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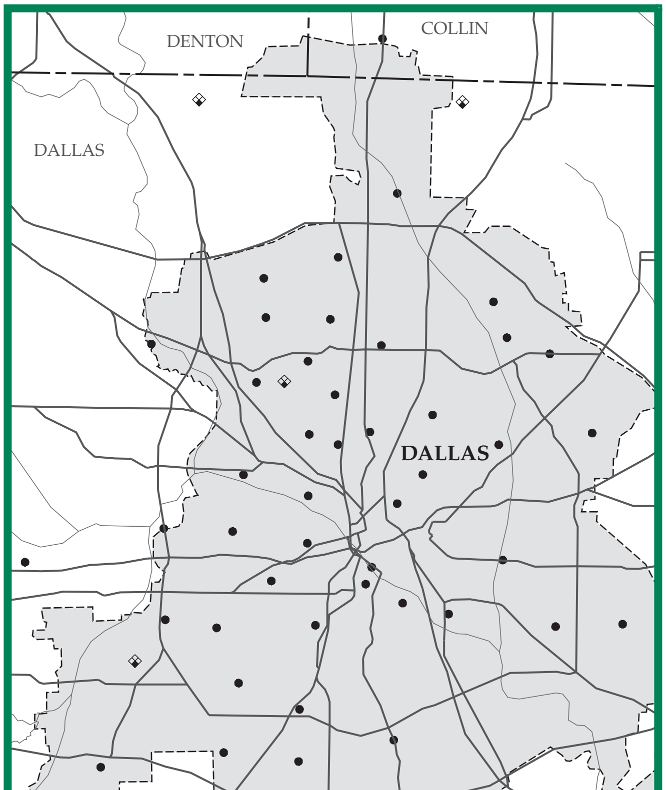
Areal-Reduction Factors for the Precipitation of the 1-Day Design Storm in Texas



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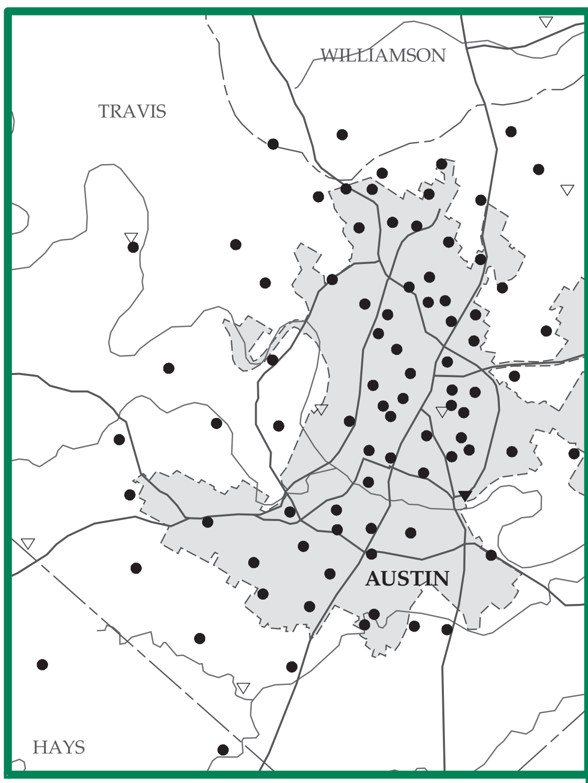

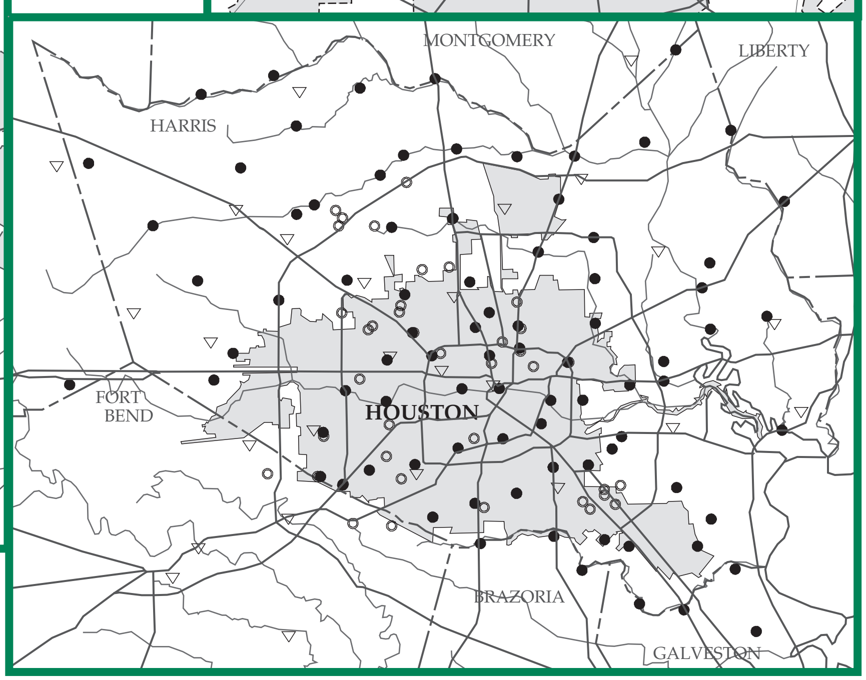

U.S. Department of the Interior
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Areal-Reduction Factors for the Precipitation of the 1-Day Design Storm in Texas

By William H. Asquith

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99–4267

In cooperation with the Texas Department of Transportation

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By William H. Asquith

Abstract

The reduction of the precipitation depth from a design storm for a point to an effective (mean) depth over a watershed often is important for cost-effective design of hydraulic structures by reducing the volume of precipitation. A design storm for a point is the depth of precipitation that has a specified duration and frequency (recurrence interval). The effective depth can be calculated by multiplying the design-storm depth by an areal-reduction factor (ARF). ARF ranges from 0 to 1, varies with the recurrence interval of the design storm, and is a function of watershed characteristics such as watershed size and shape, geographic location, and time of year that the design storm occurs. This report documents an investigation of ARF by the U.S. Geological Survey, in cooperation with the Texas Department of Transportation, for the 1-day design storm for Austin, Dallas, and Houston, Texas. The "annual maxima-centered" approach used in this report specifically considers the distribution of concurrent precipitation surrounding an annual precipitation maxima. Unlike previously established approaches, the annual maxima-centered approach does not require the spatial averaging of precipitation nor explicit definition of a representative area of a particular storm in the analysis. Graphs of the relation between ARF and circular watershed area (to about 7,000 square miles) are provided, and a technique to calculate ARF for noncircular watersheds is discussed.

INTRODUCTION

The reduction of the precipitation depth from a design storm for a point to an effective (mean) depth over a watershed often is important for cost-effective design of hydraulic structures by reducing precipitation volume. The hydraulic structures intended to control and route localized runoff include: drainage ditches, culverts, road crossings, and runoff detention or retention structures. A design storm for a point is the depth of precipitation that has a specified duration and frequency (recurrence interval). The effective depth often is computed by multiplying the design-storm depth by a "depth-area correction factor" or an "areal-reduction factor." The areal-reduction factor is generally defined as the ratio of (1) the mean precipitation depth over a watershed resulting from a design storm to (2) the point depth of the design storm. The areal-reduction factor ranges from 0 to 1, varies with the recurrence interval of the design storm, and is a function of such characteristics as watershed size, watershed shape, geographic location, and time of year that the design storm occurs.

In 1996, the U.S. Geological Survey (USGS), in cooperation with the Texas Department of Transportation (TxDOT), initiated a multi-component study of precipitation characteristics for Texas. The major objectives of this study were to (1) define the depth-duration frequency of point precipitation—design storms—for Texas, (2) investigate the extreme precipitation potential of Texas, and (3) develop areal-reduction factors for the 1-day design storm in Texas. The 1-day design storm is frequently used by TxDOT and its contractors for hydraulic structure design. This report documents the third objective and is believed to be the first such study of areal-reduction factors specifically for the 1-day design storm in Texas. Asquith (1998) documents the analysis and results of the first objective, and Lanning-Rush and others (1998) documents the analysis and results of the second objective.

Purpose and Scope

The purpose of this report is to document an investigation of areal-reduction factors for estimation of the effective (mean) precipitation depth from 1-day design storms for watersheds in Texas. Most of this report is a comprehensive documentation of the analysis leading up to the final results, areal-reduction factors. The discussion involving the final results is brief. The reader who is familiar with the methods of areal-reduction factor estimation is directed to figures 17 and 18 and the section titled "Application of Techniques." The data for this investigation include the daily values of precipitation as reported (digitally) by various precipitation-monitoring networks in the vicinity of Austin, Dallas, and Houston, Texas. Detailed data verification was not possible; however, the daily precipitation values for each network were evaluated to assess data compatibility between networks (see the section "Database Evaluation").

Daily Precipitation Data Sources

The "city databases" of daily precipitation were aggregated for Austin, Dallas, and Houston. Each city database was derived from several precipitation-station monitoring networks in the vicinity of each city. For the Austin area, two daily precipitation networks were identified: 25 National Weather Service (NWS) stations (Internet address, http://www.nws.noaa.gov/) and 83 City of Austin (AUS) stations (J. David Walker, City of Austin, written commun., 1997). For the Dallas area, two daily precipitation networks were identified: 58 NWS stations and 45 City of Dallas (DAL) stations (Don Lawrence, City of Dallas, written commun., 1998). For the Houston area, three daily precipitation networks were identified: 64 NWS stations, 84 Harris County Office of Emergency Management (HAR) stations (Internet address, http://www.hcoem.co.harris.tx.us), and 45 USGS Houston Urban Program (HURP) stations (Fred Liscum, USGS, written commun., 1998). The NWS data were adopted from a CD–ROM published by Hydrosphere Data Products, Inc. (1996).

All of the stations, organized by network, are identified along with ancillary information in tables 1–3 (at end of report—Austin, table 1; Dallas, table 2; and Houston, table 3). The NWS, AUS, DAL, and HAR networks each used a three- or four-digit station numbering system. A variable numbering system was used for the HURP network. To avoid confusion, unique "study" station numbers were assigned to the non-NWS networks. The AUS, DAL, and HAR networks were adjusted by adding 10,000, 40,000, and 70,000, respectively, to their original four-digit numbers. The HURP numbers were reassigned by dropping the alphabetical characters and adding 80,000 or 88,000 to the remaining numbers.

The stations in each network have varying periods of record (in calendar years). In general, the NWS stations have the longest periods of record. Some NWS stations have record lengths in excess of 80 years. Most NWS stations were still active as of 1995. In general, the AUS stations have start dates between about 1988 to 1990 and most were still active as of 1996. The DAL stations generally have a 1991 to 1997 or later period of record. The HAR stations have various start dates in the late 1980s, and most were still active as of 1997. The HURP stations have various periods of record, but in general the records start between about 1965 to 1975 and end about 1984 to 1989.

The stations in each network have varying degrees of record completeness. This record completeness has important implications in the analysis. The implications are addressed in the sections "Empirical Depth-Distance Relations From Sample-Ratio Calculation," "Point-Process Evaluation," and "Areal-Process Evaluation." In general, the NWS stations have the most complete record; missing record occurs primarily in the beginning and ending years. The NWS stations recorded a "trace" as part of the nonzero record. These data were assumed to be zero, and were subsequently reset to zero, and included in the analysis. Trace precipitation amounts were not reported in the other networks. Individually, the Austin, Dallas, and Houston databases have about 248,000; 429,000; and 688,000 values of daily precipitation. When combined, the three databases contain about 1,365,000 values of daily precipitation.

The locations of the three study areas are shown in figure 1. Figures 2–4 show the location of each station, along with identification of its operator, for each city. In general, the NWS stations are more widely dispersed than those for the other networks. The Austin database (fig. 2) was the smallest in overall geographic extent. The Austin database was assembled first, and preliminary analysis of the Austin database indicated that more stations (hence larger areal coverage) were needed for Dallas and Houston (figs. 3 and 4). Fortuitously, the Dallas and Houston databases benefited from a greater NWS station density, and thus, a greater number of NWS stations per county than in the Austin area. The Houston database further benefited by having two non-NWS networks (HAR and HURP). The stations in each database are reasonably well distributed geographically, except for the AUS stations, which were somewhat preferentially aligned north to south associated with how the city has grown.

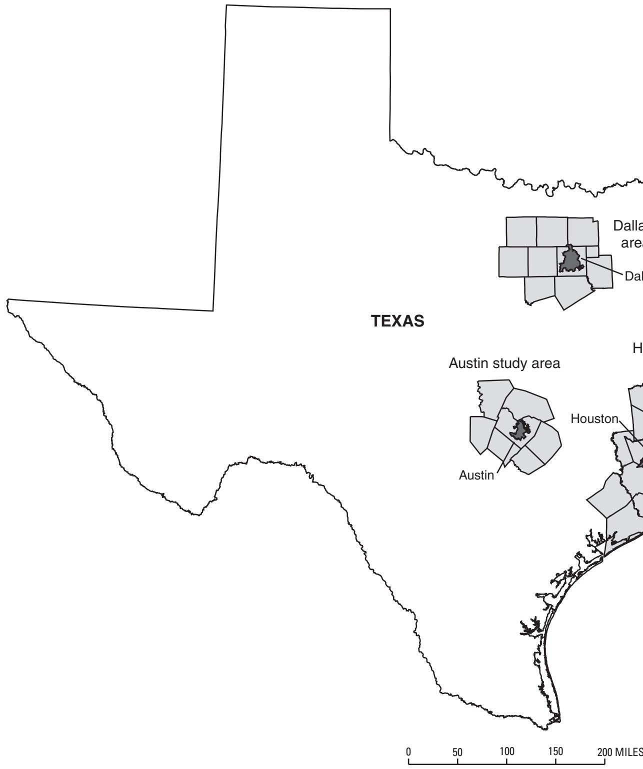


Figure 1. Location of study areas in Texas.

Background and Previous Studies

Estimation of areal-reduction factors requires the determination of effective precipitation depths. This section briefly outlines some of the various methods proposed or used to calculate effective precipitation depth—hereafter abbreviated as "Z_E". Most investigators have used an areal-reduction factor concept, which describes the ratio of effective precipitation (areal average) to point precipitation. Myers and Zehr (1980, p. 1–2) point out that an areal-reduction factor is the ratio of two different expectations and generally is not intended to describe the spatial or temporal variability of design storms, nor to describe the complex morphology of individual storms, nor to provide the basis for stochastic simulation.

Two types of areal-reduction factors—hereafter abbreviated as "ARF" are commonly used. The first type of ARF is known as the "geographically-fixed" or "fixed-area" ARF that relates the point depth to the average depth of concurrent precipitation over a specified or "fixed" area. The geographically-fixed ARF is based on extreme value analysis of an annual time series of maxima mean precipitation for a given and fixed area. Generally, an assumption of probability equivalence is made between the frequency of the point precipitation to the frequency of the areal precipitation. In other words, the T-year point precipitation is assumed to generate the T-year volume of precipitation. The second type of ARF is known as "storm-centered." The storm-centered ARF is most often associated with the calculation of Z_E for individual storms. The average storm depth is commonly derived from integration of depth contour lines divided by the maximum depth recorded in the storm (the storm center). Sivapalan and Blöschl (1998, p. 151) report that a storm-centered ARF is "usually somewhat smaller than [geographically] fixed [ARF]."

The point and areal frequency curves (distributions) would be expected to have different forms—the distribution of annual precipitation maxima point processes is far from normal (Asquith, 1998). Logic dictates that the areal distribution of the 1-day design storm would not be exactly normal because zero is the lower bound on potential precipitation for a given location within the area—whereas the normal distribution has infinite lower and upper tails. The common methods of estimating areal precipitation from point observations, however, produce approximately normal distributions of areal precipitation. This occurs because

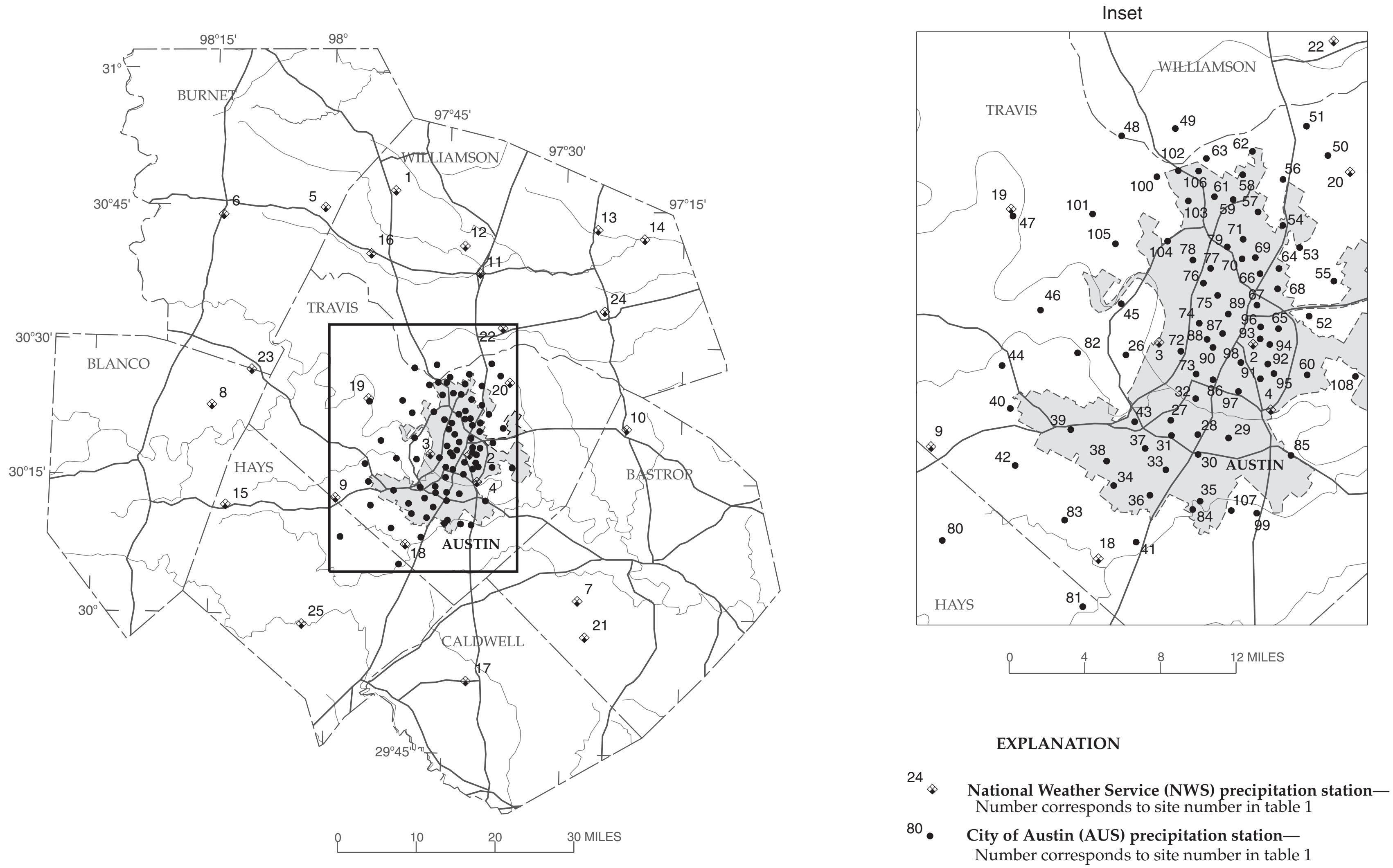


Figure 2. Location of stations for two precipitation-monitoring networks near Austin, Texas.

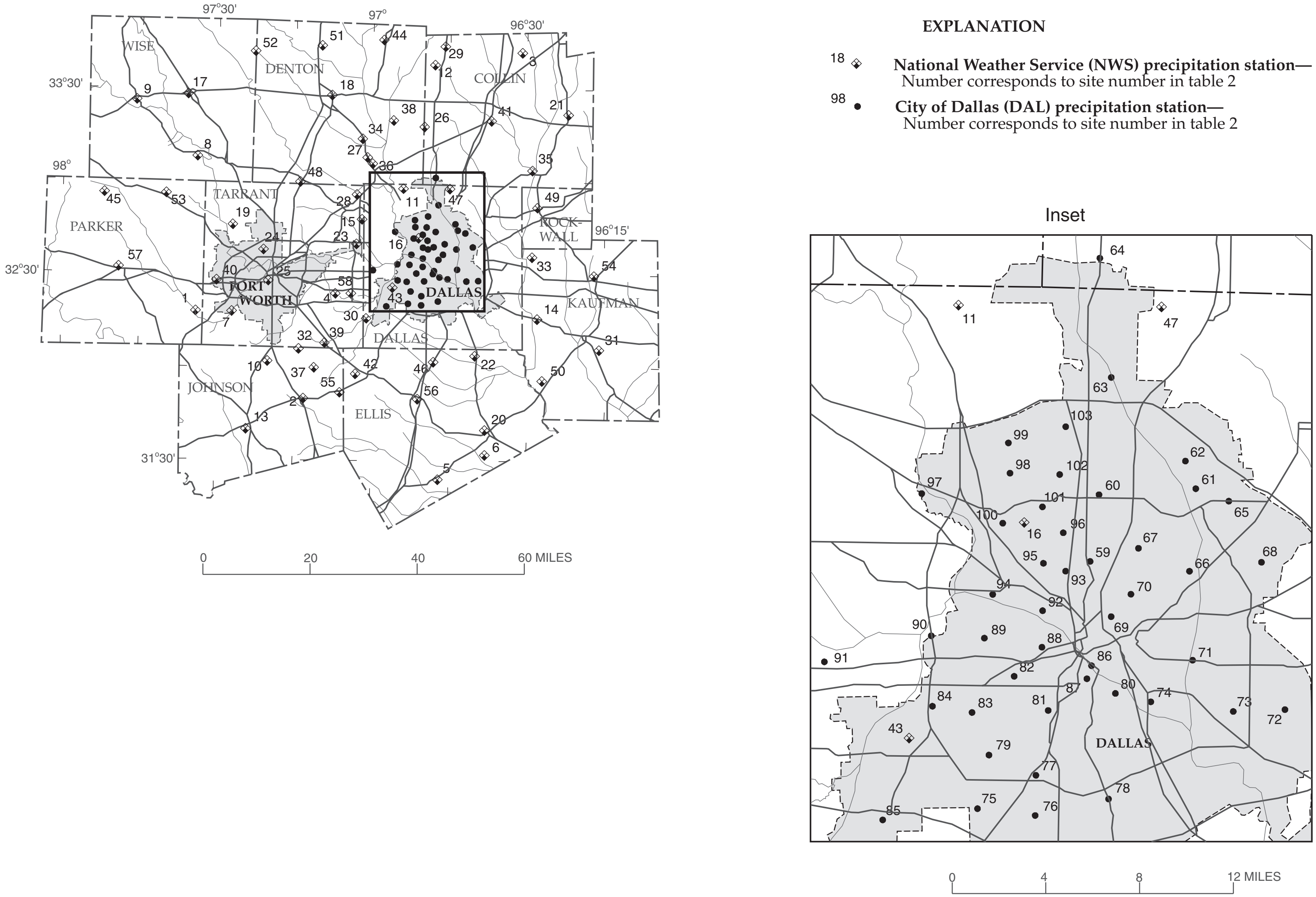


Figure 3. Location of stations for two precipitation-monitoring networks near Dallas, Texas.

