis, Missouri	40.0°N., 89.6°W.
E-11	Pittsburg, Pennsylvania	40.5°N., 80.0°W.
E-12	Baltimore, Maryland	39.2°N., 76.4°W.
E-13	Minneapolis, Minnesota	45.0°N., 93.2°W.
E-14	Miami, Florida	25.7°N., 80.2°W.
E-15	Houston, Texas	29.5°N., 95.2°W.
E-16	Buffalo, New York	42.5°N., 78.5°W.
E-17	Cincinnati, Ohio	39.1°N., 34.3°W.
E-18	Milwaukee, Wisconsin	43.0°N., 87.5°W.
E-19	San Diego, California	32.4°N., 117.1°W.
E-20	Dallas, Texas	32.4°N., 96.5°W.
E-21	Atlanta, Georgia	33.5°N., 84.2°W.
E-22	Kansas City, Missouri	39.0°N., 94.4°W.
E-23	Seattle, Washington	47.6°N., 122.3°W.
E-24	Helena, Montana	46.7°N., 112.0°W.
E-25	Cheyenne, Wyoming	41.2°N., 104.8°W.
E-26	Denver, Colorado	39.8°N., 105.0°W.
E-27	Santa Fe, New Mexico	35.5°N., 105.9°W.
E-28	Boise, Idaho	43.6°N., 116.3°W.
E-29	Salt Lake City, Utah	40.8°N., 111.9°W.
E-30	Carson City, Nevada	39.1°N., 119.8°W.
E-31	Phoenix, Arizona	33.4°N., 112.1°W.
E-32	Olympia, Washington	47.1°N., 122.9°W.
E-33	Salem, Oregon	44.9°N., 123.0°W.
E-34	Sacramento, California	38.5°N., 121.6°W.

The values of the standard storm parameters for various return periods are calculated from the corresponding standard intensity-duration relationships listed in Appendix C. The optimization technique described in connection with Eq. 22 was applied to 10 duration values for each return period to obtain the  $a_1$ ,  $b_1$ , and  $c_1$  values. The values of  $b_1$  and  $c_1$  so obtained are nearly constant for various return periods at each station studied.

**Table E-1. Storm parameter values for various frequencies at New York computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	26.716	24.295	24.865	23.836	24.481	24.979	23.175
$b_1$	9.961	8.047	8.438	7.754	8.711	8.320	8.086
$c_1$	.780	.756	.760	.752	.754	.761	.746

**Table E-2. Storm parameter values for various frequencies at Los Angeles computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	13.841	9.957	9.779	9.265	9.398	9.655	9.315
$b_1$	3.584	1.802	1.367	1.167	1.016	1.172	1.348
$c_1$	.632	.549	.527	.518	.526	.536	.526

**Table E-3. Storm parameter values for various frequencies at Chicago computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	33.823	31.405	30.632	29.801	30.022	29.098	28.903
$b_1$	9.727	9.570	9.805	9.258	9.414	9.063	9.023
$c_1$	.827	.817	.812	.801	.805	.797	.797

**Table E-4. Storm parameter values for various frequencies at Detroit computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	28.634	31.682	32.336	31.551	33.865	33.101	31.605
$b_1$	9.727	9.922	10.430	9.883	10.898	10.508	10.430
$c_1$	.795	.818	.825	.815	.830	.827	.817

**Table E-5. Storm parameter values for various frequencies at Philadelphia computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	18.871	18.409	21.143	20.285	23.691	21.083	22.039
$b_1$	5.977	5.293	6.816	6.855	7.793	6.426	6.816
$c_1$	.711	.709	.723	.714	.745	.722	.728

**Table E-6. Storm parameter values for various frequencies at San Francisco computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	12.401	11.140	10.690	11.105	11.081	11.370	12.187
$b_1$	3.672	1.626	1.543	1.714	2.451	1.812	2.568
$c_1$	.594	.560	.549	.569	.568	.575	.580

**Table E-7. Storm parameter values for various frequencies at Boston computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	18.215	22.551	21.388	21.444	21.561	21.202	21.883
$b_1$	5.605	8.086	7.012	7.012	7.246	7.422	7.246
$c_1$	.690	.726	.719	.723	.723	.723	.724