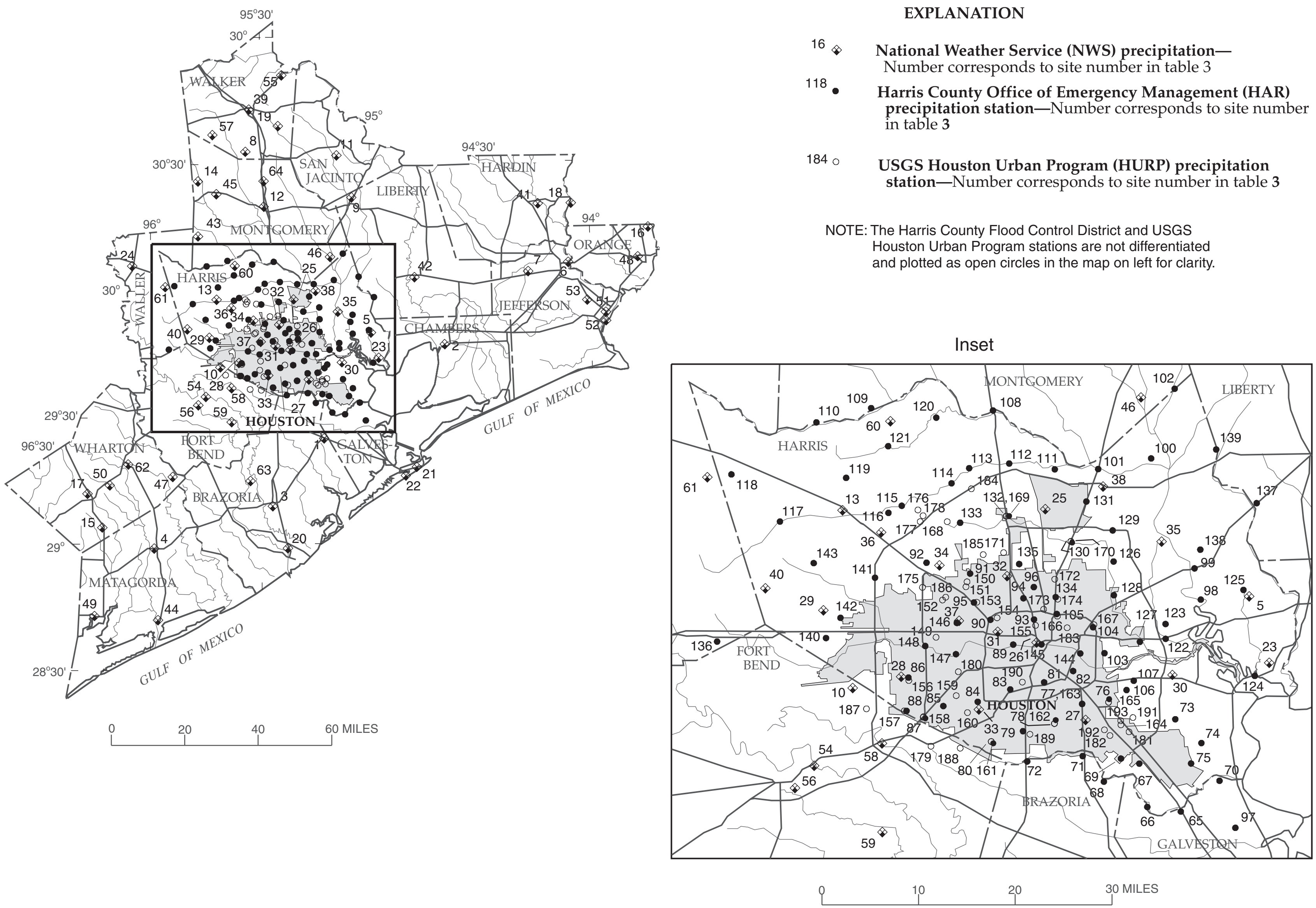


Figure 4. Location of stations for three precipitation-monitoring networks near Houston, Texas.

areal precipitation is estimated as weighted linear combinations of many point observations—the central limit theorem requires that the areal distribution derived from such methods be normal (Rodriguez-Iturbe and Mejía, 1974a, p. 732) even though the point processes are not normally distributed.

Perhaps the most common sources of ARF for the United States are Technical Paper 29 (TP–29) by the U.S. Weather Bureau (1957, 1958) and National Oceanic and Atmospheric Administration (NOAA) Atlas 2 by Miller and others (1973). TP–29 provides ARF for areas ranging from 0 to 400 square miles (mi^2) for storm durations less than or equal to 24 hours. The TP–29 analysis is based on precipitation-monitoring networks east of the Mississippi River. TP–29 defines ARF as the ratio of (1) the mean annual maxima of areal precipitation to (2) the mean annual maxima of point precipitation. TP–29 presents a single curve based on 2-year recurrence intervals. This curve was judged applicable for all return periods up to 100 years.

TP–29 implicitly equates the frequency of the point precipitation to the frequency of the areal precipitation. This assumes that the relation between depth and area is not influenced by the frequency (recurrence interval) of the point precipitation. Leclerc and Schaake (1972) express the results of TP–29 as a single equation that shows ARF to be a function of area and duration only:

$$ARF = \frac{Z_E}{Z_T} = 1 - e^{-1.1t^{0.25}} + e^{(-1.1t^{0.25} - 0.01A)}, \quad (1)$$

where

ARF = areal-reduction factor, dimensionless;

Z_E = effective precipitation over the area, in inches;

Z_T = point precipitation or the design storm depth for recurrence interval T, in inches;

t = duration time, in hours; and

A = area, in square miles.

Rodriquez-Iturbe and Mejía (1974a) developed a general methodology for converting any point precipitation to an effective precipitation. Their methodology is primarily oriented towards solutions for problems of (1) distributing precipitation from multiple inputs for rainfall-runoff modeling, (2) estimating long-term mean effective precipitation, and (3) estimating effective depths for individual storms. The ARF of Rodriquez-Iturbe and Mejía depends solely on the correlation coefficient for a “characteristic correlation distance.” The characteristic correlation distance is the expected distance between two randomly chosen points in the area. The Rodriquez-Iturbe and Mejía correction factor is as follows:

$$ARF = \sqrt{\hat{\rho}}, \quad (2)$$

where

ρ = expected correlation coefficient for the characteristic correlation distance.

Although the ARF of equation 2 is simple, estimation of ρ is a difficult problem with many uncertainties (Rodriguez-Iturbe and Mejía, 1974a and b). Like the other cited sources, the Rodriquez-Iturbe and Mejía approach equates the frequency of the point precipitation to the effective precipitation frequency. Although providing an extensive framework for transforming point depths to effective precipitation, the Rodriquez-Iturbe and Mejía approach is not specifically oriented toward estimation of the areal distribution of design storms. As reported by Sivapalan and Blöschl (1998, p. 152), “it is not clear what the relevance of [Rodriquez-Iturbe and Mejía] ARF is to extreme [design] rainfalls.” To the author’s knowledge, the Rodriquez-Iturbe and Mejía (1974a, b) methodology has not been extensively used for estimating the Z_E of design storms.

A complex and more computationally intensive methodology—although still considered as geographically-fixed—for ARF calculation is presented in Myers and Zehr (1980). The model used by Myers and Zehr (1980, p. 1.2–3) is based on extensive statistical inference to compensate for a lack of precipitation data. Myers and Zehr (1980) generated ARF for Chicago, Ill., for many durations, areas, and frequencies. The principle difference of the Myers and Zehr approach is to spatially average the moments (mean and standard deviation) and not the depths of the precipitation within an area.

Another variant of ARF calculation is proposed by Sivapalan and Blöschl (1998). Their approach determined that ARF depends heavily on the recurrence interval of the point precipitation process. The variance of a point precipitation process is greater than the variance of an areal process. The ratio of the areal variance to point variance is known as a “variance-reduction factor.” The variance-reduction factor is estimated from the spatial correlation of precipitation. The spatial correlation is defined by all the precipitation data available within a network for the duration of interest.

Though the methods of investigation vary, the ARF values from the various sources all show similar behavior. ARF values are at or near unity for very small distances or areas. For increasing areas, ARF values decrease (decay) in exponential-like fashion. The decay of ARF is more rapid for short duration storms (such as 30 minutes) than for long durations (such as 1 day). Furthermore, as the recurrence interval (intensity) of the point precipitation increases, the ARF values decay more rapidly.

The spatial distribution of precipitation in Texas shows large variation in both space and time (demonstrated in the section "Approach"); thus, most depth-area analyses have required extensive statistical inference because the underlying data sets are usually small. Because of the large amount of daily precipitation data available in Texas, an alternative approach is possible that relies on fewer assumptions. The theoretical basis of the alternative approach is presented in the next section.

APPROACH

Annual Maxima-Centered Areal-Reduction Factors

An alternative approach was adopted for the calculation of ARF in Texas. The large daily precipitation databases available in Texas allowed an approach that considers the distribution of precipitation concurrent[1] with and surrounding an annual precipitation maxima. Because the approach is based solely on annual precipitation maxima and concurrent 1-day precipitation, ARF derived from this approach are termed "annual maxima-centered areal-reduction factors." The annual maxima-centered approach, unlike some of the other approaches discussed in the "Background and Previous Studies" section, does not require spatial averaging of precipitation or explicit definition of a representative area. Defining the area of a particular storm before analysis of its spatial distribution is a particularly difficult problem.

The first step of the annual maxima-centered approach is to define the depth-distance relation (the relation between the design storm depth and the precipitation depth at other locations) as a function of separation distance between the two locations. The depth-distance relation is then integrated in space according to the specific size and shape of the watershed. An advantage of the annual maxima-centered approach is that the area over which the design storm occurs is needed only at the very end of analysis and is a known value for any watershed being considered.

[1] "Concurrent" in this context, is used since the only time frame or duration of precipitation considered in this report is 1 day. The annual precipitation maxima are for 1 day, and precipitation surrounding the annual precipitation maxima is analyzed when it is concurrent, that is, occurring on the same day as the annual precipitation maxima.

Watershed Precipitation Volume

The volume (V) of precipitation over a watershed (W) for a design criteria (such as a T-year, 6-hour storm) can be expressed as a spatial integral over the watershed:

$$V = \int_W dV = \int_W [Z(Z_T, x, y)]dxdy, \qquad (3)$$

where

$Z(Z_T, x, y)$ = precipitation for each differential location (dx,dy) and a function of the design storm precipitation.

$Z(Z_T, x, y)$ can be formulated as the product of Z_T (the design storm depth) and some unknown spatial relation function, $S'_T(x, y)$. $S'_T(x, y)$, which describes the spatial structure of the storm and will eventually provide the basis of ARF calculation, is dimensionless, continuous, nonnegative, and unbounded above. Additionally, it is necessary and sufficient for only the first moment (the mean) to exist for every (x, y) location. Equation 3 is rewritten as:

$$V = \int_W Z_T S'_T(x, y)dxdy. \qquad (4)$$

Either equation 3 or 4 characterizes a storm volume—the precipitation is allowed to vary for every location within the watershed thereby permitting the description of the complex morphology of a storm. It is assumed, for this investigation, that the largest potential volume of a storm occurs when the storm is centered at the centroid of the watershed. Therefore, by conservative definition, Z_T (a point precipitation) is located at the centroid (x_c, y_c) of the watershed. Furthermore, if it is assumed that storm orientation over the watershed is unimportant—storms are assumed to be generated by an isotropic areal process—S'_T becomes symmetric and can be generalized by the separation distance (r) between the centroid and the location of (dx,dy). This assumption is likely invalid, but it is used here to greatly simplify the mathematics. The separation distance (r) is defined as:

$$r = \sqrt{(x - x_c)^2 + (y - y_c)^2}. \tag{5}$$

Accordingly, equation 4 can be rewritten as:

$$V = \int_W Z_T S'_T(r)dxdy. \tag{6}$$

S'_T in this form is assumed to describe the spatial structure of a storm radiating away from Z_T at the centroid of the watershed.

Though the storm volume model (eqn. 6) is sufficient for volume characterization, no two storms producing a Z_T (Z_T = constant) located on the watershed centroid would be identical. Thus, $[S'_T(r)]$ is a random variable for each r and is unique for each storm. More specifically, the spatial distribution of concurrent rainfall with Z_T can be considered a random variable for each r. Storm volume is rewritten as:

$$V_i = \int_W Z_T S'_T(r, F)dxdy, \tag{7}$$

where

F = cumulative annual probability, and

S'_T = random variable having a cumulative distribution function $F[S'_T(r)]$ that can be different for each r.

The subscript "i" has been added to V to show that with stochastic integration of equation 5, a single realization of the storm volume is generated. With this storm volume characterization, it is possible to generate many realizations of V_i, which form a series of random variables (V_1, V_2, . . ., V_n) of the storm volume. The series of V_i would allow investigation of the distribution of V and formulation of its inverse cumulative distribution function $V(F)$, $0 \leq F \leq 1$.

However, by far the majority of engineering designers do not require the actual distribution of $V(F)$. They only need the expected value of $V(F)$. The expected value of $V(F)$ is termed the "design storm volume" for watershed W and T-year recurrence interval. The expected value of the design storm volume (V_T) is calculated as:

$$V_T = E[V(F)] = E\left[\int_W Z_T S'_T(r, F)dxdy\right]$$

$$= \int_W Z_T E[S'_T(r, F)]dxdy, \tag{8}$$

where the expectation operator, $E[]$ is

$$E[S'_T(r, F)] = \int_0^1 S'_T(r, F)dF = S_T(r). \tag{9}$$

Equation 9 indicates that a single expected value of the spatial relation function, $S_T(r)$, exists; this value is a function of the recurrence interval of the design storm and the distance between the centroid and the location of each (dx,dy) in the watershed. $S_T(r)$ is referred to as the "depth-distance relation." In essence, $S_T(r)$ describes the average spatial structure of the precipitation concurrent with, and radiating from, the point of an annual precipitation maxima. $S_T(r)$ is thus the **expected** value of the ratio between the depth at some location a distance "r" from the point of the design storm. This definition differs from that of Rodriguez-Iturbe and Mejía (1974a, b) and Sivapalan and Blöschl (1998), who consider the spatial structure of all precipitation for the duration of interest.

$S_T(r)$, as defined by equation 9, requires the assumption that the covariance (cross correlation) in concurrent precipitation at two non-centroid locations is insignificant. This assumption is fundamental for this investigation. Because the objective is to describe the average volume over a watershed and not the stochastic simulation of design storms, concern over the significance of ignoring the spatial covariance structure is mitigated. Regarding equations 8 and 9, only one design volume exists for V_T for a given watershed, which is a desirable property for design purposes. Also, no claim about the specific form of $S_T(r)$ is made. Finally, the expected value (mean) of $S'_T(r)$ must exist for any "r." The design storm volume is expressed as:

$$V_T = Z_T \int_W S_T(r)dxdy . \tag{10}$$

Depth of Effective Precipitation and Areal-Reduction Factors

The effective precipitation (Z_E) over a watershed and the areal-reduction factor (ARF) for recurrence interval T (ARF_T) for Z_T are expressed as:

$$Z_{Ei} = \frac{V_i}{AREA}, \tag{11}$$

$$ARF_{Ti} = \frac{Z_{Ei}}{Z_T}. \quad (12)$$

Realizations of Z_{Ei} or ARF_{Ti} analogous to V_i could be generated. Because of linearity (eqns. 11–12), either V_i, Z_{Ei}, or ARF_{Ti}, is needed to calculate the other values. The expected (design) values of Z_{ET} and ARF_T are therefore calculated as:

$$Z_{ET} = \frac{V_T}{AREA} = \frac{Z_T \int_W S_T(r)dxdy}{\int_W dxdy}; \quad (13)$$

$$ARF_T = \frac{Z_{ET}}{Z_T} = \frac{1}{Z_T} \frac{Z_T \int_W S_T(r)dxdy}{\int_W dxdy}$$

$$= \frac{\int_W S_T(r)dxdy}{\int_W dxdy}. \quad (14)$$

To illustrate further, equation 14 can be rewritten for a circular watershed as:

$$ARF_T = \frac{Z_{ET}}{Z_T} = \frac{1}{Z_T} \frac{Z_T \int_R 2\pi r S_T(r)dr}{\int_R 2\pi r dr}$$

$$= \frac{\int_0^R 2r S_T(r)dr}{R^2}, \quad (15)$$

where

$2\pi r$ = circumference of a concentric circle at radius (separation distance) r within the circular watershed, and

R = maximum radius of the circular watershed.

Equations 14 and 15 are fundamental for ARF calculation. Application of these equations is demonstrated through example calculations for circular and linear watersheds in the section "Application of Techniques." For brevity, (r) is dropped hereafter from reference to $S_T(r)$.

Empirical Depth-Distance Relations From Sample-Ratio Calculation

The basic method for deriving empirical depth-distance relations is presented in this section. The depth-distance relation is generally described as the ratio of (1) the precipitation $Z(r)$ at a distance r away from a point of the design storm to (2) the point precipitation (Z_T) of the design storm. It follows that if a sufficiently large number of ratios $(Z(r)/Z_T)$ from a densely spaced precipitation-station monitoring network are available, these "sample ratios" would provide the basis for estimating S_T (eqn. 9).

Two prominent assumptions are made for this report. The first is that S_T is assumed to be stationary over the area of investigation. The assumption that S_T is stationary requires that the moments (for example: mean, standard deviation) of S_T for a specified r be position invariant, or constant within a study area. The second assumption made is that the actual temporal distribution of precipitation within a day is unimportant. For example, it is assumed that a 2-hour and a 20-hour storm occurring on the same day at different locations are comparable, although it is recognized that the meteorologic conditions generating each event could differ.

A computer program to compute the sample ratios was developed. The program produced large files containing the ratios for each of the stations in operation for each annual precipitation maxima in the database. An abbreviated example of the program output for the Dallas database is listed in table 4 (at end of report). The table identifies the station that recorded the annual maxima (central station); the station without missing precipitation records (selected station) simultaneous with the 6-month season (summer or winter) in which the annual maxima occurred; and finally, the calendar date that the annual maxima occurred. Summer is defined as April through September, and winter is defined as October through March. Additionally, the table lists the estimated cumulative annual probability and the calculated recurrence interval of the annual maxima. The relation between recurrence interval (T) and cumulative probability (F) is $T = 1/(1-F)$. The ratio of the annual maxima to concurrent precipitation (the "sample ratio"), and the separation distance r also are listed.

Two computational checks were available in the sample-ratio program. These tests were made on the "apparent" annual precipitation maxima for a given year and given station, where "apparent annual maxima" represents the maximum of all the existing values for a year.

The first test was whether or not the apparent annual maxima for non-NWS stations was greater than 20 inches (in.); the test rejected 6 years (0.88 percent) of Austin data, 1 year (0.085 percent) of Dallas data, and 8 years (0.42 percent) of Houston data. It was decided after extensive testing that 20 in. would be the upper limit for annual precipitation maxima from non-NWS stations. Inspection of the data early in the investigation revealed that anomalously large daily precipitation values were present that did not correlate with any nearby stations. Analysis presented throughout the remainder of this report strongly indicates that the data for the non-NWS stations do not receive the quality assurance and control that the NWS stations receive. Because the percentages of rejected data are so small, there is no concern that substantial bias has been introduced.

The second test determined how much missing record was permitted for a given year in order to assume that the gaged or apparent annual maxima was the true annual maxima. If there was no missing record, then the gaged annual maxima was the annual maxima. If there was missing record, then the annual maxima was too small if, and only if, the annual maxima for the year happened to occur during days of missing record. Therefore, if too many missing days were allowed, many sample ratios were too small. Testing indicated that allowing 10 missing days provided an appropriate trade-off between determining the true annual maxima and not having an (apparent) annual maxima to perform subsequent analysis.

After the sample ratios were conditioned[2]—that is, using those sample ratios concurrent with T-year or greater annual maxima—according to recurrence interval, the mean ratio for each mile-wide window between 0 and 50 miles (mi) becomes the "empirical depth-distance relation" (empirical S_T). This can be visualized as computing the sample ratios within mile-wide concentric rings surrounding a precipitation station. Because very few annual maxima that exactly equal the T-year event were available, the conditioning was cumulative. For example, those ratios generated by a 2-year **or greater** annual maxima defined the empirical 2-year annual maxima or S_2. Eventually, the final or "estimated" S_T will be shown by a series of joined straight-line segments that pass through unity at zero distance. These segments collectively represent a line termed the "estimated depth-distance relation" (estimated S_T), and the line represents the expectation of the depth-distance relation (eqn. 9).

The ratio files were statistically summarized for each mile-wide window of separation distance. Various window widths were evaluated, and the mile-wide window was found to be satisfactory. The mean ratios for each mile-wide window provided the empirical S_T (presented in the section "Empirical Depth-Distance Relations From Sample-Ratio Calculation"). To provide an unbiased separation distance for graphical representation, the mean of the separation distance for each mile-wide window was calculated. An example of the summarization program output for the Dallas database is listed in table 5 (at end of report). In addition to the mean separation distance and mean sample ratio, the table lists the standard deviation, calculated by L-moments (Hosking, 1990), coefficient of variation of sample ratios, median sample ratio, number of sample ratios for each mile-wide segment, number of samples having zero precipitation, and the resulting probability of zero sample ratio.

A representative sample of the Dallas ratios is shown in figure 5. The sample ratios are for any annual precipitation maxima—that is, annual maxima for any recurrence interval $(1 \leq T \leq \infty)$. The sample ratios plotted in the figure represent a small random subset (only 3,215 of 41,786 ratios with separation distances less than 50 mi). From the figure, it is evident that the variability of the ratios is large. Numerous ratios are zero, and zero ratios are increasingly more likely to occur as r increases. Ratios larger than 1 are not uncommon—a fact that matches the physical reality that (dx, dy) points other than the point coincident with the annual maxima can have larger depths. The empirical S_T for any recurrence interval $(1 \leq T \leq \infty)$ (table 5) also is plotted on figure 5.

AREAL-REDUCTION FACTORS

Empirical depth-distance relations (S_T) provided the basis for the calculation (eqn. 14) of annual maxima-centered areal-reduction factors (ARF_T). Though separation distances (r) larger than 50 mi were available, the maximum r presented in this report was limited to 50 mi. An r of 50 mi corresponds to a circular area of about 7,850 mi^2, much larger than the drainage

[2] "Conditioned" in this context, and used throughout this report, refers to the selection of a subset of sample ratios from the sample-ratio database with recurrence intervals equal to or greater than a specified or "conditioning" recurrence interval.

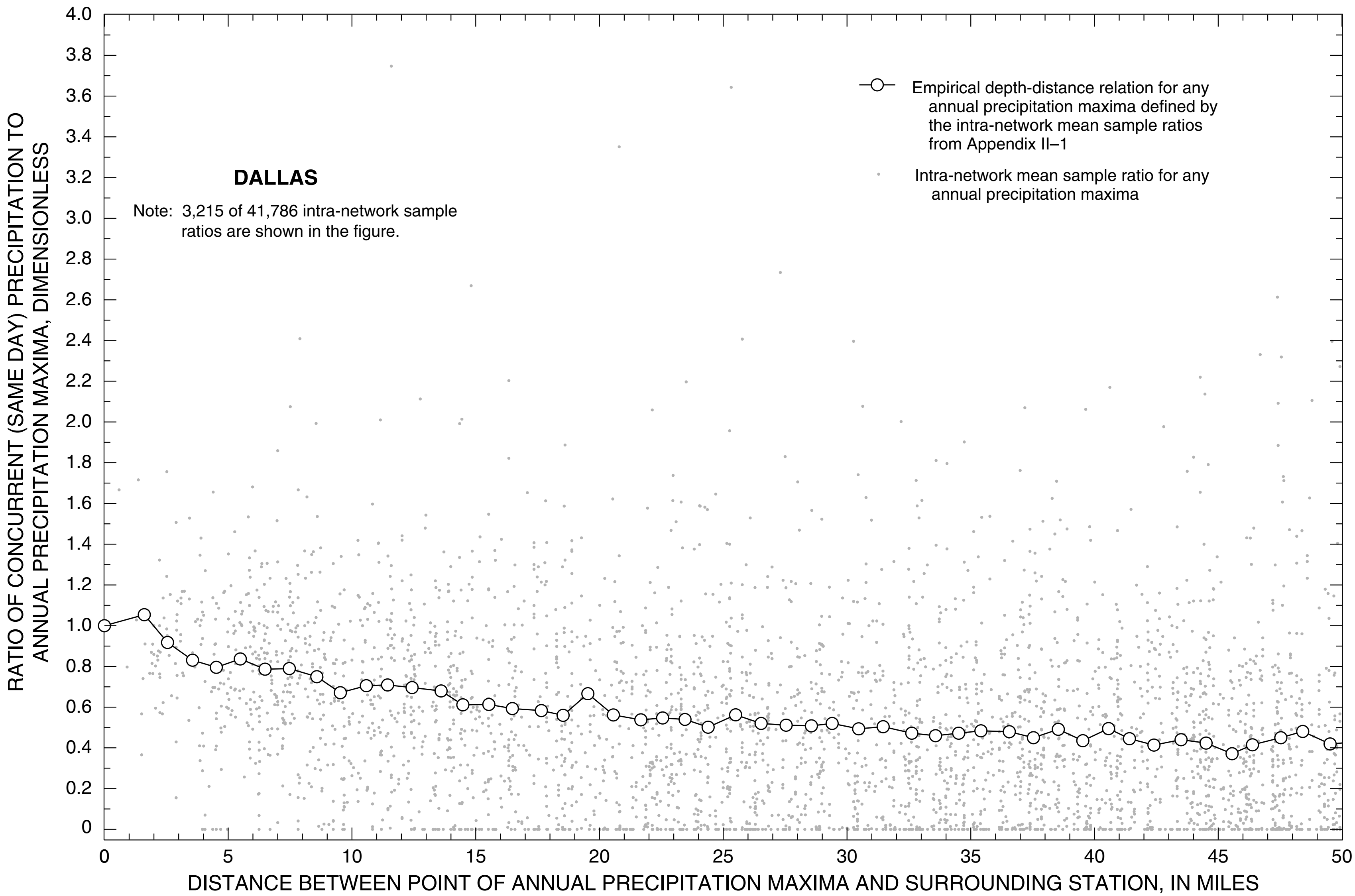


Figure 5. Empirical depth-distance relation and a subset of intra-network sample ratios for any annual precipitation maxima near Dallas, Texas.

areas for which ARF values are frequently needed or for which a single ARF would be expected to be appropriate for volume estimation. The following sections include some evaluations of each network. These evaluations provide assessment of relative network performance and compatibility.

A discussion of the evaluations is required to fully document exactly which data were used for the analysis. Empirical S_T are discussed in a later section of this report entitled "Empirical Depth-Distance Relations Near Selected Localities." This section also discusses the influence that recurrence interval and the season of occurrence of the annual precipitation maxima have on the spatial distribution of precipitation.

Database Evaluation

Before either an empirical or an estimated S_T can be derived from the networks for each city, an assessment of network performance and compatibility was necessary. Each network was operated by a different agency. The considerable differences in operation methods include, but are not limited to, differing instrument styles (recording or nonrecording), instrument types (tipping bucket or weighing), instrument models and manufacturers, instrument heights (above ground), instrument exposure (airports compared with residential backyards), reporting times (midnight to midnight or 8:00 a.m. to 8:00 a.m.), and instrument calibration (maintenance and accuracy of leveling). A comprehensive analysis of the real and potential systematic biases between the networks and of individual biases between the stations is outside the scope of this study; however, two important evaluations were performed for each network. One evaluation considered the performance of each network in recording the annual precipitation maxima (a point process). The second evaluation considered distribution of concurrent precipitation surrounding the point of an annual maxima (an areal process)—the second evaluation basically is a comparison of several S_T derived from various combinations of stations in the networks.

Point-Process Evaluation

The evaluation of how well the stations in each network recorded the annual precipitation maxima was based on the comparison of observed cumulative annual probabilities to defined probabilities. If the theoretical 2-year 1-day precipitation depth for a particular station in Austin is about 3.4 in., then about 50 percent of the observed annual precipitation maxima at the station will be less than 3.4 in. The 2-year event—the median event—has a 50-percent cumulative annual probability. Counting the number of times that the observed annual precipitation maxima for a station did not equal or exceed the depth for the defined recurrence interval and dividing the count by the total number of observed annual precipitation maxima ("storms") provided an "observed cumulative annual probability." The observed cumulative annual probabilities were compared to the defined probabilities (recurrence interval). The defined probabilities for the evaluation were 0.10, 0.20, 0.50, 0.80, and 0.90, which correspond to recurrence intervals of 1.111, 1.25, 2, 5, and 10 years. Estimates of the daily precipitation depth corresponding to each of the defined probabilities for each station within each network were derived from Asquith (1998).

Asquith (1998) presents a comprehensive study of the (point) depth-duration frequency of precipitation for Texas. From this study, essentially two independent methods are available to estimate the depth for the "defined cumulative annual probability" of the daily precipitation for each station. One method is based on the generalized logistic distribution, fit to the L-moments of the 24-hour annual precipitation maxima from many hourly recording NWS stations. The second method is based on the generalized extreme-value distribution, fit to the L-moments of the 1-day annual precipitation maxima from many daily NWS stations. The parameters of both the generalized logistic and extreme-value distributions are listed for each station in tables 1–3 (see Asquith, 1998, for further details; and Hosking, 1990, for related statistical theory). The depth of the defined cumulative probability of 1-day annual precipitation maxima was calculated from each method, and the resulting depths were averaged. It was then assumed that the average cumulative probability represents the "best" available estimate of the unknown cumulative distribution function of the 1-day design storm.

The observed cumulative annual probabilities for each of the precipitation-monitoring networks are listed in table 6 (at end of report). The differences between the defined and observed nonexceedance probabilities are also listed. Most of these differences are negative, which indicates that each network was systematically underestimating the assumed true precipitation quantiles. (Quantiles are the precipitation depths for given durations and probabilities and are derived from Asquith (1998) and based on total record for NWS stations.) Daily observations of precipitation (fixed-interval recording) are known to underestimate the true 24-hour precipitation depth by about 14 percent (Weiss, 1964). Asquith (1998) included Weiss bias corrections. The correction for the bias was only possible on the overall mean of the annual maxima of the time series and the scale or variation of the time series. It is not possible to correct individual annual maxima for the bias. Also contributing to the negative differences in table 6 was the fact that computations were done unless there were more than 10 missing days (see fig. 4, and corresponding discussion). The annual maxima will be too small if the true annual maxima for the year occurred during days of missing record.

The differences between the defined and observed cumulative probabilities decreased in the "tails" of the distribution (0.10, "left or lower tail"; or 0.90, "right or upper tail") for all the networks and were largest near the middle (0.50). The reason for the largest difference near the middle was not readily apparent, and the scope of this study precluded further investigation.

The defined-observed probability differences, which generally were smaller for the NWS stations than for the other station networks, possibly could be related to NWS instrumentation and record length. The climatological network of the NWS is widely regarded as reliable and accurate. The stations in the NWS network are expected to have less bias because of standardized instrumentation and calibration (previously identified). The NWS stations generally have longer periods of record. Larger sample sizes allow more precise statistical inferences that are less likely to be biased because of climatic cycles.

The HURP stations also show small defined-observed probability differences, and in some cases the differences are smaller than for the NWS stations. Thus, the HURP stations might provide an important independent verification of the daily precipitation frequency values from Asquith (1998). The HURP stations benefit by having considerably longer record lengths than either the AUS, DAL, and HAR networks. Statistics derived from the HURP stations therefore are expected to better estimate the unknown population statistics. However, the stations in the HURP network have much more missing record than the NWS stations, which suggests that the HURP stations are actually over-recording precipitation depths (as discussed in the next section), and it is a coincidence that the annual maxima from the HURP stations nearly match the annual maxima from the NWS stations.

Areal-Process Evaluation

An evaluation was conducted to assess network compatibility of the annual precipitation maxima with the concurrent daily precipitation. The basis of the evaluation was the empirical S_T derived specifically from each network. For example, if the empirical S_T from each network are similar, then the networks were recording essentially the same information about the spatial distribution of precipitation. The empirical S_T that are used to judge network compatibility corresponds to stations surrounding annual maxima that are greater than or equal to the 2-year recurrence interval. The "conditioned" empirical S_T are referred to as the "empirical 2-year **or greater** depth-distance relations" or empirical S_2.

Various empirical S_2 derived from the AUS and NWS networks in the Austin area are presented in figure 6. The plotted points represent the mean sample ratio calculated independently from each network (intra-network) without regard to the presence of, or "cross" comparison to, the other network. The number of samples available to compute each mean ratio also is shown. The mean ratio decreases for increasing distance. The AUS network provides most of the available ratio information for small separation distances. The NWS network provides most of the available ratio information for large separation distances.

The "intra-network empirical S_2" (solid line) (fig. 6) represents the combined weighted average of the AUS and NWS mean ratios, and is based on sample ratios derived individually within each network. In other words, the intra-network empirical S_2 for a particular network is derived independently from the other networks. The solid line closely matches AUS ratios when no NWS ratios (small distances) are available, and closely matches the NWS ratios when no AUS ratios (large distances) are available. The "inter-network empirical S_2" (heavy, longer dashed line) is based on sample ratios derived from cross comparison of NWS (AUS) annual precipitation maxima to AUS (NWS) concurrent precipitation.

The dotted or shorter dashed line represents the combination of the intra- (within) and inter- (between) network lines. Initially, this line was considered the best estimate of S_2 because the line contains both the ratios derived from within and between the networks—more data are supposed to yield a better estimate. However, that line is systematically smaller than the intra-network relations. This implies a substantial and nonrandom bias

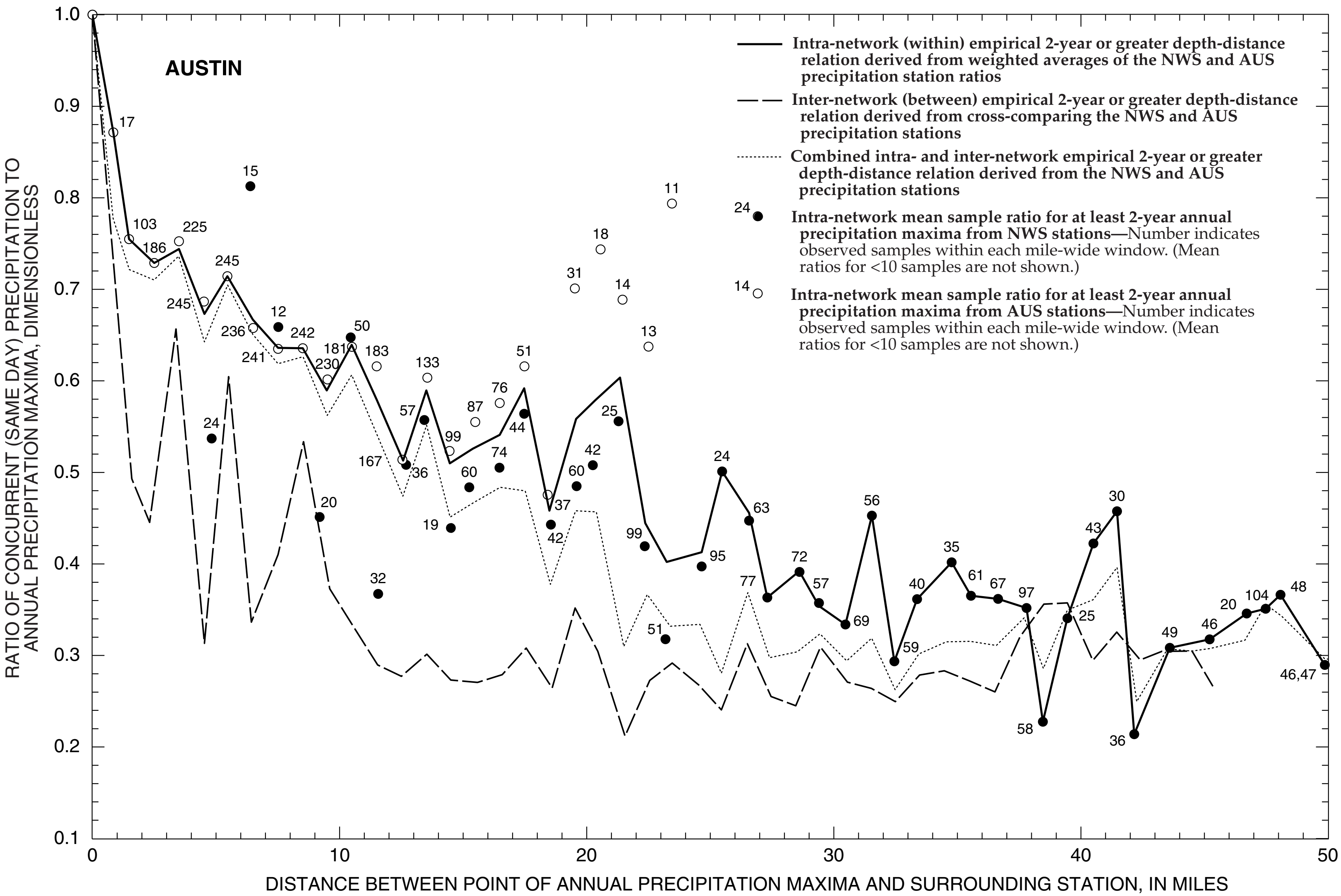


Figure 6. Comparison of empirical 2-year or greater depth-distance relations for two Austin precipitation-station networks, National Weather Service (NWS) and City of Austin (AUS).

when comparing the precipitation recorded between the networks. This bias is indicated by the lack of similarity between the inter-network empirical S_2 and the intra-network empirical S_2.

To explain the bias, it is concluded that the AUS network has a systematic and negative bias. Specifically, the AUS network under-records precipitation depths when recording daily precipitation, although the magnitude of the bias is unknown. The negative bias conclusion is supported by three lines of evidence. First, and most important, because the AUS network systematically under-recorded the annual maxima (table 6), it follows that the network would under-record precipitation. Second, even though the intra-network ratios from the AUS network are slightly larger than similar intra-network ratios from the NWS network, a curvilinear best-fit line would smoothly pass through both the AUS and NWS intra-network ratios. The intra-network ratios are therefore judged to be compatible. This analysis is essential, because, although the data from the AUS network are biased, the AUS and NWS data points are deemed comparable because the systematic bias of the AUS network is divided out when the sample ratios are calculated. The third line of evidence is more complicated and requires the following extended explanation.

If the data from the AUS network were underestimated, the ratios of AUS concurrent precipitation to NWS annual maxima (AUS/NWS) would be too small. Accordingly, the ratios of NWS concurrent precipitation to AUS annual maxima (NWS/AUS) would be too large. If the number of AUS/NWS ratios equaled the number of NWS/AUS ratios, the inter-network empirical S_2 would be expected to be equivalent to the intra-network empirical S_2. However, it is much more common for an AUS station to have more than 10 days of missing record—10 days was the maximum amount of missing record allowed for a station before rejecting a year (fig. 4). Substantially more NWS annual maxima are available; therefore, substantially more negatively biased (smaller) AUS/NWS ratios are available than the positively biased (larger) NWS/AUS ratios. There were 5,707 ratios of AUS concurrent precipitation to NWS annual maxima and 2,483 ratios of NWS concurrent precipitation to AUS annual maxima available. As a result, the inter-network empirical S_2 is systematically too small.

Because of the above arguments, the ratios judged to best represent the spatial distribution of precipitation surrounding annual maxima in the Austin area were the intra-network ratios rather than the inter-network ratios. The intra-network ratios for the AUS and NWS networks were judged compatible and were used in the final analysis (next section).

Empirical S_2 derived from the DAL and NWS networks for the Dallas area are presented in figure 7. Similar to the Austin data (fig. 6), the mean ratios decrease for increasing distance. The intra-network DAL mean ratios are larger than the intra-network NWS mean ratios for comparable distances. However, the two networks show nearly the same mean ratio for separation distances between about 7 to 11 mi—a large number of samples from both networks are available in this range. As in the discussion for the Austin database, the inter-network empirical S_2 is substantially less than the intra-network empirical S_2. There are 3,148 ratios of DAL concurrent precipitation to NWS annual maxima and 2,636 ratios of NWS concurrent precipitation to DAL annual maxima available. The ratios judged to best represent the spatial distribution of precipitation surrounding annual maxima in the Dallas area are intra-network ratios rather than inter-network ratios. The intra-network ratios for the DAL and NWS networks are judged compatible and were used in the final analysis (next section).

Empirical S_2, derived from the NWS, HAR, and HURP networks in the Houston area, are presented in figure 8. These S_2 are analogous to those derived for Austin and Dallas. Conclusions comparable to that presented for Austin and Dallas databases can be made. Specifically, for the inter-network empirical S_2, there are 33,180 ratios of HAR or HURP concurrent precipitation to NWS annual maxima; 19,846 ratios of NWS or HURP concurrent precipitation to HAR annual maxima; and 8,030 ratios of NWS or HAR concurrent precipitation to HURP annual maxima available.

The intra-network HURP mean ratios do not conform with either the intra-network NWS or HAR precipitation mean ratios. An explanation is not readily apparent; however, the HURP stations have considerable missing record and therefore the annual maxima are frequently underestimated. Therefore, only the HAR and NWS intra-network ratios were used in the final analysis (next section).

Empirical Depth-Distance Relations Near Selected Localities

The large sample-ratio files generated by the computer program were used to define various

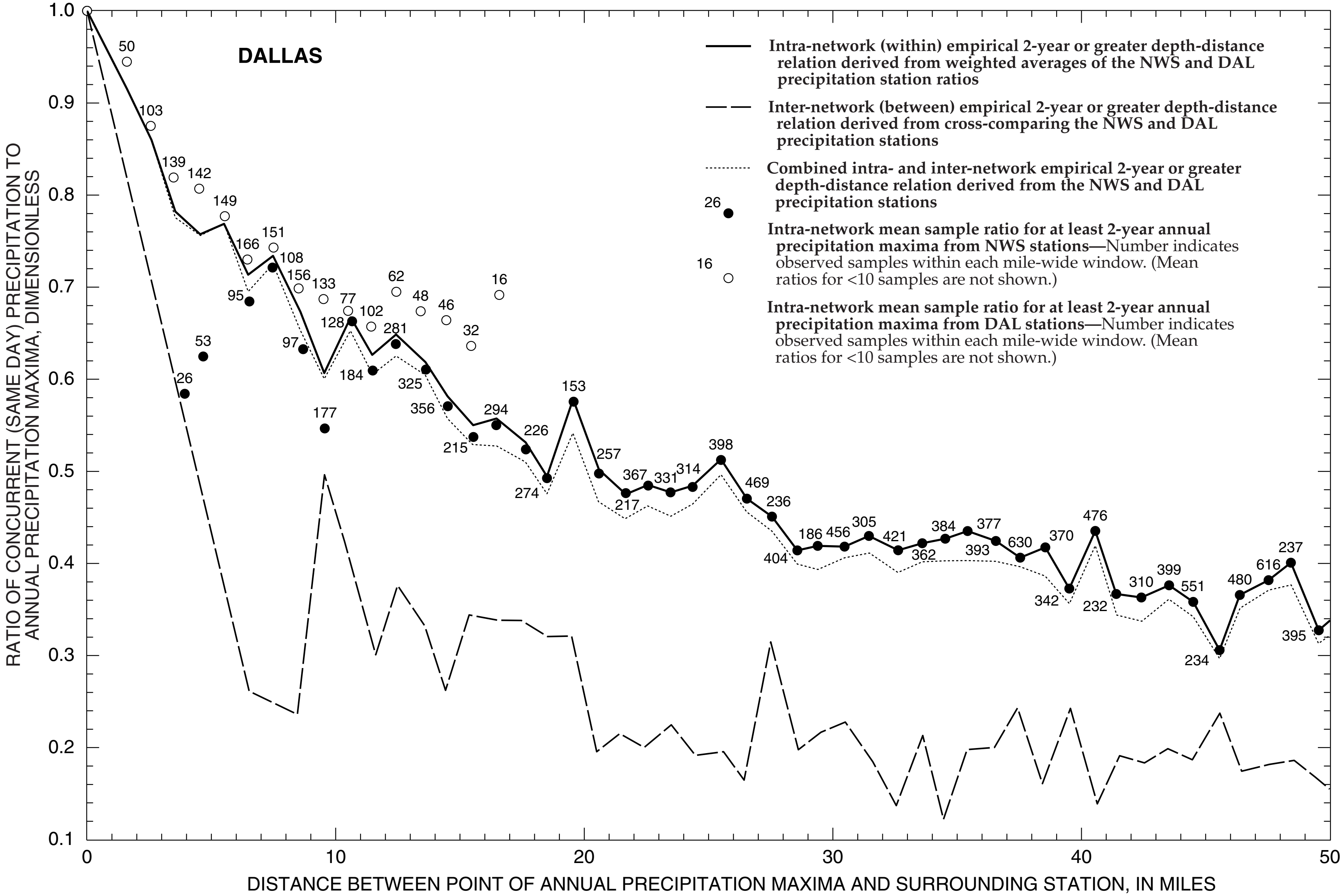


Figure 7. Comparison of empirical 2-year or greater depth-distance relations for two Dallas precipitation-station networks, National Weather Service (NWS) and City of Dallas (DAL).

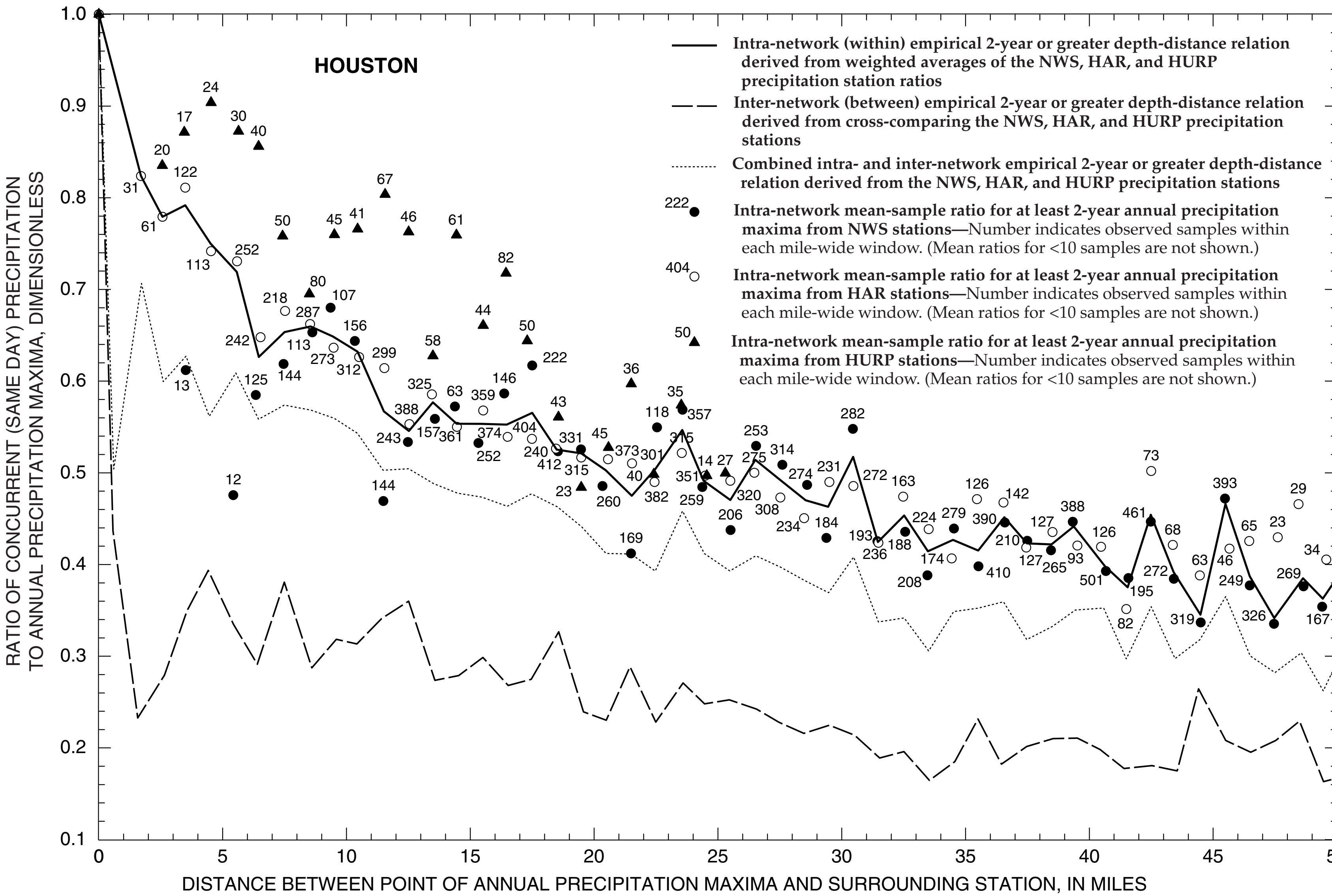


Figure 8. Comparison of empirical 2-year or greater depth-distance relations for three Houston precipitation-station networks: National Weather Service (NWS), Harris County Office of Emergency Management (HAR), and Houston Urban Program (HURP).

empirical S_T. Two major perspectives of S_T are frequency and seasonal considerations. Frequency considerations (or recurrence interval) of S_T are the most important from a design standpoint. Seasonal considerations provide valuable insight into the spatial nature of precipitation surrounding an annual maxima but have limited utility in hydraulic design using an annual risk basis.

Frequency Considerations

The magnitude and frequency of the storm center (the point of an annual maxima) have considerable influence on the expected (average) decrease of ARF with increasing distance from the storm center, which in turn influences the expected areal distribution of precipitation. It is hypothesized that as the maximum point depth (intensity) of a storm increases, the surrounding depths decrease more substantially as area increases. In other words, the rainfall depths for large or very intense storms typically are not as widely or as evenly distributed in space as smaller more frequent storms. Each of the three databases support this hypothesis, as do the pertinent references (for further details, see Myers and Zehr, 1980; or Sivapalan and Blöschl, 1998).