**Table E-8. Storm parameter values for various frequencies at Washington, D. C. computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	36.151	32.692	32.182	30.223	31.268	34.449	29.799
$b_1$	11.523	9.648	9.805	9.805	9.570	10.664	9.180
$c_1$	.844	.831	.825	.809	.817	.833	.805



**Table E-9. Storm parameter values for various frequencies at Cleveland computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	33.089	29.336	30.286	32.586	32.546	34.348	32.975
$b_1$	10.898	8.555	9.258	10.273	10.039	10.508	10.430
$c_1$	.821	.800	.813	.821	.825	.831	.825

**Table E-10. Storm parameter values for various frequencies at St. Louis computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	32.442	26.954	28.247	28.838	29.099	30.527	27.700
$b_1$	10.078	8.320	9.102	9.102	9.375	9.883	9.141
$c_1$	.817	.781	.789	.794	.797	.806	.788

**Table E-11. Storm parameter values for various frequencies at Pittsburg computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	25.660	27.575	27.471	29.124	27.572	30.404	30.168
$b_1$	8.320	9.336	8.633	9.414	8.945	9.609	9.766
$c_1$	.767	.780	.791	.794	.785	.808	.801

**Table E-12. Storm parameter values for various frequencies at Baltimore computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	31.512	31.867	29.640	28.625	30.378	34.547	33.456
$b_1$	10.898	10.586	9.023	9.727	9.258	11.289	11.289
$c_1$	.811	.817	.807	.797	.806	.820	.820

**Table E-13. Storm parameter values for various frequencies at Minneapolis computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	30.923	34.258	30.302	33.106	29.385	32.633	32.820
$b_1$	9.727	10.508	9.102	10.117	8.945	10.430	9.883
$c_1$	.814	.835	.811	.827	.807	.825	.824

**Table E-14. Storm parameter values for various frequencies at Miami computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	24.380	21.999	24.765	20.933	20.691	21.311	21.525
$b_1$	7.266	6.387	8.203	7.168	7.051	7.461	7.637
$c_1$	.769	.739	.758	.722	.720	.722	.720

**Table E-15. Storm parameter values for various frequencies at Houston computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	33.336	27.422	28.326	26.083	24.477	25.020	24.595
$b_1$	11.055	9.219	9.570	9.102	8.086	8.711	8.281
$c_1$	.824	.781	.785	.771	.757	.762	.756

**Table E-16. Storm parameter values for various frequencies at Buffalo computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	24.169	26.860	27.132	26.708	25.533	26.281	28.044
$b_1$	7.598	8.164	8.477	8.320	8.164	8.008	8.789
$c_1$	.757	.786	.783	.778	.769	.773	.785

**Table E-17. Storm parameter values for various frequencies at Cincinnati computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
a <sub>1</sub>	30.037	27.827	29.137	30.179	29.308	30.713	31.916
b <sub>1</sub>	9.883	8.477	9.258	9.727	9.336	9.961	9.961
c <sub>1</sub>	.798	.787	.798	.804	.798	.809	.816

**Table E-18. Storm parameter values for various frequencies at Milwaukee computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
a <sub>1</sub>	34.759	33.557	31.656	31.946	29.150	29.097	30.095
b <sub>1</sub>	10.898	10.234	9.883	10.273	9.375	9.023	9.609
c <sub>1</sub>	.839	.832	.819	.816	.801	.799	.807

**Table E-19. Storm parameter values for various frequencies at San Diego computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
a <sub>1</sub>	21.121	15.595	21.729	21.975	20.419	20.290	20.830
b <sub>1</sub>	6.738	3.418	6.543	6.699	5.879	5.957	6.191
c <sub>1</sub>	.715	.665	.731	.731	.715	.716	.716

**Table E-20. Storm parameter values for various frequencies at Dallas computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
a <sub>1</sub>	29.854	29.930	28.986	26.658	27.768	25.897	24.812
b <sub>1</sub>	8.711	9.102	8.945	8.242	9.023	8.086	8.086
c <sub>1</sub>	.808	.803	.798	.776	.783	.771	.761