Comparisons between empirical S_T for selected recurrence intervals for Austin, Dallas, and Houston are shown in figures 9–11. As presented earlier, the frequency levels are defined in a cumulative type, that is, the "empirical T-year **or greater** depth-distance relation" (empirical S_T) is derived from only those ratios for which the recurrence interval of the annual maxima of the storm center (central station, fig. 4) was equal to **or greater** than T years and not simply just the "T-year depth-distance relation." The empirical S_T for recurrence intervals greater than 5 years are not presented for Austin and Dallas because the record lengths of the AUS and DAL networks are short. The 5-year recurrence interval corresponds to the 0.80 cumulative annual probability. When the NWS and HAR networks are combined, a larger and denser database is available for Houston than for Austin or Dallas. Therefore, the empirical S_T for 10-year or greater recurrence intervals for Houston is also presented (fig. 11). Several observations of the empirical relations (figs. 9–11) are:

1. A tendency of more rapid decrease (decay) of ARF_T with increasing r for larger recurrence intervals exists. This does not necessarily imply that extremely intense (rare) storms do not produce less rainfall volume than moderately intense (common) storms but indicates that large storms have (on average) a smaller spatial extent.
2. Even with the large number of precipitation stations and sample ratios, accurate estimation of ARF for r less than about 2 mi remains difficult.
3. All of the empirical S_T appear to flatten or level off at ratios of about 0.2 to 0.3 for large r.
4. As recurrence interval of the annual maxima increases, the variability of the empirical S_T increases because of a reduction of sample size for each mile-wide window, which occurs because the available data diminishes.

The summary statistics (similar to table 5) for each of the empirical S_T (figs. 9–11) are listed in Appendices I–III. For the Austin database (App. I), the CV is about 0.5 for small r and increases with recurrence interval. Also, for each recurrence interval, the CV increases substantially with increasing r. Similar behavior of CV is shown for the Dallas (App. II) and Houston (App. III) databases. CV indicates that the spatial variability of precipitation centered on an annual maxima is large. Also, the number of samples for each mile-wide window increases substantially for about 6 to 12 mi and then gradually diminishes for increases in r.

The probability of a station proximate to a site experiencing a 2-year or greater annual maxima in the Austin area recording concurrent zero precipitation increases with increasing r. However, the zero-precipitation probability shows substantial variation and is therefore difficult to assess. The zero-precipitation probability for Austin stations is about 5 to 10 percent for small r and increases for large r. The zero precipitation probabilities for Dallas and Houston show similar magnitudes and trends. The probability of a station close to a 2-year or greater annual maxima in Dallas not recording concurrent precipitation is about 1 to 2 percent for small r, about 7 to 9 percent for moderate r, and about 10 to 12 percent for large r. Likewise, the probability that a station for a 2-year or greater annual maxima in Houston not recording concurrent precipitation is about 3 to 5 percent for small r, about 5 to 7 percent for moderate r, and about 9 to 12 percent for large r. It is expected that the zero probabilities are sensitive to both the systematic and individual station biases. However, the apparent trends are in agreement with the conceptual spatial model used in this report—

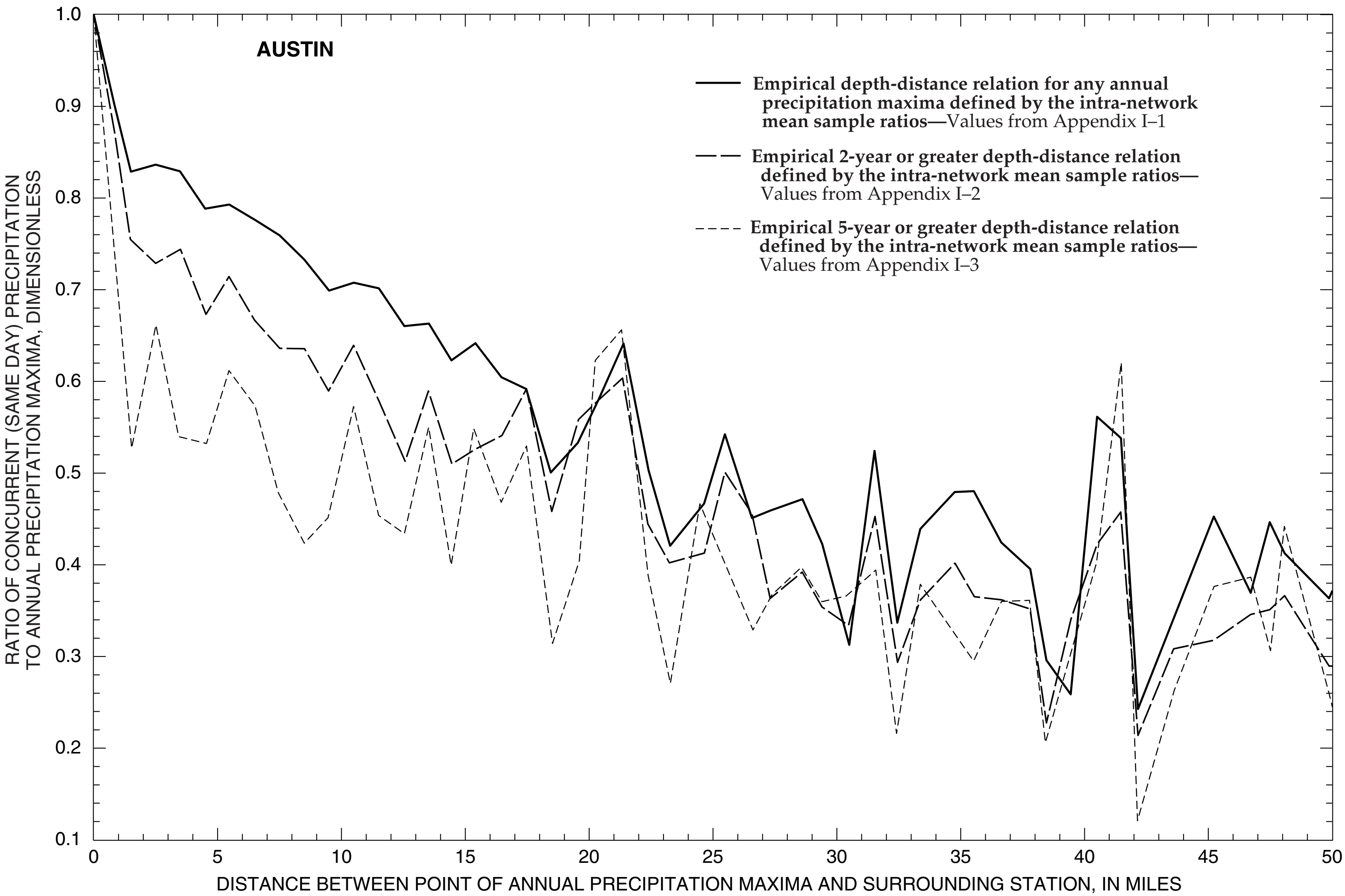


Figure 9. Empirical depth-distance relations for selected recurrence intervals for Austin, Texas.

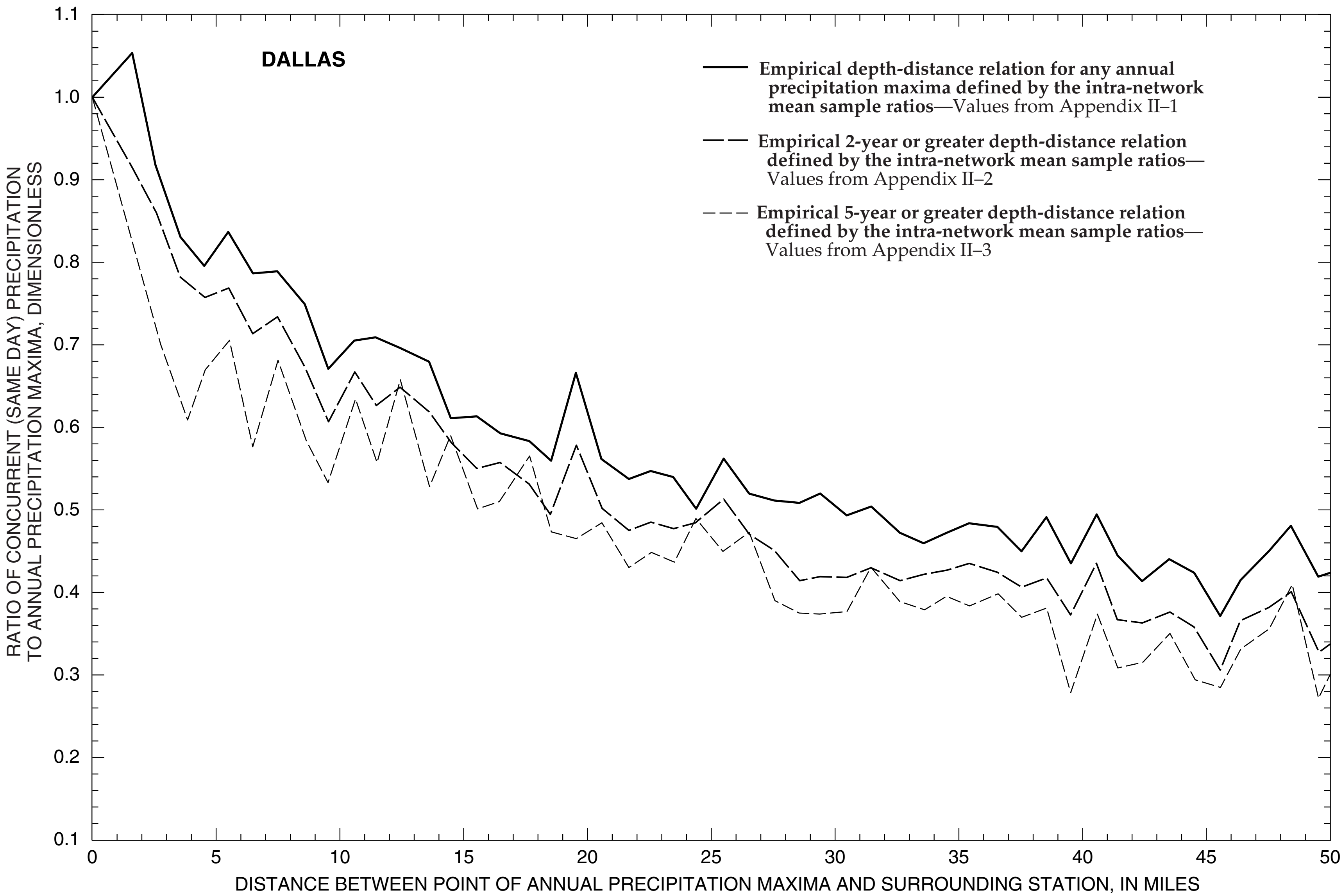


Figure 10. Empirical depth-distance relations for selected recurrence intervals for Dallas, Texas.

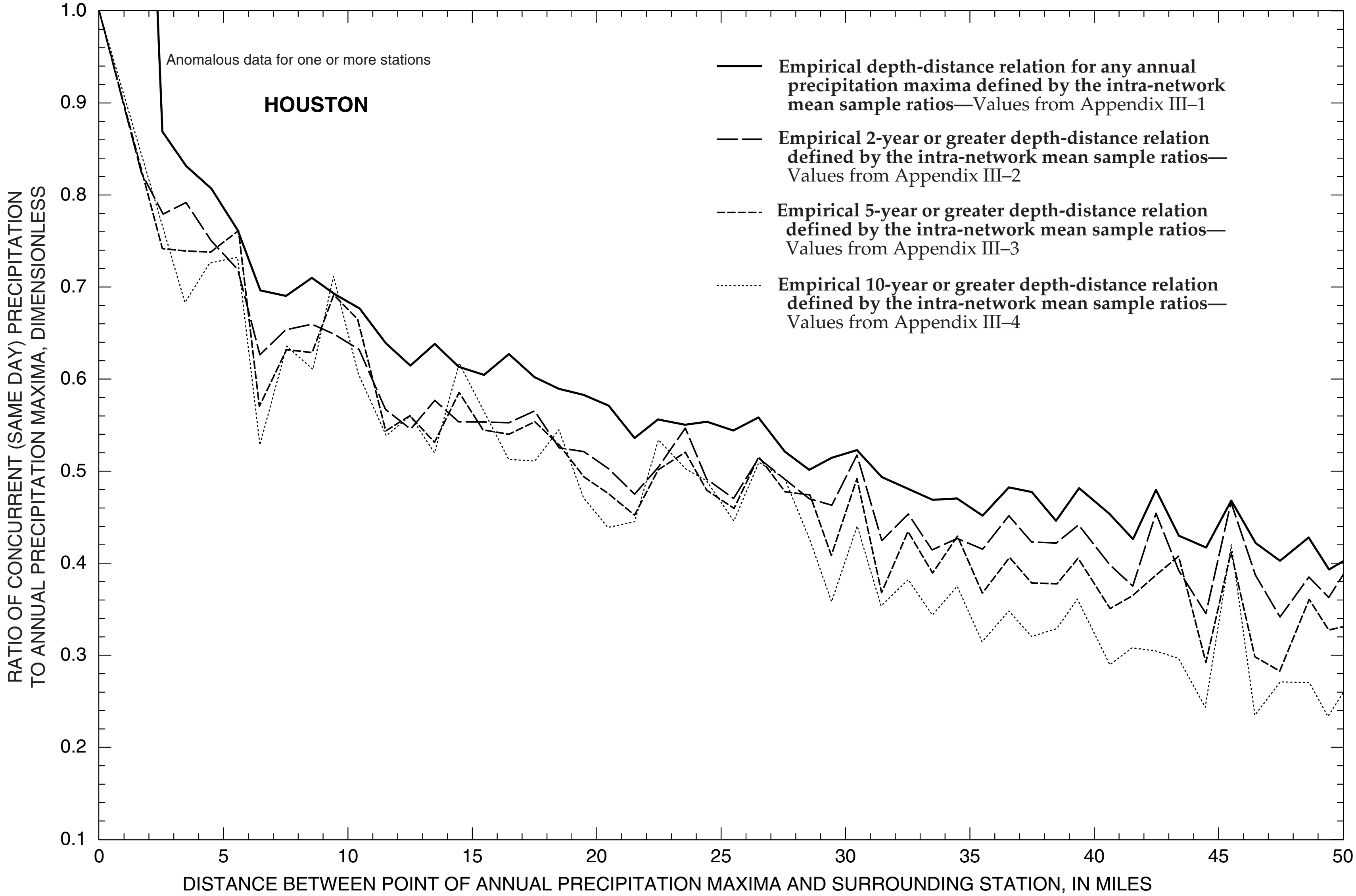


Figure 11. Empirical depth-distance relations for selected recurrence intervals for Houston, Texas.

specifically that a storm decays on average with radial distance away from its intensity center (annual precipitation maxima).

Seasonal Considerations

Detailed discussion of the various climatic and meteorologic factors affecting the areal distribution of precipitation is beyond the scope of this report. Bomar (1995) provides an excellent and detailed discussion of Texas weather.

The season in which an annual maxima occurs has an important influence on the resulting spatial distribution of precipitation. Comparisons between the empirical S_2 for 6-month seasons, termed "summer" and "winter", are presented in figure 12. Summer is defined as April through September, and winter is defined as October through March. The greatest difference between the winter and summer empirical S_2 for the three cities exists for Austin—the winter ratios are larger than the summer ratios. This observation is expected because the winter precipitation in the Austin area is generally from large low pressure systems that originate from the northwest and west. These fronts typically move eastward and show circulation along the frontal boundary to the northeast. Numerous rainfall "cells" are commonly embedded in and along the fronts. Frontal precipitation occurs principally during the winter. Additionally, precipitation from tropical storms and hurricanes that originate from the Gulf of Mexico might contribute to the differences between summer and winter S_2. These storms often produce extensive regional precipitation during late August, September, and October. Contrasted with the winter, most of the summer precipitation largely is due to relatively isolated and largely convective thunderstorms.

The winter and summer S_2 for Dallas are substantially different from each other, though not as different from each other as the winter and summer are for Austin. Like the winter S_2 for Austin, the winter S_2 for Dallas are larger than the summer. Again, this might be expected because Dallas is similarly affected by fronts during the winter season. The summer S_2 for Dallas is larger in magnitude than the summer S_2 for Austin.

The winter and summer S_2 show considerably different results for Houston than for Austin or Dallas. The two S_2 do not show the large separation like those for either Austin or Dallas. The summer S_2 are larger than the winter S_2, although the differences are not large. Houston experiences a more similar climate from month to month than Austin and Dallas because of its immediate proximity to the Gulf of Mexico.

While is it clear that seasonality has a large influence on the spatial distribution of precipitation surrounding an annual maxima, virtually all uses of design storm data rely on an annual probability perspective and therefore, do not use seasonal considerations.

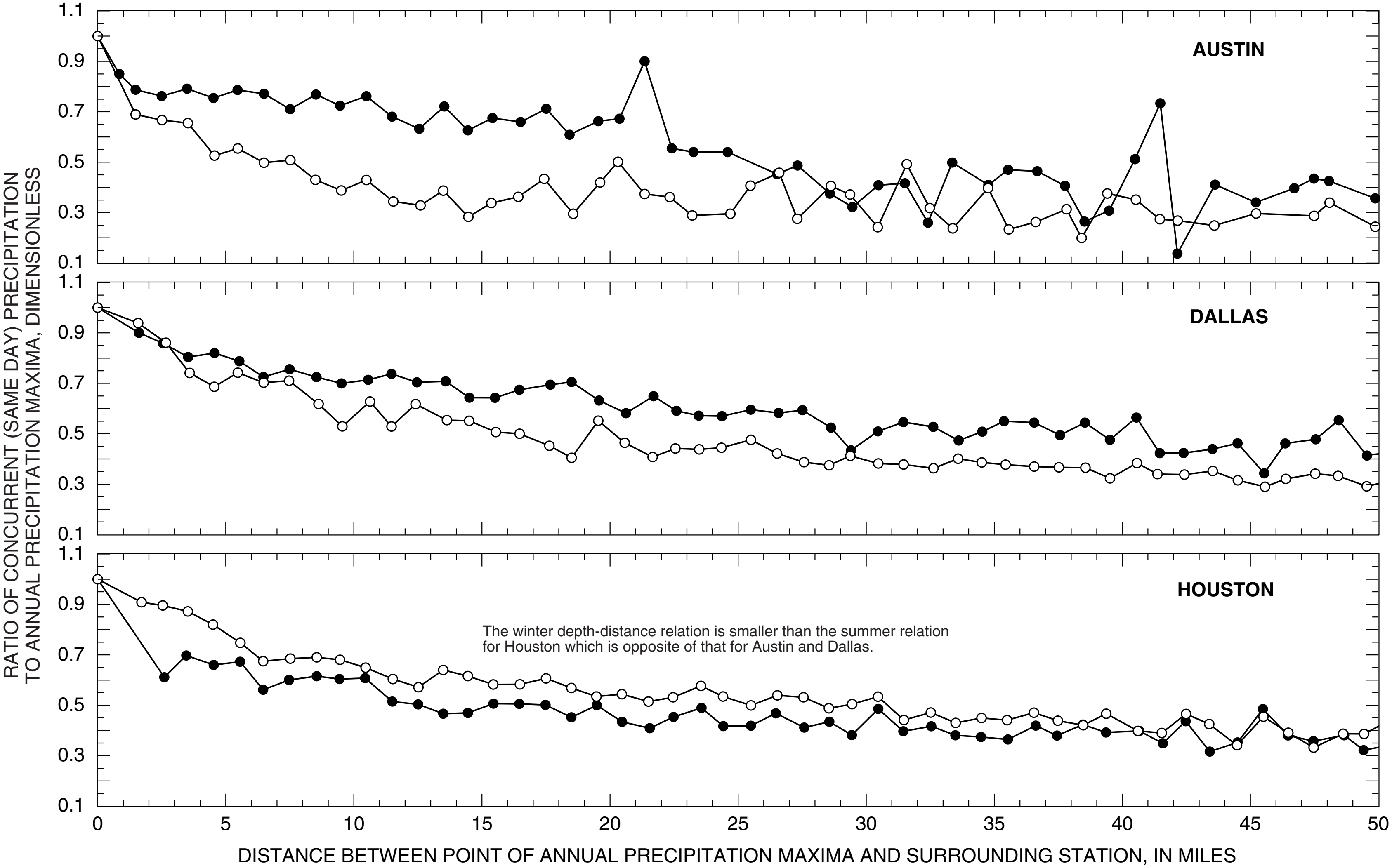
Estimation of Areal-Reduction Factors

The estimated S_T for the calculation of ARF for 1-day design storms near Austin, Dallas, and Houston are presented in this section. Also presented are ARF relations for circular watersheds near these localities.

The final results were limited to only one recurrence interval, that for 2 or more years, because of limited "observation" of data for greater recurrence intervals, for the sake of conservative ARF estimation, and for simplicity of application in hydraulic design. Consequently, estimated S_T for specific recurrence intervals other than 2 or more years are not presented. However, empirical S_T for 5 or more years (Austin, Dallas, and Houston) and 10 or more years (Houston) were discussed in the previous section. These empirical S_T could be used to derive associated values for ARF_T. The number of sample ratios decreases substantially for increasing recurrence intervals for each city; as a consequence, reliable assessment of S_T is difficult for large recurrence intervals. The number of sample ratios for the Austin database decreases from 17,242 (any T year), to 5,226 (2 year), and to 1,293 (5 year). Likewise, for the Dallas database, the number of sample ratios decreases from 41,786 (any T year), to 15,775 (2 year), and to 5,146 (5 year). Finally, the number of sample ratios for the Houston database decreases from 69,370 (any T year), to 21,392 (2 year), to 8,536 (5 year), and to 4,654 (10 year).

The estimated S_T and ARF_T values were derived for those annual precipitation maxima having recurrence intervals of at least 2 years. Empirical S_T for increasingly large recurrence intervals indicate larger decreases in ARF. Consequently, S_2 is negatively biased (underestimated) for recurrence intervals of about 2 years and positively biased (overestimated) for larger recurrence intervals. This should provide conservative estimation (higher values) of areal-reduction factors. The S_2 relation is used to produce the 2-year or greater areal-reduction factor (ARF_2).

Before ARF_2 can be calculated, the estimated S_2 must be defined. A comparison of the empirical S_2 for



EXPLANATION

- Winter (October through March) empirical 2-year or greater depth-distance relation
- Summer (April through September) empirical 2-year or greater depth-distance relation

Figure 12. Empirical 2-year or greater depth-distance relations for winter and summer for Austin, Dallas, and Houston, Texas.

Austin, Dallas, and Houston is presented in figure 13. The estimated S_2 for Austin, Dallas, and Houston are shown in figures 14–16 with the "averaged" relations between S_T and r. The estimated S_2 in the figures are defined by a series of straight-line segments, which were manually fit to the data. The data indicate that the best relation is curvilinear. Exponential-like decay functions, logarithmic and power transformations, were evaluated but proved to be unsatisfactory. Eventually, the straight-line segments were used to define S_2. The equations associated with each straight-line segment in each figure are listed in table 7 (at end of report).

Also shown in figures 14–16 are the intra-network medians (Apps. I–III) for each mile-wide window. Comparison of the mean and the median characterizes the skewness of the distributions. Symmetric distributions have similar median and mean values. Left-skewed distributions have medians that are larger (have longer lower tails) than the means. Right-skewed distributions have medians that are smaller (have longer upper tails) than the means.

The ARF_2 values for circular watersheds were calculated by equation 15 using the depth-distance S_2 equations (table 7). The ARF_2 values for large circular watersheds in the vicinity of Austin, Dallas, and Houston are shown in figure 17. To increase the resolution of the figure, a separate graph showing ARF_2 values for small circular watersheds is shown in figure 18.

The depth-area analysis presented in this report is believed to be the first such analysis done for the 1-day design storm specifically on precipitation-monitoring networks in Texas. Thus, these results should be more directly applicable for Texas than are results from previous studies. The empirical S_2 were derived from databases for each city; thus, the empirical S_2 are more applicable for watersheds in or near these cities. The applicability of S_2 for watersheds probably diminishes with increasing distance from the corresponding city. A further limitation in the use of this report (figs. 17–18, table 7) is that the applicability of the results diminishes as the duration of the design storm increasingly differs from that of 1 day.

A final observation regarding the use of this depth-reduction method is needed. The method is based only on daily rainfall data and represents the 1-day duration, and thus the method is most appropriate for design analyses for basins having about a 1-day time of concentration. Design-storm analyses for watersheds with other times of concentration require rainfall durations other than 1 day. The validity of using the areal-reduction factors from this report for design durations other than 1 day cannot be verified within the scope of this study.

Application of Techniques

Two examples are presented to acquaint the reader with the application of techniques to calculate ARF_2. The first example illustrates the calculation of ARF_2 for a circular watershed. The second example illustrates the calculation of ARF_2 for a noncircular watershed.

Suppose the ARF_2 is needed for a 12.57-mi^2 ($R = 2$ mi) approximately circular watershed in the Austin area. Asquith (1998) shows the 50-year 1-day design storm to be about 8.3 in. and a 100-year 1-day storm to be about 9.5 in. Both recurrence intervals for this example are greater than 2 years, so S_2 is applicable. From table 7, $S_2 = 1.0000 - 0.1400r$ for $0 \le r \le 1$, and $S_2 = 0.9490 - 0.0890r$ for $1 \le r \le 2$. From equation 15, ARF_2 is calculated as:

$$ARF_2 = \frac{\int_0^R 2rS_2(r)dr}{R^2}$$

$$= \frac{2}{(2)^2}\left\{\int_0^1 r[1 - 0.14r]dr + \int_1^2 r[0.949 - 0.089r]dr\right\};$$

$$ARF_2 = \frac{1}{2}\left\{\left[\frac{1}{2}r^2 - \frac{0.14}{3}r^3\right]\Bigg|_0^1 + \left[\frac{0.949}{2}r^2 - \frac{0.089}{3}r^3\right]\Bigg|_1^2\right\}$$

$$= \frac{1}{2}(0.453 + 1.216);$$

$$ARF_2 = 0.83.$$

The effective depth of the 50-year design storm is $Z_{E50} = Z_{50} = 0.83(8.3) = 6.9$ in. and accordingly, Z_{E100} is 0.83(9.5) = 7.9 in. The total volume of Z_{E50} is ($V_{50} = Z_{E50}AREA = 6.9$ in. (12.57 mi^2)) or about 4,626 acre-feet (acre-ft).

The calculation of ARF_2 for a highly noncircular watershed is listed in table 8 (at end of report). This watershed is linear, and its drainage area is nearly

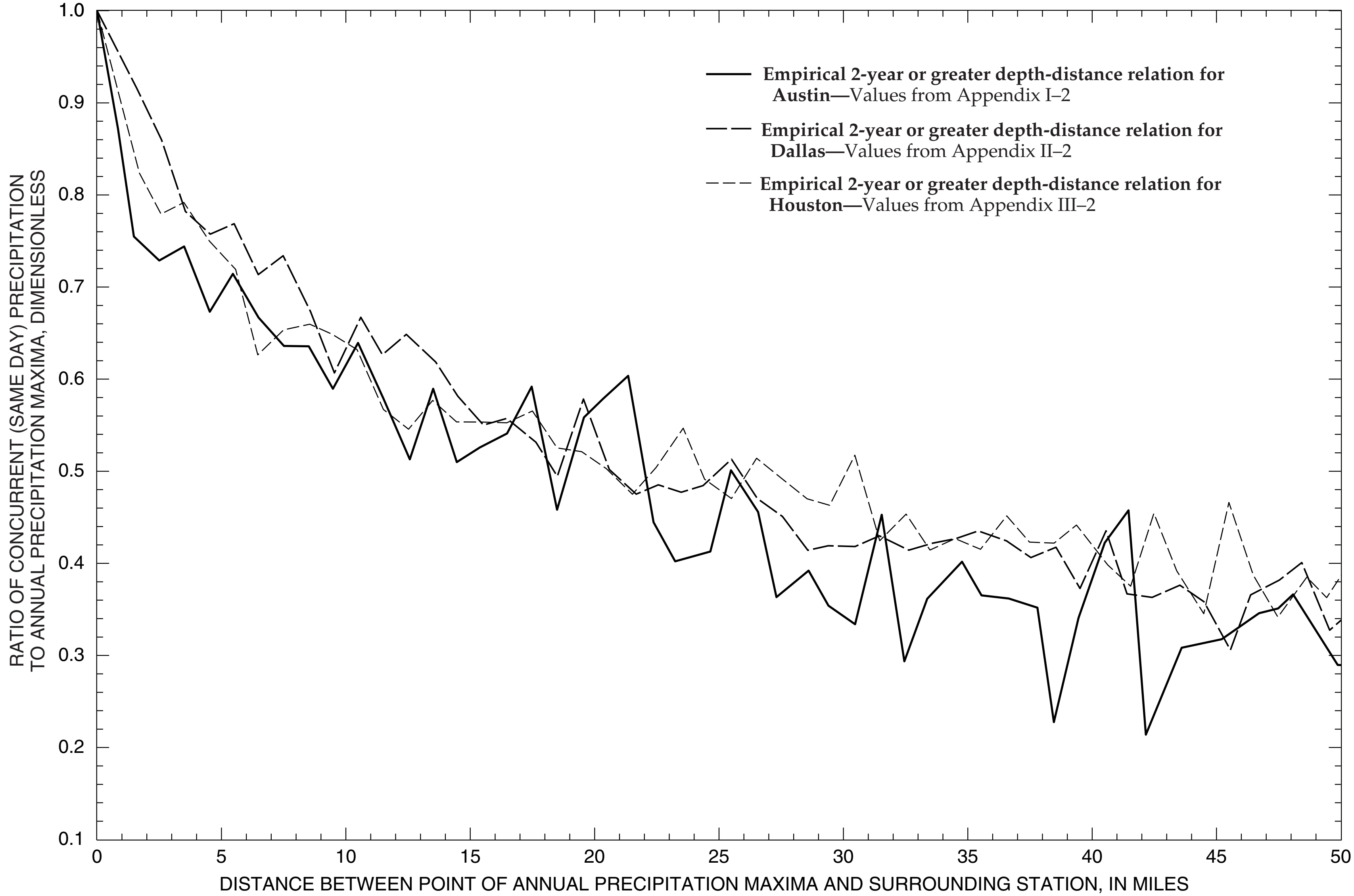


Figure 13. Empirical 2-year or greater depth-distance relations for Austin, Dallas, and Houston, Texas.

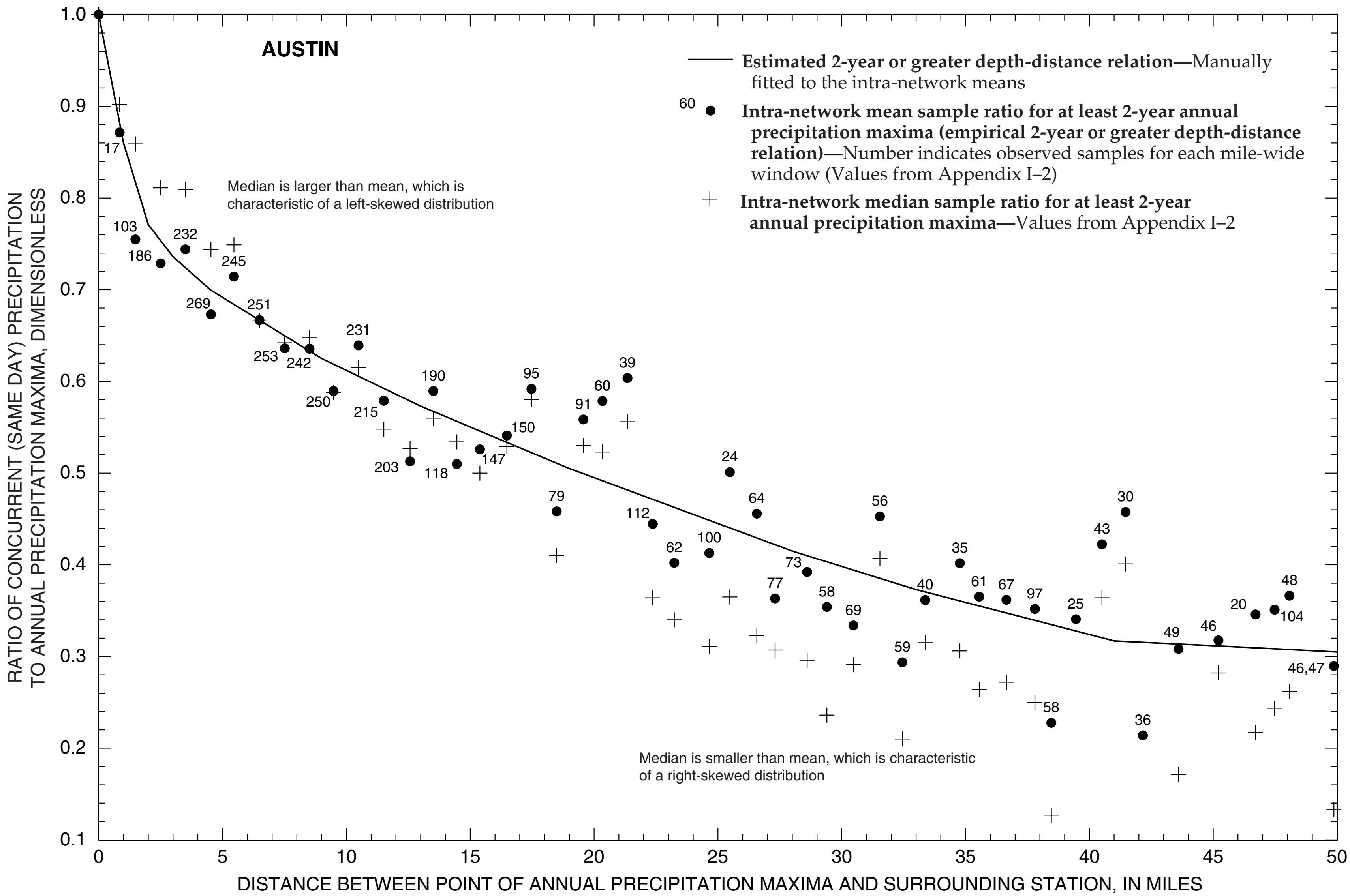


Figure 14. Estimated 2-year or greater depth-distance relations for Austin, Texas.

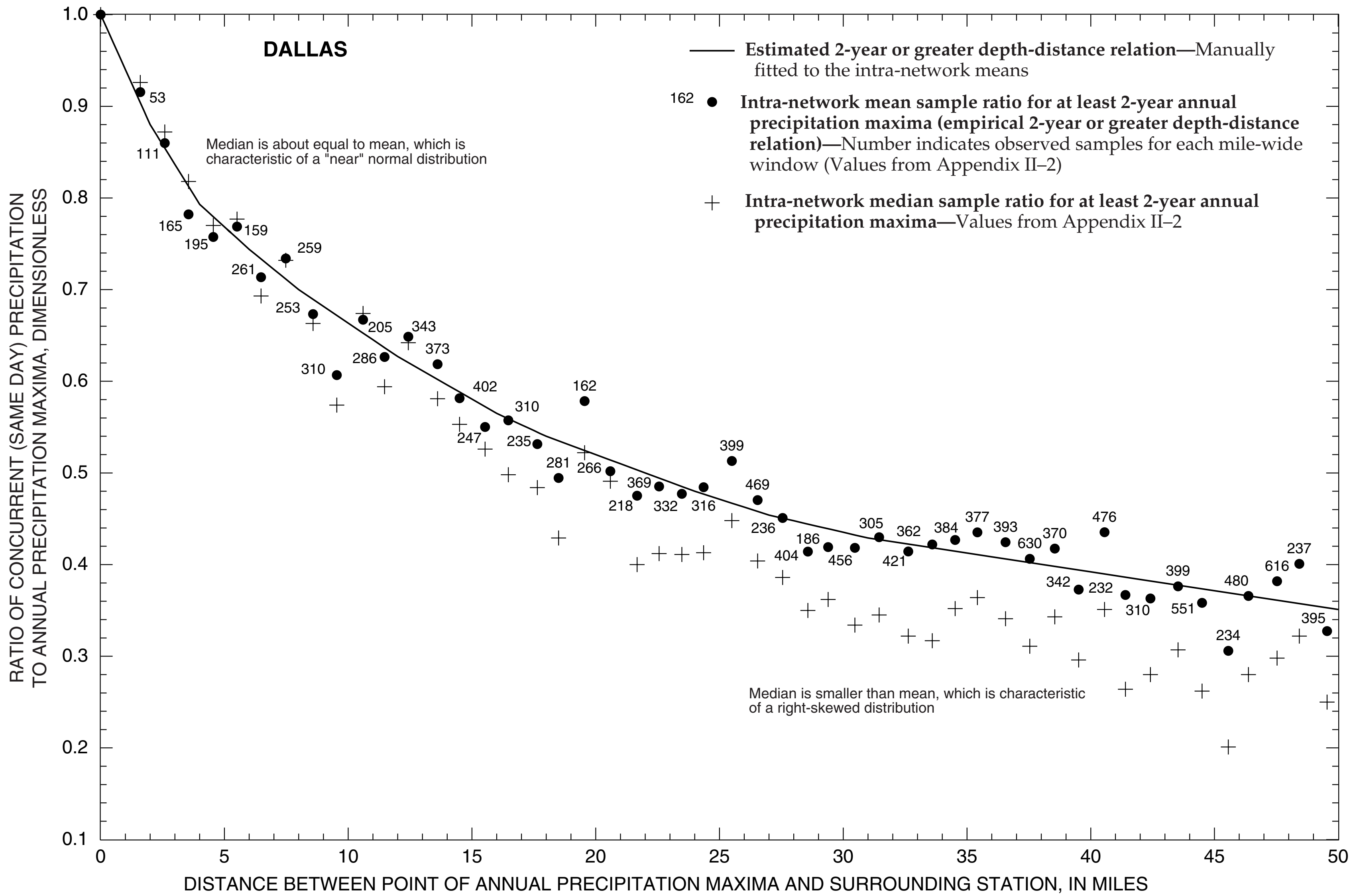


Figure 15. Estimated 2-year or greater depth-distance relations for Dallas, Texas.

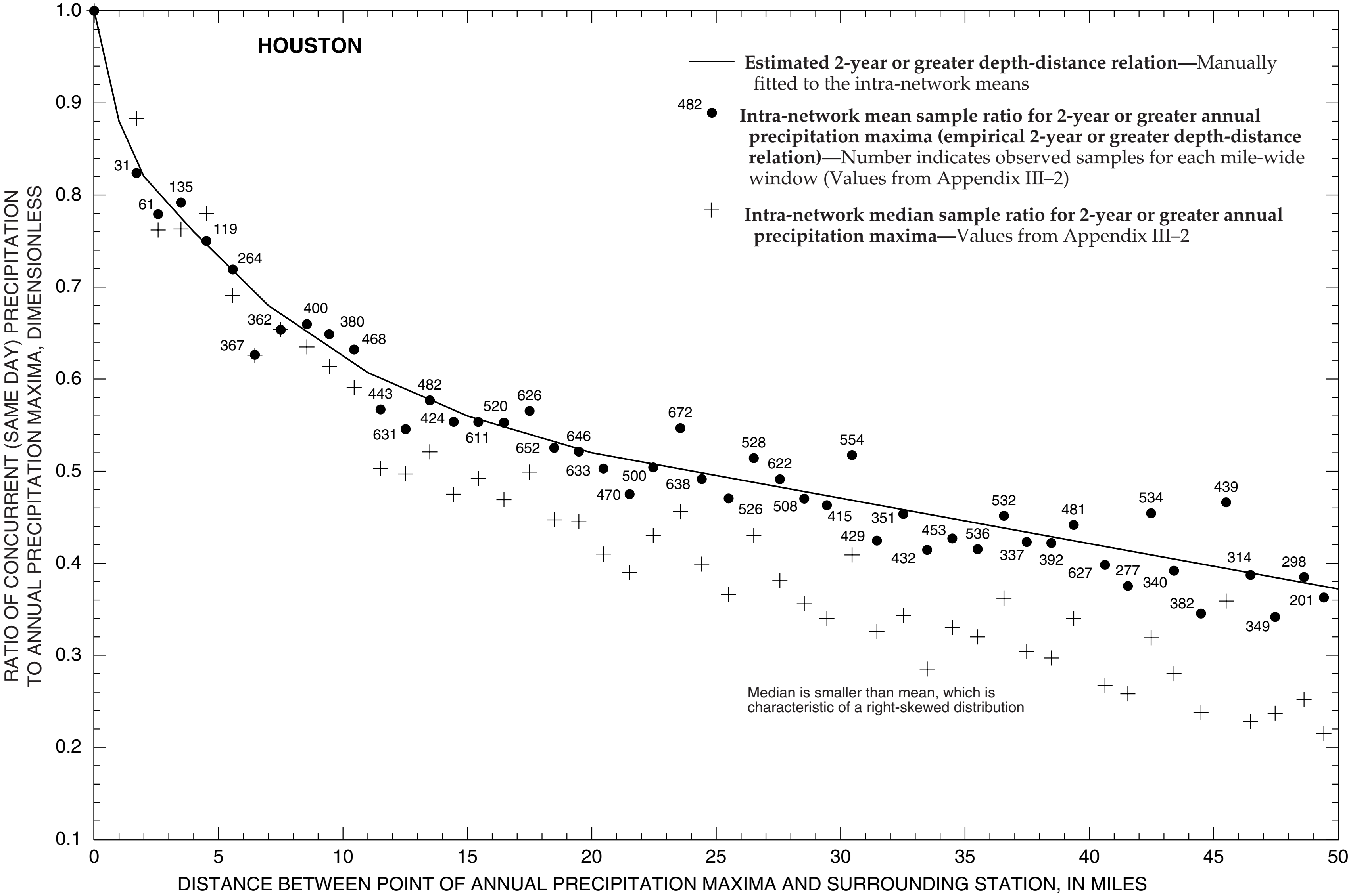


Figure 16. Estimated 2-year or greater depth-distance relations for Houston, Texas.

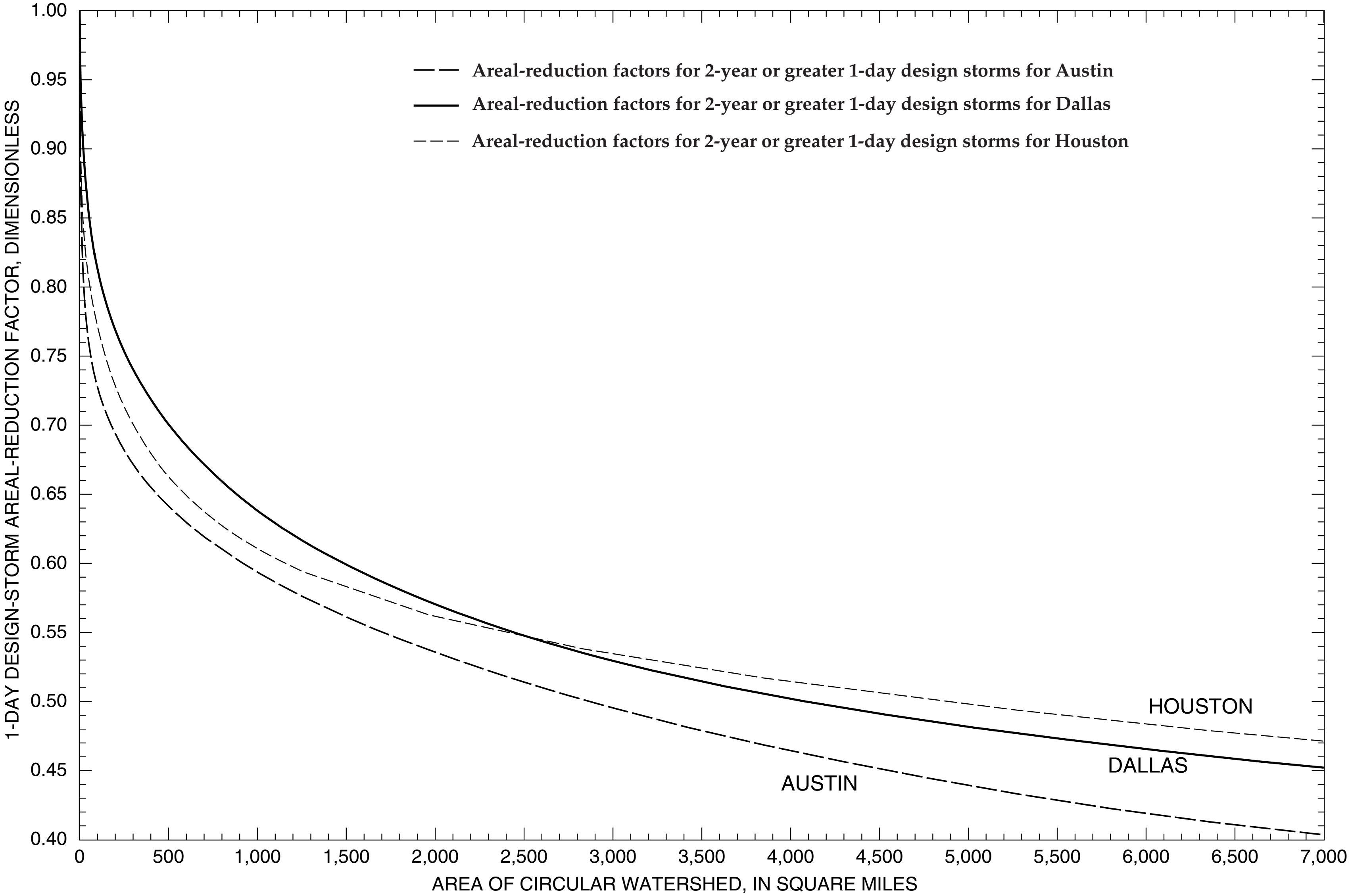


Figure 17. Areal-reduction factors for 2-year or greater 1-day design storms for large circular watersheds for Austin, Dallas, and Houston, Texas.

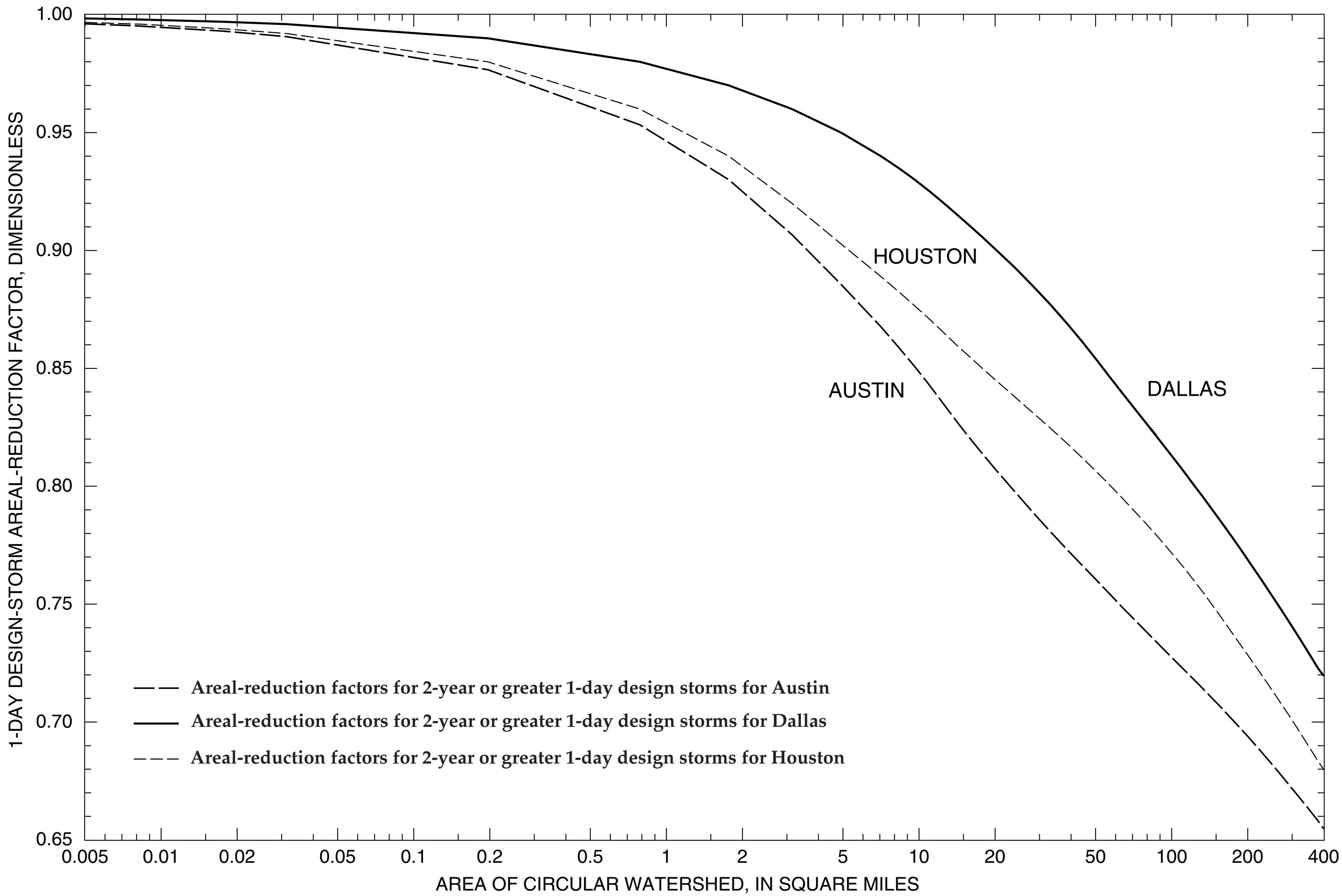


Figure 18. Areal-reduction factors for 2-year or greater 1-day design storms for small circular watersheds for Austin, Dallas, and Houston, Texas.

identical to the above example. The ARF_2 for a watershed is the weighted mean S_2. The steps to calculate ARF_2 are (1) represent the watershed as discrete cells, the cells do not have to have the same area, (2) locate the cell containing the centroid, (3) for each cell, calculate the distance to the centroid, (4) using the distance from step 3, solve the appropriate equations from table 7 for S_2, (5) multiply the S_2 by the corresponding cell area to compute ARF_2, the area multiplication simply acts as a weight for a weighted mean, (6) compute the sum of the cell areas, (7) compute the sum of the product of S_2 and cell area from step 5, and (8) divide the result of step 7 by step 6. These steps are shown in table 8. The ARF_2 is 0.76, which is substantially smaller than the 0.83 computed in the previous circular watershed example. Therefore, watershed shape might significantly influence ARF_2 calculation.