**Table E-21. Storm parameter values for various frequencies at Atlanta computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	30.275	31.066	26.884	27.599	27.123	23.385	27.252
$b_1$	9.414	9.727	8.633	9.297	9.219	7.539	9.375
$c_1$	.809	.809	.780	.784	.778	.750	.779

**Table E-22. Storm parameter values for various frequencies at Kansas City computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	32.546	29.884	30.268	29.402	29.146	27.900	26.942
$b_1$	9.883	9.414	9.570	9.570	9.102	8.945	8.477
$c_1$	.825	.801	.805	.798	.799	.788	.781

**Table E-23. Storm parameter values for various frequencies at Seattle computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	9.702	9.745	7.871	8.667	8.120	7.455	8.867
$b_1$	1.216	1.060	-.171	.107	.227	1.001	1.099
$c_1$	.518	.513	.469	.487	.480	.481	.514

**Table E-24. Storm parameter values for various frequencies at Helena computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	17.971	19.046	26.888	26.442	30.112	26.165	27.868
$b_1$	5.957	7.402	10.117	8.438	11.758	9.570	8.164
$c_1$	.685	.708	.776	.777	.802	.776	.785

**Table E-25. Storm parameter values for various frequencies at Cheyenne computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	33.759	35.470	36.300	34.595	38.519	37.672	35.510
$b_1$	8.945	10.742	10.469	10.977	11.367	11.289	10.664
$c_1$	.826	.848	.853	.851	.865	.860	.846

**Table E-26. Storm parameter values for various frequencies at Denver computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	26.287	29.746	34.319	31.283	42.196	36.189	35.294
$b_1$	9.961	10.508	10.898	9.180	12.773	9.883	19.820
$c_1$	.780	.799	.841	.826	.870	.845	.842

**Table E-27. Storm parameter values for various frequencies at Santa Fe computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	23.149	29.640	31.098	30.077	33.002	31.311	31.205
$b_1$	9.023	10.664	11.250	10.898	11.250	9.883	10.039
$c_1$	.761	.806	.808	.815	.826	.817	.810

**Table E-28. Storm parameter values for various frequencies at Boise computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	9.059	9.112	15.135	12.870	15.657	13.959	15.848
$b_1$	.381	1.484	2.129	2.939	4.453	4.160	3.818
$c_1$	.516	.538	.630	.616	.653	.642	.652

**Table E-29. Storm parameter values for various frequencies at Salt Lake City computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	11.624	13.808	15.785	15.735	16.165	18.686	15.603
$b_1$	3.984	3.848	4.375	4.512	4.805	5.996	4.512
$c_1$	.583	.612	.653	.657	.661	.687	.657

**Table E-30. Storm parameter values for various frequencies at Carson City computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	10.788	13.189	12.316	13.609	15.645	16.842	15.748
$b_1$	1.567	2.646	1.899	4.043	4.277	4.902	5.059
$c_1$	.553	.590	.593	.617	.629	.655	.656

**Table E-31. Storm parameter values for various frequencies at Phoenix computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	33.897	35.023	30.559	30.101	30.194	30.866	29.300
$b_1$	10.039	11.836	10.508	10.469	10.352	10.156	9.414
$c_1$	.828	.834	.804	.809	.802	.804	.797

**Table E-32. Storm parameter values for various frequencies at Olympia computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	6.908	6.650	6.998	7.445	6.664	6.621	7.397
$b_1$	-1.060	-1.145	-.684	-.190	-.588	-.515	-.161
$c_1$	.431	.440	.444	.459	.436	.437	.446

**Table E-33. Storm parameter values for various frequencies at Salem computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	7.463	8.596	7.909	7.590	8.200	8.649	9.561
$b_1$	-.359	.962	.210	-.261	.210	1.025	1.328
$c_1$	.457	.486	.481	.468	.492	.502	.521

**Table E-34. Storm parameter values for various frequencies at Sacramento computed from the corresponding standard intensity-duration relationships in Appendix C.**

Rainstorm Parameters	Return Period (Years)						
	1	2	5	10	25	50	100
$a_1$	10.154	11.438	10.320	11.198	11.410	10.374	10.753
$b_1$	1.060	1.313	.845	2.158	2.725	1.895	1.709
$c_1$	.545	.571	.548	.572	.577	.564	.566