SUMMARY

This report documents an investigation by the U.S. Geological Survey, in cooperation with the Texas Department of Transportation, of areal-reduction factors for the 1-day design storm in Texas. The reduction of the precipitation depth from a design storm for a point to an effective (mean) depth over a watershed is important for cost-effective design of hydraulic structures. A design storm for a point is the depth of precipitation for a specified duration and frequency or recurrence interval. An effective depth can be calculated by multiplying the design-storm depth by an areal-reduction factor. The areal-reduction factor (ARF) is generally defined as the ratio of (1) the mean precipitation depth over a watershed resulting from a design storm to (2) the point depth of the design storm. The areal-reduction factor ranges from 0 to 1, varies with the recurrence interval of the design storm, and is a function of such characteristics as watershed size, watershed shape, geographic location, and time of year that the design storm occurs.

The data for the investigation include the daily values of precipitation as reported (digitally) by various precipitation-station monitoring networks in the vicinity of Austin, Dallas, and Houston. Databases of daily precipitation were separately aggregated for the Austin, Dallas, and Houston areas. Each city database was derived from several precipitation-station monitoring networks. For the Austin area, two daily precipitation networks were identified: the daily values for 25 National Weather Service (NWS) stations and for 83 City of Austin (AUS) stations. For the Dallas area, two daily precipitation networks were identified: the daily values for 58 NWS stations and for 45 City of Dallas (DAL) stations. For the Houston area, three daily precipitation networks were identified: the daily values for 64 NWS stations, for 84 Harris County Office of Emergency Management (HAR) stations, and for 45 USGS Houston Urban Program (HURP) stations. Individually, the Austin, Dallas, and Houston databases have about 248,000; 429,000; and 688,000 daily precipitation values, a total of about 1,365,000 values.

An annual maxima-centered approach was used to analyze the data. From the approach, the "depth-distance relation," $S(r)$, is the basis of ARF definition. $S(r)$ is the ratio of (1) the precipitation at a distance r away from the design storm to (2) the point precipitation of the annual precipitation maxima. Thus, $S(r)$ describes the average radial structure of the precipitation concurrent with and surrounding the point of an annual maxima. ARF is calculated by integrating $S(r)$ over the entire watershed and dividing by the watershed area.

The three city databases provided a total of more than 128,000 "sample ratios" for $r \leq 50$ mi. Though separation distances (r) larger than 50 mi were available, the maximum r presented in this report was limited to 50 mi. The sample ratios were statistically summarized for each mile-wide window of r separation distance. To provide an unbiased separation distance for graphical representation and analysis, the means of the separation distances for each mile-wide window were calculated.Various preliminary or empirical $S(r)$ were estimated from the daily precipitation data. Before a final $S(r)$ was derived from the combination of the networks for each city, two evaluations were performed for each network. One evaluation considered the performance of each network in recording the annual precipitation maxima (a point process); whereas, the other evaluation considered areal distribution of concurrent precipitation surrounding that point of an annual maxima (an areal process).

The point-process evaluation was based on the comparison of observed cumulative annual probabilities to those by definition. The comparison was made, using an "observed cumulative annual probability" calculated by counting the number of times that the observed annual precipitation maxima for a station did not equal or exceed the depth for the defined recurrence interval and dividing the count by the total number of observed annual precipitation maxima (storms). The observed cumulative annual probability was compared to defined probabilities. The defined cumulative annual probabilities for this investigation were 0.10, 0.20, 0.50, 0.80, and 0.90, which correspond to recurrence intervals of 1.111, 1.25, 2, 5, and 10 years. The comparison indicates that each network is systematically underestimating the assumed true precipitation quantiles or depths for the given frequencies. The differences decreased in the tails of the distribution (0.10, left or lower-tail; or 0.90, right or upper tail) for all the networks and were largest near the middle (0.50). The observed-defined probability differences generally were smaller for the NWS stations than for the other station networks. The HURP stations also showed small differences; the HURP stations might provide an independent verification of the daily precipitation frequency values for the Houston area. However, the stations in the HURP network have much more missing record than the NWS stations, which indicated that the HURP stations are really over-recording precipitation, and it is a coincidence that the annual maxima from the HURP stations nearly match the annual maxima from the NWS stations.

The areal-process evaluation is based on comparison of empirical $S(r)$ derived specifically from each network. For example, if the empirical $S(r)$ from each network are similar, then evidence is established that provides assurance that each network was recording essentially the same information about the spatial distribution of precipitation. The empirical $S_2(r)$ used to judge network compatibility was surrounding annual maxima greater than or equal to the 2-year recurrence interval. The intra-network empirical $S_2(r)$ is based on sample ratios derived from the data of each network, independent of the data from the other networks. The inter-network empirical $S_2(r)$ is based on sample ratios derived from cross-comparison of the data from the other networks. The intra- and inter-network lines are substantially different. The presence of a substantial and nonrandom bias is implied by the inter-network empirical $S_2(r)$ clearly not agreeing with the intra-network empirical $S_2(r)$. Potential explanations for the bias were discussed. The bias is removed when only intra-network empirical $S_2(r)$ are used. Thus, only the intra-network $S(r)$ were judged as appropriate for estimating $S_2(r)$. The areal-process evaluation determined that all the intra-network empirical $S_2(r)$ are applicable, except for the intra-network empirical $S_2(r)$ from the HURP network. The HURP network appears to over record precipitation, in agreement with the point-process evaluation. The HURP network was not used for subsequent analysis.

Two major perspectives of $S(r)$ are frequency and seasonal considerations. The magnitude and frequency of the storm center (the point of an annual maxima) has a large influence on the expected (average) decrease of $S(r)$ with increasing distance from the storm center, which in turn influences the expected areal distribution of precipitation. A tendency for more rapid decrease of $S(r)$ with increasing r for larger recurrence intervals exists (figs. 9–11). Even with the considerable number of stations and a very large number of ratios, reliable estimation of ARF for r less than about 2 mi remains difficult. The variability of the empirical $S(r)$ increases with increasing recurrence interval partially because of a systematic reduction of sample size for each mile-wide window.

The season in which an annual maxima occurs has an influence on the resulting spatial distribution of precipitation. Comparisons between the empirical $S_2(r)$ for 6-month seasons termed summer and winter are shown. The $S_2(r)$ for the Austin seasons show the greatest difference for the three cities. The winter relation is larger than the summer relation. The winter and summer $S_2(r)$ for Dallas are substantially different from each other, though not as different as for Austin. Similar to the relations for Austin, the winter relation is larger than the summer relation. The winter and summer $S_2(r)$ for Houston show considerably different results than those for Austin or Dallas. The two Houston $S_2(r)$ do not show the large differences like those for either Austin or Dallas. The summer $S_2(r)$ for Houston is slightly larger than the winter $S_2(r)$.

The final results present only the 2 or more year recurrence interval because of limited "observation" of less frequent annual maxima, for the sake of conservative ARF estimation, and to simplify application of the results. Estimated S_T for specific recurrence intervals greater than 2 years are not included. However, the empirical S_T for 5 years or greater (Austin, Dallas, and Houston) and 10 years or greater (Houston) are included. The number of sample ratios decreases very rapidly for increasing recurrence interval for each city, hence reliable assessment of S_T for recurrence intervals larger than 2 or more years is difficult.

The final or estimated $S_2(r)$ are defined by a series of hand-fit straight-line segments. The underlying relation is curvilinear. Exponential-like decay functions, logarithmic and power transformations, were evaluated but proved to be unsatisfactory. Finally,

ARF_2 is calculated by integrating $S_2(r)$ over the entire watershed and dividing by the watershed area. Graphs of the relation between ARF_2 and circular watershed area (to about 7,000 mi^2) are shown, and a technique to calculate ARF_2 for noncircular watersheds also is discussed.

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Table 1. Stations for two precipitation-monitoring networks near Austin, Texas

[GLO, generalized logistic distribution; in., inches; --, dimensionless; GEV, generalized extreme-value distribution; NWS, National Weather Service; AUS, City of Austin]

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
1	246	246	NWS	Andice 1 W-NW	30°47'	97°52'	28	1968	1995	3.116	0.635	–0.245	2.819	1.007	–0.0954
2	428	428	NWS	Austin Weather Service Office Airport	30°18'	97°42'	66	1930	1995	3.334	.699	–.212	3.003	1.296	–.0954
3	430	430	NWS	Austin Dam	30°18'	97°47'	18	1948	1965	3.330	.693	–.217	2.954	1.235	–.0954
4	432	432	NWS	Austin Montopolis Bridge	30°15'	97°41'	16	1948	1963	3.348	.707	–.209	3.031	1.312	–.0954
5	738	738	NWS	Bertram 3 E-NE	30°45'	98°01'	28	1968	1995	3.068	.630	–.249	2.794	.971	–.0954
6	1250	1250	NWS	Burnet	30°44'	98°14'	87	1909	1995	2.966	.623	–.253	2.748	.962	–.0954
7	1541	1541	NWS	Cedar Creek 4 SE	30°02'	97°28'	18	1978	1995	3.371	.758	–.200	3.248	1.272	–.0954
8	2210	2210	NWS	Cypress Mill	30°23'	98°15'	17	1948	1964	3.222	.667	–.246	2.933	1.022	–.0954
9	2585	2585	NWS	Dripping Springs SE	30°13'	97°59'	12	1984	1995	3.348	.695	–.227	3.210	1.179	–.0954
10	2820	2820	NWS	Elgin	30°21'	97°22'	34	1962	1995	3.333	.729	–.201	3.134	1.267	–.0954
11	3506	3506	NWS	Georgetown	30°38'	97°43'	25	1959	1983	3.219	.662	–.228	2.991	1.186	–.0954
12	3507	3507	NWS	Georgetown Lake	30°41'	97°43'	15	1981	1995	3.194	.654	–.233	2.971	1.138	–.0954
13	3685	3685	NWS	Granger	30°43'	97°26'	28	1968	1995	3.237	.675	–.215	3.011	1.227	–.0954
14	3686	3686	NWS	Granger Dam	30°42'	97°20'	16	1980	1995	3.258	.689	–.209	3.010	1.210	–.0954
15	4088	4088	NWS	Henly	30°12'	98°13'	18	1948	1965	3.362	.692	–.240	3.345	1.128	–.0954
16	5202	5202	NWS	Liberty Hill	30°40'	97°55'	18	1948	1965	3.147	.642	–.244	2.870	1.004	–.0954
17	5284	5284	NWS	Lockhart	29°53'	97°42'	49	1947	1995	3.411	.759	–.202	3.250	1.300	–.0954
18	5538	5538	NWS	Manchaca	30°08'	97°50'	18	1948	1965	3.376	.712	–.213	3.262	1.304	–.0954
19	5561	5561	NWS	Mansfield Dam	30°24'	97°55'	21	1944	1964	3.276	.673	–.231	2.882	1.056	–.0954
20	6992	6992	NWS	Pflugerville	30°26'	97°37'	18	1948	1965	3.296	.689	–.213	3.029	1.306	–.0954
21	7497	7497	NWS	Red Rock	29°58'	97°27'	30	1965	1994	3.385	.769	–.200	3.254	1.280	–.0954
22	7791	7791	NWS	Round Rock 3 NW	30°32'	97°38'	28	1968	1995	3.261	.677	–.220	3.008	1.252	–.0954
23	8531	8531	NWS	Spicewood 1 S	30°29'	98°10'	28	1968	1995	3.195	.659	–.245	2.841	.990	–.0954
24	8861	8861	NWS	Taylor	30°34'	97°25'	67	1929	1995	3.280	.696	–.207	3.041	1.254	–.0954
25	9815	9815	NWS	Wimberley 2	29°59'	98°03'	12	1984	1995	3.423	.726	–.223	3.373	1.297	–.0954

Table 1. Stations for two precipitation-monitoring networks near Austin, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
26	10700	700	AUS	Westlake High School	30°17'24"	97°48'45"	8	1989	1996	3.332	0.692	–0.219	2.943	1.218	–0.0954
27	10800	800	AUS	1301 W. Oltorf St.	30°14'26"	97°46'18"	8	1989	1996	3.349	.701	–.215	3.000	1.282	–.0954
28	10810	810	AUS	St. Edwards Dr.	30°13'48"	97°44'51"	8	1989	1996	3.353	.704	–.213	3.025	1.297	–.0954
29	10820	820	AUS	E. Riverside Dr.	30°13'40"	97°43'13"	8	1989	1996	3.354	.707	–.211	3.045	1.307	–.0954
30	10830	830	AUS	S. I–35/IRS Service Center	30°12'53"	97°44'49"	5	1992	1996	3.357	.706	–.212	3.047	1.302	–.0954
31	10840	840	AUS	3616 S. First St.	30°13'44"	97°46'15"	5	1992	1996	3.353	.703	–.214	3.013	1.288	–.0954
32	10850	850	AUS	S. First/OTC	30°15'27"	97°45'00"	5	1992	1996	3.345	.701	–.214	2.997	1.286	–.0954
33	10910	910	AUS	5100 S. Congress Ave.	30°12'09"	97°46'31"	7	1990	1996	3.360	.706	–.213	3.064	1.296	–.0954
34	10920	920	AUS	Seminary Ridge	30°11'23"	97°49'16"	6	1991	1996	3.362	.705	–.215	3.120	1.284	–.0954
35	11000	1000	AUS	S. Pleasant Valley	30°10'44"	97°44'40"	8	1989	1996	3.366	.711	–.211	3.114	1.311	–.0954
36	11010	1010	AUS	W. Dittmar	30°10'58"	97°47'20"	9	1988	1996	3.364	.708	–.213	3.123	1.299	–.0954
37	11020	1020	AUS	5000 Manchaca	30°13'07"	97°47'38"	8	1989	1996	3.355	.703	–.215	3.029	1.281	–.0954
38	11100	1100	AUS	3400 William Cannon Blvd.	30°12'30"	97°49'40"	8	1989	1996	3.357	.702	–.217	3.066	1.268	–.0954
39	11120	1120	AUS	US 290 W.	30°13'55"	97°51'36"	9	1988	1996	3.348	.698	–.220	3.027	1.230	–.0954
40	11140	1140	AUS	Oak Hill Volunteer Fire Department	30°14'50"	97°54'50"	9	1988	1996	3.340	.693	–.224	3.024	1.184	–.0954
41	11160	1160	AUS	Old San Antonio Hwy. at Slaughter Creek	30°08'48"	97°48'01"	6	1991	1996	3.373	.712	–.212	3.221	1.307	–.0954
42	11180	1180	AUS	FM 1826 at Slaughter Creek	30°12'13"	97°54'31"	7	1990	1996	3.356	.699	–.221	3.157	1.223	–.0954
43	11210	1210	AUS	Loop 360 at Loop 1 (MoPac)	30°14'20"	97°48'13"	5	1992	1996	3.349	.700	–.217	2.994	1.263	–.0954
44	11300	1300	AUS	11100 State Hwy. 71 W.	30°16'48"	97°55'19"	8	1989	1996	3.327	.689	–.226	2.967	1.146	–.0954
45	11500	1500	AUS	St. Stevens School	30°19'45"	97°49'03"	8	1989	1996	3.317	.687	–.221	2.933	1.182	–.0954
46	11520	1520	AUS	Metropolitan Park WX Station	30°19'23"	97°53'20"	9	1988	1996	3.313	.684	–.226	2.908	1.124	–.0954
47	11600	1600	AUS	Mansfield Dam	30°23'41"	97°54'54"	9	1988	1996	3.279	.674	–.230	2.885	1.059	–.0954
48	11800	1800	AUS	Purple Sage School	30°27'28"	97°49'12"	7	1990	1996	3.265	.671	–.228	2.942	1.110	–.0954
49	11810	1810	AUS	Northwest Optimist	30°27'51"	97°46'21"	6	1991	1996	3.269	.673	–.225	2.968	1.150	–.0954
50	11900	1900	AUS	Pflugerville High School	30°26'44"	97°38'12"	9	1988	1996	3.290	.686	–.215	3.021	1.290	–.0954

Table 1. Stations for two precipitation-monitoring networks near Austin, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
51	11910	1910	AUS	Pflugerville/Picadilly	30°28'04"	97°39'22"	8	1989	1996	3.281	0.682	–0.217	3.013	1.266	–0.0954
52	12000	2000	AUS	Old Manor Rd. at Walnut Creek	30°19'20"	97°39'03"	9	1988	1996	3.330	.699	–.210	3.017	1.312	–.0954
53	12010	2010	AUS	Dessau Rd. at Walnut Creek	30°22'29"	97°39'37"	10	1987	1996	3.314	.692	–.213	3.010	1.300	–.0954
54	12020	2020	AUS	12100 N. I–35	30°23'29"	97°40'32"	9	1988	1996	3.307	.689	–.215	3.005	1.284	–.0954
55	12030	2030	AUS	Blue Goose Rd.	30°20'58"	97°37'46"	7	1990	1996	3.322	.698	–.210	3.021	1.317	–.0954
56	12050	2050	AUS	1500 Howard Ln.	30°25'36"	97°40'34"	7	1990	1996	3.294	.685	–.216	3.005	1.266	–.0954
57	12060	2060	AUS	12000 Metric Blvd.	30°24'05"	97°41'52"	4	1993	1996	3.302	.686	–.217	2.998	1.258	–.0954
58	12070	2070	AUS	4000 Oak Creek Dr.	30°25'47"	97°42'43"	7	1990	1996	3.290	.681	–.219	2.992	1.225	–.0954
59	12080	2080	AUS	3700 Duval Rd. at Loop 1 (MoPac)	30°24'38"	97°43'12"	7	1990	1996	3.297	.683	–.219	2.988	1.226	–.0954
60	12090	2090	AUS	7000 FM 969	30°16'38"	97°39'06"	7	1990	1996	3.343	.705	–.208	3.026	1.316	–.0954
61	12100	2100	AUS	5300 Duval Rd./Fire Station	30°24'45"	97°44'12"	9	1988	1996	3.294	.682	–.220	2.978	1.206	–.0954
62	12120	2120	AUS	Howard Ln. at Abbott	30°26'52"	97°42'13"	9	1988	1996	3.284	.680	–.219	2.996	1.224	–.0954
63	12140	2140	AUS	6500 CC Dr.	30°26'30"	97°44'40"	9	1988	1996	3.282	.677	–.222	2.977	1.185	–.0954
64	12200	2200	AUS	E. Rundberg Ln. at Fire Station	30°21'30"	97°40'42"	8	1989	1996	3.318	.693	–.214	3.005	1.293	–.0954
65	12210	2210	AUS	2700 Loyola Ln.	30°18'44"	97°40'40"	9	1988	1996	3.332	.699	–.211	3.009	1.304	–.0954
66	12220	2220	AUS	8700 Georgian Dr.	30°21'15"	97°41'42"	8	1989	1996	3.318	.692	–.215	3.000	1.283	–.0954
67	12230	2230	AUS	7500 Bennett Ave.	30°19'48"	97°41'50"	8	1989	1996	3.326	.695	–.213	3.000	1.289	–.0954
68	12240	2240	AUS	8800 Cameron Rd.	30°20'34"	97°40'45"	8	1989	1996	3.323	.694	–.213	3.006	1.296	–.0954
69	12300	2300	AUS	1000 Rutland Dr.	30°21'59"	97°41'58"	9	1988	1996	3.314	.690	–.216	2.998	1.274	–.0954
70	12320	2320	AUS	9100 Parkfield Dr.	30°21'55"	97°42'40"	9	1988	1996	3.313	.689	–.216	2.994	1.262	–.0954
71	12340	2340	AUS	Golden Meadow Dr.	30°22'49"	97°42'38"	9	1988	1996	3.308	.687	–.217	2.994	1.255	–.0954
72	12370	2370	AUS	1600 W. Enfield Rd.	30°17'37"	97°45'50"	8	1989	1996	3.333	.695	–.216	2.963	1.256	–.0954
73	12380	2380	AUS	W. 12th St. at Shoal Creek	30°16'35"	97°45'00"	8	1989	1996	3.339	.698	–.214	2.983	1.276	–.0954
74	12400	2400	AUS	W. 45th St. at Shoal Creek	30°18'55"	97°44'53"	8	1989	1996	3.327	.693	–.215	2.973	1.256	–.0954
75	12410	2410	AUS	6500 Arroyo Seca	30°20'13"	97°43'56"	8	1989	1996	3.321	.692	–.216	2.986	1.257	–.0954

Table 1. Stations for two precipitation-monitoring networks near Austin, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
76	12500	2500	AUS	6700 Shoal Creek Blvd.	30°20'46"	97°44'42"	8	1989	1996	3.317	0.690	–0.217	2.980	1.239	–0.0954
77	12520	2520	AUS	3000 Foster Ln. at Shoal Creek	30°21'27"	97°44'20"	9	1988	1996	3.313	.689	–.217	2.983	1.238	–.0954
78	12540	2540	AUS	7600 Woodhollow	30°21'49"	97°45'17"	8	1989	1996	3.310	.687	–.219	2.973	1.218	–.0954
79	12550	2550	AUS	Loop 1 (MoPac) at US 183 at frontage road	30°22'27"	97°43'28"	7	1990	1996	3.309	.687	–.218	2.989	1.242	–.0954
80	12600	2600	AUS	FM 1826 at Goldwood	30°08'42"	97°58'18"	8	1989	1996	3.374	.705	–.223	3.323	1.243	–.0954
81	12720	2720	AUS	FM 967 at Buda and Onion Creek	30°05'47"	97°50'47"	7	1990	1996	3.385	.717	–.213	3.301	1.312	–.0954
82	12730	2730	AUS	900 Barton Creek Blvd.	30°17'27"	97°51'19"	7	1990	1996	3.329	.690	–.222	2.941	1.184	–.0954
83	12750	2750	AUS	11200 Brodie Ln.	30°09'45"	97°51'50"	7	1990	1996	3.369	.707	–.217	3.226	1.281	–.0954
84	12790	2790	AUS	William Cannon Dr. at Onion Creek	30°10'21"	97°45'03"	5	1992	1996	3.367	.712	–.211	3.126	1.311	–.0954
85	12900	2900	AUS	Del Valle School	30°12'55"	97°39'53"	6	1991	1996	3.357	.713	–.207	3.069	1.315	–.0954
86	13000	3000	AUS	E. 12th St. at Red River	30°16'20"	97°44'06"	6	1991	1996	3.341	.700	–.213	2.998	1.288	–.0954
87	13100	3100	AUS	4400 Ave. F	30°18'28"	97°43'38"	9	1988	1996	3.330	.696	–.214	2.990	1.278	–.0954
88	13110	3110	AUS	38th St. at Guadalupe St.	30°18'11"	97°44'27"	8	1989	1996	3.331	.696	–.215	2.980	1.269	–.0954
89	13120	3120	AUS	500 Koenig Ln. at FM 2222	30°19'22"	97°43'21"	9	1988	1996	3.326	.694	–.214	2.989	1.274	–.0954
90	13130	3130	AUS	3200 Hemphill Park	30°17'49"	97°44'08"	5	1992	1996	3.333	.697	–.214	2.986	1.277	–.0954
91	13200	3200	AUS	3700 Oak Springs Dr.	30°16'25"	97°41'35"	8	1989	1996	3.342	.703	–.210	3.014	1.306	–.0954
92	13210	3210	AUS	MLK Blvd. at Morris Williams Golf Course	30°17'06"	97°41'12"	9	1988	1996	3.339	.702	–.210	3.011	1.306	–.0954
93	13220	3220	AUS	2100 E. 51st St.	30°18'15"	97°41'38"	9	1988	1996	3.333	.699	–.212	3.004	1.299	–.0954
94	13300	3300	AUS	5300 Manor Rd.	30°18'00"	97°41'07"	10	1987	1996	3.335	.700	–.211	3.008	1.303	–.0954
95	13310	3310	AUS	1650 Webberville Rd.	30°16'40"	97°40'52"	9	1988	1996	3.341	.703	–.210	3.016	1.309	–.0954
96	13320	3320	AUS	3320 Berkman Dr.	30°18'48"	97°41'37"	9	1988	1996	3.331	.697	–.212	3.003	1.297	–.0954
97	13400	3400	AUS	2600 Webberville Rd.	30°15'49"	97°42'44"	8	1989	1996	3.344	.703	–.211	3.014	1.301	–.0954
98	13410	3410	AUS	2900 Manor Rd.	30°17'09"	97°42'38"	9	1988	1996	3.338	.700	–.212	3.002	1.296	–.0954
99	13500	3500	AUS	5400 US 183 S.	30°10'14"	97°41'39"	8	1989	1996	3.367	.716	–.208	3.130	1.315	–.0954
100	13600	3600	AUS	Canyon Vista School	30°25'37"	97°47'17"	9	1988	1996	3.282	.677	–.225	2.949	1.148	–.0954

Table 1. Stations for two precipitation-monitoring networks near Austin, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
101	13610	3610	AUS	River Place at FM 2222	30°23'51"	97°50'40"	8	1989	1996	3.287	0.677	–0.226	2.915	1.105	–0.0954
102	13620	3620	AUS	8300 Fathom Cir.	30°25'55"	97°46'09"	7	1990	1996	3.282	.677	–.224	2.960	1.165	–.0954
103	13630	3630	AUS	10700 Floral Park	30°24'32"	97°45'35"	8	1989	1996	3.292	.681	–.222	2.959	1.185	–.0954
104	13700	3700	AUS	Loop 360 at Bull Creek	30°22'40"	97°46'39"	9	1988	1996	3.302	.684	–.221	2.948	1.185	–.0954
105	13710	3710	AUS	Long Canyon Volunteer Fire Department	30°22'30"	97°49'25"	6	1991	1996	3.299	.681	–.223	2.912	1.138	–.0954
106	14800	4800	AUS	Texas Instruments WX Station	30°25'55"	97°45'04"	8	1989	1996	3.285	.678	–.222	2.971	1.183	–.0954
107	14900	4900	AUS	McKinney Falls	30°10'20"	97°43'00"	9	1988	1996	3.367	.714	–.209	3.128	1.315	–.0954
108	15000	5000	AUS	Decker WX Station	30°16'36"	97°36'32"	9	1988	1996	3.341	.709	–.206	3.044	1.317	–.0954

Table 2. Stations for two precipitation-monitoring networks near Dallas, Texas

[GLO, generalized logistic distribution; in., inches; --, dimensionless; GEV, generalized extreme-value distribution; NWS, National Weather Service; DAL, City of Dallas]

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
1	129	129	NWS	Aledo 4 SE	32°39'	97°34'	35	1960	1995	3.220	0.720	–0.220	2.920	1.050	–0.0954
2	201	201	NWS	Alvarado	32°25'	97°13'	16	1948	1964	3.320	.740	–.210	2.990	1.100	–.0954
3	262	262	NWS	Anna	33°21'	96°31'	47	1948	1995	3.620	.800	–.220	3.260	1.240	–.0954
4	337	337	NWS	Arlington	32°42'	97°07'	47	1948	1995	3.340	.750	–.220	2.990	1.110	–.0954
5	440	440	NWS	Avalon	32°12'	96°47'	31	1964	1995	3.470	.780	–.200	3.100	1.200	–.0954
6	518	518	NWS	Bardwell Dam	32°16'	96°38'	30	1965	1995	3.520	.790	–.200	3.150	1.210	–.0954
7	691	691	NWS	Benbrook Dam	32°39'	97°27'	46	1949	1995	3.250	.730	–.220	2.950	1.070	–.0954
8	996	996	NWS	Boyd	33°04'	97°34'	47	1948	1995	3.230	.710	–.230	2.980	1.090	–.0954
9	1063	1063	NWS	Bridgeport	33°13'	97°46'	47	1948	1995	3.180	.700	–.230	2.970	1.070	–.0954
10	1245	1245	NWS	Burleson 2 S-SW	32°31'	97°20'	37	1948	1985	3.280	.730	–.220	2.970	1.080	–.0954

Table 2. Stations for two precipitation-monitoring networks near Dallas, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
11	1490	1490	NWS	Carrollton	32°59'	96°54'	47	1948	1995	3.410	0.770	–0.220	3.080	1.170	–0.0954
12	1573	1573	NWS	Celina	33°19'	96°48'	35	1948	1983	3.460	.790	–.220	3.250	1.210	–.0954
13	1800	1800	NWS	Cleburne	32°20'	97°24'	80	1915	1995	3.270	.720	–.220	2.960	1.090	–.0954
14	2080	2080	NWS	Crandall	32°38'	96°28'	34	1960	1994	3.610	.790	–.200	3.180	1.210	–.0954
15	2242	2242	NWS	Dallas-Fort Worth Regional Weather Service Office Airport	32°54'	97°02'	21	1974	1995	3.370	.750	–.220	3.010	1.140	–.0954
16	2244	2244	NWS	Dallas FAA Airport	32°51'	96°51'	47	1948	1995	3.430	.770	–.210	3.040	1.170	–.0954
17	2334	2334	NWS	Decatur	33°14'	97°36'	23	1972	1995	3.230	.710	–.230	3.030	1.110	–.0954
18	2403	2403	NWS	Denton	33°14'	97°08'	16	1949	1965	3.360	.750	–.220	3.140	1.170	–.0954
19	2677	2677	NWS	Eagle Mountain Lake	32°53'	97°27'	17	1978	1995	3.260	.720	–.220	2.970	1.070	–.0954
20	2925	2925	NWS	Ennis	32°20'	96°38'	40	1951	1991	3.520	.790	–.200	3.140	1.200	–.0954
21	3080	3080	NWS	Farmersville	33°11'	96°22'	48	1947	1995	3.700	.800	–.210	3.250	1.240	–.0954
22	3133	3133	NWS	Ferris	32°32'	96°40'	45	1950	1995	3.510	.780	–.210	3.100	1.200	–.0954
23	3283	3283	NWS	Fort Worth Weather Service Office Airport	32°50'	97°03'	20	1953	1973	3.360	.750	–.220	2.990	1.130	–.0954
24	3284	3284	NWS	Fort Worth Meacham Weather Service Office Airport	32°49'	97°21'	3	1992	1995	3.280	.730	–.220	2.970	1.080	–.0954
25	3286	3286	NWS	Fort Worth Vickery Blvd.	32°44'	97°20'	13	1953	1966	3.280	.730	–.220	2.970	1.080	–.0954
26	3370	3370	NWS	Frisco	33°09'	96°50'	29	1966	1995	3.440	.780	–.220	3.180	1.190	–.0954
27	3476	3476	NWS	Garza Little Elm Dam	33°04'	97°01'	14	1949	1963	3.370	.760	–.220	3.090	1.160	–.0954
28	3691	3691	NWS	Grapevine Dam	32°58'	97°03'	46	1949	1995	3.360	.750	–.220	3.030	1.140	–.0954
29	3822	3822	NWS	Gunter 5 S	33°22'	96°46'	47	1948	1995	3.480	.790	–.220	3.260	1.220	–.0954
30	4597	4597	NWS	Joe Pool Lake	32°38'	97°01'	11	1984	1995	3.370	.760	–.210	2.990	1.130	–.0954
31	4705	4705	NWS	Kaufman 3 SE	32°33'	96°16'	80	1915	1995	3.720	.800	–.200	3.260	1.220	–.0954
32	4761	4761	NWS	Kennedale 6 S-SW	32°33'	97°14'	32	1949	1981	3.310	.740	–.210	2.990	1.090	–.0954
33	4914	4914	NWS	Lake Ray Hubbard	32°48'	96°29'	15	1978	1993	3.610	.790	–.210	3.180	1.220	–.0954
34	4977	4977	NWS	Lake Dallas	33°07'	97°02'	9	1947	1956	3.370	.760	–.220	3.110	1.160	–.0954
35	5094	5094	NWS	Lavon Dam	33°02'	96°29'	46	1949	1995	3.620	.800	–.210	3.220	1.230	–.0954

Table 2. Stations for two precipitation-monitoring networks near Dallas, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
36	5191	5191	NWS	Lewisville	33°03'	97°00'	12	1947	1959	3.380	0.760	–0.220	3.080	1.160	–0.0954
37	5216	5216	NWS	Lillian	32°30'	97°11'	12	1947	1959	3.320	.750	–.210	3.000	1.100	–.0954
38	5258	5258	NWS	Little Elm	33°10'	96°56'	20	1946	1966	3.400	.770	–.220	3.160	1.180	–.0954
39	5560	5560	NWS	Mansfield	32°34'	97°09'	17	1947	1964	3.330	.750	–.210	3.000	1.100	–.0954
40	5646	5646	NWS	Marys Creek	32°44'	97°30'	26	1947	1973	3.240	.720	–.220	2.940	1.060	–.0954
41	5766	5766	NWS	McKinney 3 S	33°10'	96°37'	80	1915	1995	3.530	.790	–.210	3.220	1.220	–.0954
42	5896	5896	NWS	Midlothian	32°29'	97°03'	17	1947	1964	3.370	.760	–.210	3.000	1.120	–.0954
43	6116	6116	NWS	Mountain Creek	32°43'	96°56'	17	1947	1964	3.400	.760	–.210	3.000	1.150	–.0954
44	7028	7028	NWS	Pilot Point	33°23'	96°58'	48	1947	1995	3.410	.780	–.220	3.240	1.200	–.0954
45	7165	7165	NWS	Poolville	32°58'	97°52'	10	1947	1957	3.150	.700	–.230	2.870	1.030	–.0954
46	7495	7495	NWS	Red Oak	32°31'	96°48'	30	1964	1994	3.450	.780	–.210	3.040	1.180	–.0954
47	7588	7588	NWS	Richardson	32°59'	96°45'	45	1950	1995	3.460	.780	–.210	3.120	1.190	–.0954
48	7659	7659	NWS	Roanoke	33°00'	97°14'	48	1947	1995	3.320	.740	–.220	3.010	1.110	–.0954
49	7707	7707	NWS	Rockwall	32°56'	96°28'	49	1946	1995	3.620	.800	–.210	3.210	1.220	–.0954
50	7773	7773	NWS	Rosser	32°28'	96°27'	48	1947	1995	3.610	.800	–.200	3.200	1.210	–.0954
51	8043	8043	NWS	Sanger	33°22'	97°10'	5	1990	1995	3.360	.750	–.220	3.190	1.180	–.0954
52	8378	8378	NWS	Slidell	33°21'	97°23'	48	1947	1995	3.310	.730	–.230	3.120	1.150	–.0954
53	8561	8561	NWS	Springtown	32°58'	97°40'	21	1957	1978	3.200	.710	–.220	2.930	1.060	–.0954
54	8929	8929	NWS	Terrell	32°45'	96°17'	48	1947	1995	3.730	.800	–.200	3.240	1.230	–.0954
55	9337	9337	NWS	Venus	32°26'	97°06'	17	1947	1964	3.350	.750	–.210	3.000	1.120	–.0954
56	9522	9522	NWS	Waxahachie	32°25'	96°51'	80	1915	1995	3.440	.770	–.210	3.050	1.170	–.0954
57	9532	9532	NWS	Weatherford	32°46'	97°49'	80	1915	1995	3.160	.710	–.220	2.860	1.030	–.0954
58	9538	9538	NWS	Webb	32°42'	97°04'	12	1947	1959	3.360	.750	–.210	2.990	1.120	–.0954
59	40155	155	DAL	Turtle Creek at Willow Wood St.	32°49'35"	96°48'04"	7	1991	1997	3.450	.770	–.210	3.050	1.180	–.0954
60	40195	195	DAL	NW Hwy. at Edgemere Rd.	32°52'03"	96°47'42"	7	1991	1997	3.450	.770	–.210	3.060	1.180	–.0954

Table 2. Stations for two precipitation-monitoring networks near Dallas, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
61	40915	915	DAL	McCree Branch at White Rock Tr.	32°52'18"	96°43'25"	7	1991	1997	3.480	0.780	–0.210	3.090	1.190	–0.0954
62	40935	935	DAL	Jackson Branch at Skillman Ave.	32°53'19"	96°43'53"	7	1991	1997	3.470	.780	–.210	3.090	1.190	–.0954
63	41055	1055	DAL	White Rock Creek at Spring Valley	32°56'23"	96°47'12"	7	1991	1997	3.450	.780	–.210	3.090	1.180	–.0954
64	41095	1095	DAL	Preston Rd. at Olive	33°00'47"	96°47'45"	7	1991	1997	3.450	.780	–.220	3.120	1.190	–.0954
65	41235	1235	DAL	Dixon Branch below NW Hwy.	32°51'51"	96°41'57"	7	1991	1997	3.490	.780	–.210	3.100	1.190	–.0954
66	41515	1515	DAL	White Rock Lake Dam	32°49'15"	96°43'40"	7	1991	1997	3.480	.780	–.210	3.080	1.190	–.0954
67	41535	1535	DA	Stonewall Jackson School	32°50'05"	96°45'56"	7	1991	1997	3.460	.770	–.210	3.060	1.180	–.0954
68	41755	1755	DAL	Harry Stone Park at Millmar Dr.	32°49'36"	96°40'29"	7	1991	1997	3.500	.780	–.210	3.100	1.200	–.0954
69	41855	1855	DAL	Exall Park at Bryan St.	32°47'33"	96°47'07"	7	1991	1997	3.450	.770	–.210	3.050	1.180	–.0954
70	41955	1955	DAL	Garrett Park at Bryan St.	32°48'23"	96°46'15"	7	1991	1997	3.460	.770	–.210	3.060	1.180	–.0954
71	42055	2055	DAL	White Rock Creek at Scyene Rd.	32°45'58"	96°43'30"	7	1991	1997	3.480	.780	–.210	3.070	1.190	–.0954
72	42535	2535	DAL	Lake June Branch at St. Augustine Dr.	32°44'10"	96°39'24"	7	1991	1997	3.510	.780	–.210	3.100	1.200	–.0954
73	42555	2555	DAL	Elam Creek at Lake June Rd.	32°44'05"	96°41'41"	7	1991	1997	3.490	.780	–.210	3.080	1.190	–.0954
74	43075	3075	DAL	SMBX (Street Station)-Municipal at Budd	32°44'25"	96°45'20"	7	1991	1997	3.470	.780	–.210	3.050	1.180	–.0954
75	44135	4135	DAL	Woody Branch at Westmoreland Rd.	32°40'25"	96°52'57"	7	1991	1997	3.420	.770	–.210	3.010	1.160	–.0954
76	44155	4155	DAL	Woody Branch at Polk St.	32°40'11"	96°50'24"	7	1991	1997	3.430	.770	–.210	3.030	1.170	–.0954
77	44515	4515	DAL	Five Mile Creek at Polk St.	32°41'40"	96°50'23"	7	1991	1997	3.430	.770	–.210	3.030	1.170	–.0954
78	44535	4535	DAL	Five Mile Creek at Lancaster Rd.	32°40'49"	96°47'10"	7	1991	1997	3.460	.770	–.210	3.050	1.180	–.0954
79	44555	4555	DAL	Five Mile Creek at Westmoreland Rd.	32°42'24"	96°52'28"	7	1991	1997	3.420	.770	–.210	3.020	1.160	–.0954
80	44855	4855	DAL	Sargent Rd. at Morrell Ave.	32°44'43"	96°46'54"	7	1991	1997	3.450	.770	–.210	3.050	1.180	–.0954
81	45055	5055	DAL	Cedar Creek at Clarendon Dr.	32°44'04"	96°49'52"	7	1991	1997	3.440	.770	–.210	3.030	1.170	–.0954
82	45235	5235	DAL	Coombs Creek at Hampton Rd.	32°45'19"	96°51'23"	7	1991	1997	3.430	.770	–.210	3.020	1.160	–.0954
83	45295	5295	DAL	L.O. Donald School	32°43'58"	96°53'14"	7	1991	1997	3.410	.770	–.210	3.010	1.160	–.0954
84	45515	5515	DAL	Jefferson Blvd. at Ira Ave.	32°44'11"	96°54'59"	7	1991	1997	3.400	.760	–.210	3.010	1.150	–.0954
85	45535	5535	DAL	Camp Wisdom Rd. at Sarah Dr.	32°39'58"	96°57'08"	7	1991	1997	3.390	.760	–.210	2.990	1.140	–.0954

Table 2. Stations for two precipitation-monitoring networks near Dallas, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
86	46135	6135	DAL	Upper A Sump at 1200 Industrial	32°45'44"	96°47'58"	7	1991	1997	3.450	0.770	–0.210	3.040	1.170	–0.0954
87	46235	6235	DAL	Corinth St. Intake at W. Levee	32°45'15"	96°48'10"	7	1991	1997	3.450	.770	–.210	3.040	1.170	–.0954
88	46355	6355	DAL	Sylvan at Union Pacific Railroad	32°46'24"	96°50'10"	7	1991	1997	3.430	.770	–.210	3.030	1.170	–.0954
89	46475	6475	DAL	Singleton Blvd. at Shadrack Dr.	32°46'43"	96°52'43"	7	1991	1997	3.420	.770	–.210	3.020	1.160	–.0954
90	46505	6505	DAL	Eagleford Control Gate	32°46'47"	96°55'04"	7	1991	1997	3.400	.760	–.210	3.010	1.150	–.0954
91	46635	6635	DAL	West Fork at Belt Line	32°45'47"	96°59'47"	7	1991	1997	3.380	.760	–.210	2.990	1.140	–.0954
92	46715	6715	DAL	2255 Irving Blvd.	32°47'45"	96°50'09"	7	1991	1997	3.430	.770	–.210	3.030	1.170	–.0954
93	46775	6775	DAL	Cedar Spring at Kings Rd.	32°49'13"	96°49'09"	7	1991	1997	3.440	.770	–.210	3.040	1.170	–.0954
94	46835	6835	DAL	Mockingbird at CRI&P Railroad	32°48'20"	96°52'22"	7	1991	1997	3.420	.770	–.210	3.020	1.160	–.0954
95	46855	6855	DAL	Knights Branch at Denton Dr.	32°49'30"	96°50'08"	7	1991	1997	3.430	.770	–.210	3.040	1.170	–.0954
96	46895	6895	DAL	Inwood Rd. at University Blvd.	32°50'38"	96°49'16"	7	1991	1997	3.440	.770	–.210	3.050	1.170	–.0954
97	47035	7035	DAL	Elm Fork at California Crossing	32°52'02"	96°55'33"	7	1991	1997	3.400	.760	–.220	3.030	1.160	–.0954
98	47535	7535	DAL	Joes Creek at Walnut Hill	32°52'49"	96°51'39"	7	1991	1997	3.420	.770	–.220	3.050	1.170	–.0954
99	47555	7555	DAL	Townsend at Royal Park	32°53'56"	96°51'44"	7	1991	1997	3.420	.770	–.220	3.060	1.170	–.0954
100	47725	7725	DAL	Bachman Dam	32°50'58"	96°51'57"	7	1991	1997	3.420	.770	–.210	3.040	1.170	–.0954
101	47735	7735	DAL	Bachman Branch at Midway Rd.	32°51'35"	96°50'12"	7	1991	1997	3.430	.770	–.210	3.050	1.170	–.0954
102	47755	7755	DAL	Bachman Branch at Walnut Hill	32°52'47"	96°49'27"	7	1991	1997	3.440	.770	–.210	3.060	1.180	–.0954
103	47775	7775	DAL	Bachman Branch at Forest Ln.	32°54'33"	96°49'12"	7	1991	1997	3.440	.770	–.210	3.070	1.180	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas

[GLO, generalized logistic distribution; in., inches; --, dimensionless; GEV, generalized extreme-value distribution; NWS, National Weather Service; WSCMO, Weather Service Contract Meteorological Observatory; FAA, Federal Aviation Administration; HAR, Harris County Office of Emergency Management; HURP, U.S. Geological Survey Houston Urban Program]

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
1	204	204	NWS	Alvin	29°25'	95°13'	2	1995	1996	4.380	1.150	–0.250	4.100	1.500	–0.0954
2	235	235	NWS	Anahuac	29°47'	94°40'	66	1931	1996	4.700	1.180	–.250	4.380	1.550	–.0954
3	257	257	NWS	Angleton 2 W	29°09'	95°27'	82	1915	1996	4.400	1.150	–.250	4.240	1.510	–.0954
4	569	569	NWS	Bay City Waterworks	28°59'	95°59'	55	1942	1996	4.320	1.120	–.250	3.980	1.470	–.0954
5	586	586	NWS	Baytown	29°50'	95°00'	15	1982	1996	4.440	1.170	–.250	4.200	1.490	–.0954
6	611	611	NWS	Beaumont City	30°06'	94°06'	82	1915	1996	4.840	1.170	–.250	4.610	1.720	–.0954
7	613	613	NWS	Beaumont Research Center	30°04'	94°17'	19	1978	1996	4.840	1.180	–.250	4.530	1.740	–.0954
8	1034	1034	NWS	Brazoria	29°93'	95°34'	15	1915	1929	3.720	.990	–.250	3.570	1.280	–.0954
9	1810	1810	NWS	Cleveland	30°22'	95°05'	43	1954	1996	4.320	1.150	–.250	3.710	1.440	–.0954
10	1838	1838	NWS	Clodine	29°42'	95°41'	46	1951	1996	4.020	1.070	–.250	3.620	1.390	–.0954
11	1870	1870	NWS	Cold Spring 5 S-SW	30°32'	95°09'	43	1954	1996	4.220	1.120	–.250	3.590	1.420	–.0954
12	1956	1956	NWS	Conroe	30°20'	95°29'	49	1948	1996	3.870	1.080	–.250	3.650	1.310	–.0954
13	2206	2206	NWS	Cypress	29°58'	95°42'	7	1990	1996	3.850	1.030	–.250	3.580	1.350	–.0954
14	2218	2218	NWS	Dacus	30°26'	95°47'	43	1954	1996	3.600	.930	–.250	3.570	1.240	–.0954
15	2266	2266	NWS	Danevang 1 W	29°04'	96°13'	82	1915	1996	4.140	1.090	–.250	3.830	1.410	–.0954
16	2436	2436	NWS	Deweyville 5 S	30°14'	93°44'	33	1954	1986	4.780	1.090	–.250	4.820	1.650	–.0954
17	2786	2786	NWS	El Campo	29°12'	96°17'	34	1941	1974	3.970	1.050	–.250	3.670	1.360	–.0954
18	3000	3000	NWS	Evadale	30°20'	94°05'	5	1992	1996	4.750	1.100	–.250	4.420	1.570	–.0954
19	3298	3298	NWS	Four Notch Guard Station	30°39'	95°25'	25	1940	1964	3.900	1.020	–.250	3.540	1.350	–.0954
20	3340	3340	NWS	Freeport 2 NW	28°59'	95°23'	66	1931	1996	4.380	1.160	–.250	4.380	1.580	–.0954
21	3430	3430	NWS	Galveston Weather Service Office	29°18'	94°48'	51	1946	1996	4.530	1.180	–.250	4.390	1.560	–.0954
22	3431	3431	NWS	Galveston Weather Bureau Airport	29°16'	94°51'	16	1948	1963	4.500	1.170	–.250	4.390	1.560	–.0954
23	3640	3640	NWS	Goose Creek	29°44'	94°58'	36	1921	1956	4.470	1.170	–.250	4.240	1.490	–.0954
24	4080	4080	NWS	Hempstead	30°06'	96°05'	33	1946	1978	3.600	.900	–.250	3.460	1.310	–.0954
25	4300	4300	NWS	Houston WSCMO Airport	29°58'	95°21'	28	1969	1996	4.160	1.130	–.250	3.940	1.430	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
26	4305	4305	NWS	Houston Weather Bureau City	29°46'	95°22'	29	1941	1969	4.230	1.130	–0.250	3.870	1.440	–0.0954
27	4307	4307	NWS	Houston FAA Airport	29°39'	95°17'	33	1941	1973	4.310	1.140	–.250	3.930	1.460	–.0954
28	4311	4311	NWS	Houston—Alief	29°43'	95°36'	17	1948	1964	4.070	1.090	–.250	3.670	1.410	–.0954
29	4313	4313	NWS	Houston—Barker	29°49'	95°44'	49	1948	1996	3.910	1.040	–.250	3.550	1.380	–.0954
30	4315	4315	NWS	Houston—Deer Park	29°43'	95°08'	52	1945	1996	4.380	1.160	–.250	4.100	1.470	–.0954
31	4321	4321	NWS	Houston—Heights	29°47'	95°26'	8	1989	1996	4.170	1.120	–.250	3.790	1.430	–.0954
32	4323	4323	NWS	Houston—Independence Heights	29°52'	95°25'	48	1948	1995	4.150	1.120	–.250	3.810	1.420	–.0954
33	4325	4325	NWS	Houston—Westbury	29°40'	95°28'	49	1948	1996	4.200	1.120	–.250	3.800	1.430	–.0954
34	4327	4327	NWS	Houston—N Houston	29°53'	95°32'	49	1948	1996	4.050	1.100	–.250	3.670	1.400	–.0954
35	4328	4328	NWS	Houston—San Jacinto St.	29°55'	95°09'	43	1954	1996	4.330	1.160	–.250	4.110	1.460	–.0954
36	4329	4329	NWS	Houston—Satsuma	29°56'	95°38'	17	1948	1964	3.930	1.060	–.250	3.610	1.370	–.0954
37	4331	4331	NWS	Houston—Spring Branch	29°48'	95°30'	7	1990	1996	4.110	1.110	–.250	3.720	1.420	–.0954
38	4362	4362	NWS	Humble	30°00'	95°15'	32	1954	1985	4.250	1.150	–.250	4.030	1.450	–.0954
39	4382	4382	NWS	Huntsville	30°43'	95°33'	51	1946	1996	3.750	.970	–.250	3.510	1.300	–.0954
40	4704	4704	NWS	Katy-Wolf Hill	29°51'	95°50'	2	1995	1996	3.810	1.010	–.250	3.510	1.360	–.0954
41	4878	4878	NWS	Kountze 3 SE	30°20'	94°14'	5	1992	1996	4.750	1.120	–.250	4.370	1.600	–.0954
42	5196	5196	NWS	Liberty	30°03'	94°48'	82	1915	1996	4.620	1.170	–.250	4.220	1.570	–.0954
43	5496	5496	NWS	Magnolia 1 W	30°13'	95°47'	11	1976	1986	3.670	.970	–.250	3.580	1.270	–.0954
44	5659	5659	NWS	Matagorda 2	28°42'	95°58'	82	1915	1996	4.410	1.140	–.250	4.360	1.650	–.0954
45	6024	6024	NWS	Montgomery	30°23'	95°42'	43	1954	1996	3.650	.970	–.250	3.600	1.260	–.0954
46	6280	6280	NWS	New Caney 2 E	30°08'	95°11'	45	1952	1996	4.290	1.150	–.250	3.980	1.440	–.0954
47	6286	6286	NWS	New Gulf	29°16'	95°54'	51	1946	1996	4.180	1.090	–.250	3.700	1.400	–.0954
48	6664	6664	NWS	Orange 4 NW	30°07'	93°47'	59	1938	1996	4.830	1.150	–.250	4.760	1.680	–.0954
49	6750	6750	NWS	Palacios FAA Airport	28°43'	96°15'	54	1943	1996	4.340	1.120	–.250	4.330	1.640	–.0954
50	7020	7020	NWS	Pierce 1 E	29°14'	96°11'	82	1915	1996	4.000	1.060	–.250	3.650	1.370	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
51	7172	7172	NWS	Port Arthur City	29°54'	93°56'	22	1975	1996	4.860	1.220	–0.250	4.680	1.720	–0.0954
52	7173	7173	NWS	Port Arthur	29°52'	93°56'	22	1946	1967	4.860	1.230	–.250	4.680	1.730	–.0954
53	7174	7174	NWS	Port Arthur Weather Service Office Airport	29°57'	94°01'	50	1947	1996	4.850	1.210	–.250	4.660	1.730	–.0954
54	7594	7594	NWS	Richmond	29°53'	95°45'	51	1946	1996	4.030	1.070	–.250	3.610	1.400	–.0954
55	7651	7651	NWS	Riverside	30°51'	95°24'	25	1946	1970	3.880	.980	–.250	3.460	1.370	–.0954
56	7756	7756	NWS	Rosenberg	29°33'	95°47'	20	1941	1960	4.030	1.070	–.250	3.590	1.390	–.0954
57	8045	8045	NWS	San Jacinto	30°37'	95°43'	10	1977	1986	3.620	.930	–.250	3.520	1.250	–.0954
58	8728	8728	NWS	Sugar Land	29°37'	95°38'	51	1946	1996	4.100	1.090	–.250	3.690	1.410	–.0954
59	8996	8996	NWS	Thompsons 3 W-SW	29°29'	95°38'	40	1957	1996	4.200	1.100	–.250	3.760	1.420	–.0954
60	9076	9076	NWS	Tomball	30°06'	95°37'	51	1946	1996	3.850	1.050	–.250	3.650	1.330	–.0954
61	9448	9448	NWS	Waller 3 S-SW	30°01'	95°56'	50	1947	1996	3.670	.950	–.250	3.490	1.330	–.0954
62	9655	9655	NWS	Wharton	29°19'	96°06'	51	1946	1996	3.980	1.050	–.250	3.590	1.370	–.0954
63	9772	9772	NWS	William Harris Reservoir	29°15'	95°33'	16	1949	1964	4.360	1.130	–.250	4.050	1.470	–.0954
64	9780	9780	NWS	Willis	30°26'	95°29'	10	1919	1928	3.840	1.050	–.250	3.600	1.300	–.0954
65	70110	110	HAR	A100 Clear Creek at I–45	29°30'41"	95°07'16"	12	1986	1997	4.400	1.160	–.250	4.160	1.490	–.0954
66	70120	120	HAR	A100 Clear Creek at FM 2351	29°31'07"	95°10'43"	12	1986	1997	4.380	1.160	–.250	4.080	1.490	–.0954
67	70140	140	HAR	A119 Turkey Creek at FM 1959	29°35'02"	95°11'30"	12	1986	1997	4.370	1.150	–.250	4.030	1.480	–.0954
68	70150	150	HAR	A100 Clear Creek at Country Club	29°33'26"	95°15'10"	12	1986	1997	4.350	1.150	–.250	3.970	1.470	–.0954
69	70160	160	HAR	A120 Beamer Ditch at Hughes Rd.	29°35'30"	95°13'23"	12	1986	1997	4.350	1.150	–.250	3.990	1.470	–.0954
70	70170	170	HAR	A104 Nasa Rd. 1 at Taylor Lake	29°33'25"	95°03'15"	12	1986	1997	4.420	1.170	–.250	4.220	1.500	–.0954
71	70180	180	HAR	A100 Clear Creek at Telephone	29°35'45"	95°17'20"	12	1986	1997	4.320	1.140	–.250	3.930	1.470	–.0954
72	70190	190	HAR	A100 Clear Creek at State Hwy. 288	29°35'18"	95°23'03"	12	1986	1997	4.280	1.130	–.250	3.870	1.450	–.0954
73	70220	220	HAR	B100 Middle Bayou at Genoa and Red Bluff	29°39'00"	95°07'45"	12	1986	1997	4.380	1.160	–.250	4.100	1.480	–.0954
74	70230	230	HAR	B106 Big Island Slough at Fairmont	29°36'50"	95°05'05"	12	1986	1997	4.400	1.160	–.250	4.160	1.490	–.0954
75	70250	250	HAR	B104 Bay Area Blvd. at Clear Lake	29°35'00"	95°06'10"	12	1986	1997	4.400	1.160	–.250	4.160	1.490	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
76	70320	320	HAR	C106 Berry Bayou at Forest Oaks	29°40'35"	95°14'37"	12	1986	1997	4.330	1.150	–0.250	3.970	1.460	–0.0954
77	70340	340	HAR	C100 Sims Bayou at Telephone	29°40'27"	95°17'21"	12	1986	1997	4.300	1.140	–.250	3.930	1.460	–.0954
78	70360	360	HAR	C100 Sims Bayou at MLK Blvd.	29°38'42"	95°20'13"	12	1986	1997	4.280	1.130	–.250	3.890	1.460	–.0954
79	70370	370	HAR	C100 Sims Bayou at State Hwy. 288	29°38'02"	95°23'28"	12	1986	1997	4.260	1.130	–.250	3.850	1.450	–.0954
80	70380	380	HAR	C100 Sims Bayou at Hiram Clarke	29°37'07"	95°26'45"	12	1986	1997	4.230	1.120	–.250	3.820	1.440	–.0954
81	70400	400	HAR	D109 at Holcombe Blvd.	29°42'25"	95°21'15"	12	1986	1997	4.250	1.130	–.250	3.870	1.450	–.0954
82	70410	410	HAR	D100 Brays Bayou at Lawndale	29°43'25"	95°18'15"	12	1986	1997	4.280	1.140	–.250	3.930	1.450	–.0954
83	70420	420	HAR	D100 Brays Bayou at S. Main	29°41'48"	95°24'45"	12	1986	1997	4.220	1.120	–.250	3.820	1.440	–.0954
84	70440	440	HAR	D100 Brays Bayou at Rice	29°40'42"	95°28'07"	12	1986	1997	4.190	1.110	–.250	3.790	1.430	–.0954
85	70460	460	HAR	D100 Brays Bayou at Gessner	29°40'20"	95°31'40"	12	1986	1997	4.150	1.110	–.250	3.750	1.420	–.0954
86	70470	470	HAR	D100 Brays Bayou at High Star	29°42'55"	95°35'15"	12	1986	1997	4.080	1.090	–.250	3.680	1.410	–.0954
87	70480	480	HAR	D118 Keegans Bayou at Roark	29°39'20"	95°33'45"	12	1986	1997	4.140	1.100	–.250	3.730	1.420	–.0954
88	70490	490	HAR	D118 Keegans Bayou at Keegan	29°39'55"	95°35'28"	12	1986	1997	4.110	1.090	–.250	3.710	1.410	–.0954
89	70520	520	HAR	E100 White Oak Bayou at Heights	29°45'50"	95°24'25"	12	1986	1997	4.200	1.120	–.250	3.820	1.440	–.0954
90	70530	530	HAR	E100 White Oak Bayou at Ella Blvd.	29°48'05"	95°26'45"	12	1986	1997	4.160	1.120	–.250	3.770	1.430	–.0954
91	70540	540	HAR	E100 White Oak Bayou at Alabonson	29°52'15"	95°28'50"	12	1986	1997	4.100	1.110	–.250	3.730	1.410	–.0954
92	70550	550	HAR	E100 White Oak Bayou at Lakeview	29°53'15"	95°33'20"	12	1986	1997	4.030	1.090	–.250	3.650	1.400	–.0954
93	70560	560	HAR	E101 Little White Oak Bayou at Trimble	29°48'05"	95°22'15"	12	1986	1997	4.210	1.130	–.250	3.870	1.440	–.0954
94	70570	570	HAR	E101 Little White Oak Bayou at Tidwell	29°50'00"	95°23'20"	12	1986	1997	4.190	1.130	–.250	3.850	1.430	–.0954
95	70580	580	HAR	E115 Brickhouse Gully at Costa Rica	29°48'40"	95°28'15"	12	1986	1997	4.120	1.110	–.250	3.740	1.420	–.0954
96	70590	590	HAR	E117 Cole Creek at Deihl	29°51'00"	95°22'15"	12	1986	1997	4.190	1.130	–.250	3.880	1.430	–.0954
97	70620	620	HAR	F216 Little Cedar Bayou at Eighth St.	29°29'10"	95°01'40"	12	1986	1997	4.430	1.170	–.250	4.270	1.510	–.0954
98	70710	710	HAR	G103 San Jacinto at G103–07–05	29°49'45"	95°05'00"	12	1986	1997	4.390	1.160	–.250	4.150	1.470	–.0954
99	70720	720	HAR	G103 San Jacinto River at US 90	29°52'34"	95°05'37"	12	1986	1997	4.380	1.160	–.250	4.150	1.470	–.0954
100	70750	750	HAR	G103 at Lake Houston Dam Spillway	30°02'30"	95°10'00"	12	1986	1997	4.320	1.160	–.250	4.060	1.460	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
101	70760	760	HAR	G103 San Jacinto River at US 59	30°01'35"	95°15'30"	12	1986	1997	4.240	1.140	–0.250	4.020	1.440	–0.0954
102	70790	790	HAR	G103 East Fork San Jacinto at FM 1485	30°08'45"	95°07'30"	12	1986	1997	4.340	1.160	–.250	3.990	1.450	–.0954
103	70820	820	HAR	H100 Hunting Bayou at I–10	29°45'00"	95°15'00"	12	1986	1997	4.310	1.150	–.250	3.990	1.460	–.0954
104	70830	830	HAR	H100 Hunting Bayou at Loop 610 E.	29°47'35"	95°16'10"	12	1986	1997	4.280	1.140	–.250	3.990	1.450	–.0954
105	70840	840	HAR	H100 Hunting Bayou at Lockwood	29°48'34"	95°19'54"	12	1986	1997	4.240	1.130	–.250	3.920	1.440	–.0954
106	70920	920	HAR	I100 Vince Bayou at Southmore	29°41'40"	95°12'45"	12	1986	1997	4.340	1.150	–.250	4.010	1.460	–.0954
107	70940	940	HAR	I100 Little Vince Bayou at Jackson	29°42'30"	95°12'00"	12	1986	1997	4.340	1.150	–.250	4.030	1.460	–.0954
108	71050	1050	HAR	J100 Spring Creek at I–45	30°06'55"	95°26'22"	12	1986	1997	4.030	1.110	–.250	3.790	1.380	–.0954
109	71070	1070	HAR	J100 Spring Creek at State Hwy. 249	30°07'11"	95°39'00"	12	1986	1997	3.800	1.040	–.250	3.630	1.320	–.0954
110	71090	1090	HAR	J100 Spring Creek at Hegar Rd.	30°05'55"	95°44'41"	12	1986	1997	3.740	1.000	–.250	3.580	1.310	–.0954
111	71110	1110	HAR	K100 Cypress Creek at Cypresswood	30°01'35"	95°20'00"	12	1986	1997	4.170	1.130	–.250	3.960	1.430	–.0954
112	71120	1120	HAR	K100 Cypress Creek at I–45	30°02'08"	95°24'43"	12	1986	1997	4.090	1.120	–.250	3.840	1.410	–.0954
113	71130	1130	HAR	K100 Cypress Creek at Kuykendahl	30°01'44"	95°28'52"	12	1986	1997	4.020	1.100	–.250	3.750	1.390	–.0954
114	71140	1140	HAR	K100 Cypress Creek at Stuebner-Airline	30°00'23"	95°30'42"	12	1986	1997	4.010	1.100	–.250	3.720	1.390	–.0954
115	71160	1160	HAR	K100 Cypress Creek at Grant	29°58'23"	95°35'52"	12	1986	1997	3.950	1.070	–.250	3.640	1.370	–.0954
116	71170	1170	HAR	K100 Cypress Creek at Huffmeister Rd.	29°57'45"	95°37'15"	12	1986	1997	3.930	1.060	–.250	3.620	1.370	–.0954
117	71180	1180	HAR	K100 Cypress Creek at Katy-Hockley	29°57'00"	95°48'29"	12	1986	1997	3.770	1.000	–.250	3.530	1.350	–.0954
118	71190	1190	HAR	K166 Little Mound Creek at Betka	30°01'15"	95°53'30"	12	1986	1997	3.690	.960	–.250	3.510	1.330	–.0954
119	71220	1220	HAR	L100 Little Cypress at Cypress Rosehill	30°00'55"	95°41'37"	12	1986	1997	3.820	1.030	–.250	3.590	1.340	–.0954
120	71320	1320	HAR	M100 Willow Creek at Kuykendahl	30°06'18"	95°32'15"	12	1986	1997	3.930	1.090	–.250	3.700	1.350	–.0954
121	71340	1340	HAR	M100 Willow Creek at FM 249	30°03'45"	95°37'15"	12	1986	1997	3.860	1.050	–.250	3.640	1.350	–.0954
122	71420	1420	HAR	N100 Carpenters Bayou at I–10	29°46'15"	95°08'40"	12	1986	1997	4.360	1.160	–.250	4.090	1.470	–.0954
123	71440	1440	HAR	N100 Carpenters Bayou at Wallisville	29°47'35"	95°08'40"	12	1986	1997	4.360	1.160	–.250	4.100	1.470	–.0954
124	71520	1520	HAR	O100 Goose Creek at State Hwy. 146	29°42'50"	94°59'30"	12	1986	1997	4.450	1.170	–.250	4.230	1.490	–.0954
125	71540	1540	HAR	O100 Goose Creek at Baker Rd.	29°50'35"	95°00'35"	12	1986	1997	4.440	1.170	–.250	4.190	1.490	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998): GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
126	71600	1600	HAR	P100 Greens Bayou at Mount Houston Pkwy.	29°53'15"	95°13'59"	12	1986	1997	4.280	1.150	–0.250	4.060	1.450	–0.0954
127	71610	1610	HAR	P100 Greens Bayou at Normandy	29°46'00"	95°11'20"	12	1986	1997	4.340	1.150	–.250	4.050	1.460	–.0954
128	71620	1620	HAR	P100 Greens Bayou at Ley Rd.	29°50'13"	95°13'59"	12	1986	1997	4.300	1.150	–.250	4.050	1.450	–.0954
129	71630	1630	HAR	P130 Garners Bayou at Beltway 8	29°56'03"	95°14'03"	12	1986	1997	4.270	1.150	–.250	4.060	1.450	–.0954
130	71640	1640	HAR	P100 Greens Bayou at US 59	29°55'06"	95°18'23"	12	1986	1997	4.210	1.140	–.250	4.000	1.440	–.0954
131	71650	1650	HAR	P130 Garners at US 59	29°58'40"	95°16'45"	12	1986	1997	4.220	1.140	–.250	4.020	1.440	–.0954
132	71660	1660	HAR	P100 Greens Bayou at Knobcrest	29°57'25"	95°25'02"	12	1986	1997	4.110	1.120	–.250	3.820	1.420	–.0954
133	71670	1670	HAR	P100 Greens Bayou at Cutten Rd.	29°56'50"	95°29'50"	12	1986	1997	4.050	1.100	–.250	3.720	1.400	–.0954
134	71680	1680	HAR	P118 Halls Bayou at Jensen	29°50'05"	95°20'00"	12	1986	1997	4.230	1.130	–.250	3.930	1.440	–.0954
135	71690	1690	HAR	P118 Halls Bayou at Airline	29°53'05"	95°23'45"	12	1986	1997	4.160	1.120	–.250	3.850	1.430	–.0954
136	71720	1720	HAR	Q100 Cedar Bayou at State Hwy. 146	29°46'12"	95°55'00"	12	1986	1997	3.800	1.000	–.250	3.480	1.360	–.0954
137	71740	1740	HAR	Q100 Cedar Bayou at US 90	29°58'23"	94°59'07"	12	1986	1997	4.460	1.170	–.250	4.170	1.490	–.0954
138	71840	1840	HAR	R102 Gum Gully at Diamond Head	29°54'15"	95°05'00"	12	1986	1997	4.380	1.170	–.250	4.150	1.470	–.0954
139	71940	1940	HAR	S100 Luce Bayou at FM 2100	30°03'15"	95°03'15"	12	1986	1997	4.400	1.160	–.250	4.110	1.480	–.0954
140	72020	2020	HAR	T101 Mason Creek at Prince Creek	29°46'30"	95°43'45"	12	1986	1997	3.940	1.050	–.250	3.560	1.380	–.0954
141	72040	2040	HAR	T100 Cane Island Branch at Franz Rd.	29°51'55"	95°38'40"	12	1986	1997	3.960	1.070	–.250	3.590	1.380	–.0954
142	72150	2150	HAR	U101 S Mayde at Greenhouse	29°48'19"	95°42'15"	12	1986	1997	3.940	1.050	–.250	3.570	1.380	–.0954
143	72180	2180	HAR	U102 Bear Creek at FM 529	29°53'15"	95°45'00"	12	1986	1997	3.850	1.030	–.250	3.550	1.360	–.0954
144	72210	2210	HAR	W100 Buffalo Bayou at Turning Basin	29°45'00"	95°17'30"	12	1986	1997	4.280	1.140	–.250	3.950	1.450	–.0954
145	72220	2220	HAR	W100 Buffalo Bayou at Milam	29°45'50"	95°21'30"	12	1986	1997	4.230	1.130	–.250	3.880	1.440	–.0954
146	72250	2250	HAR	W140 State Hwy. 6 at Bingle	29°47'49"	95°30'14"	12	1986	1997	4.110	1.100	–.250	3.710	1.420	–.0954
147	72260	2260	HAR	W100 Buffalo Bayou at San Felipe	29°45'00"	95°30'20"	12	1986	1997	4.130	1.110	–.250	3.730	1.420	–.0954
148	72270	2270	HAR	W100 Buffalo Bayou at West Belt	29°45'45"	95°33'30"	12	1986	1997	4.080	1.100	–.250	3.680	1.410	–.0954
149	83630	3630	HURP	Bettina St. ditch at Houston	29°46'32"	95°32'23"	6	1979	1984	4.090	1.100	–.250	3.690	1.410	–.0954
150	84145	4145	HURP	Bingle Rd. storm sewer at Houston	29°51'31"	95°29'09"	5	1980	1984	4.100	1.110	–.250	3.720	1.410	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998) GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
151	84150	4150	HURP	Cole Creek at Deihl Rd.	29°51'04"	95°29'16"	26	1964	1989	4.100	1.110	–0.250	3.720	1.410	–0.0954
152	84200	4200	HURP	Brickhouse Gully at Clarblak at Houston	29°49'53"	95°31'42"	6	1979	1984	4.070	1.100	–.250	3.680	1.410	–.0954
153	84250	4250	HURP	Brickhouse Gully at Costa Rica St.	29°49'40"	95°28'09"	26	1964	1989	4.130	1.110	–.250	3.740	1.420	–.0954
154	84400	4400	HURP	Lazybrook St. storm sewer	29°48'15"	95°26'04"	6	1979	1984	4.160	1.120	–.250	3.780	1.430	–.0954
155	84540	4540	HURP	Little Whiteoak Bayou at Trimble St.	29°47'33"	95°22'06"	5	1980	1984	4.220	1.130	–.250	3.870	1.440	–.0954
156	84760	4760	HURP	Brays Bayou at Alief Rd.	29°42'39"	95°35'13"	4	1981	1984	4.090	1.090	–.250	3.690	1.410	–.0954
157	84780	4780	HURP	Keegans Bayou at Keegan Rd.	29°39'55"	95°35'42"	6	1979	1984	4.110	1.090	–.250	3.700	1.410	–.0954
158	84800	4800	HURP	Keegans Bayou at Roark Rd.	29°39'23"	95°33'43"	26	1964	1989	4.140	1.100	–.250	3.730	1.420	–.0954
159	84850	4850	HURP	Bintliff ditch at Bissonnet at Houston	29°41'16"	95°30'20"	2	1979	1980	4.160	1.110	–.250	3.760	1.430	–.0954
160	84910	4910	HURP	Hummingbird St. ditch at Houston	29°39'44"	95°29'11"	6	1979	1984	4.190	1.110	–.250	3.780	1.430	–.0954
161	85400	5400	HURP	Sims Bayou at Hiram Clarke St.	29°37'07"	95°26'45"	21	1964	1984	4.230	1.120	–.250	3.820	1.440	–.0954
162	85470	5470	HURP	Sims Bayou at MLK Blvd.	29°38'42"	95°20'13"	6	1979	1984	4.280	1.130	–.250	3.890	1.460	–.0954
163	85500	5500	HURP	Sims Bayou at Houston	29°40'27"	95°17'21"	15	1975	1989	4.300	1.140	–.250	3.930	1.460	–.0954
164	85550	5550	HURP	Berry Bayou at Gilpin St. at Houston	29°38'32"	95°13'22"	6	1979	1984	4.340	1.150	–.250	3.990	1.470	–.0954
165	85650	5650	HURP	Berry Bayou at Forest Oaks St.	29°40'35"	95°14'37"	26	1964	1989	4.330	1.150	–.250	3.970	1.460	–.0954
166	85760	5760	HURP	Hunting Bayou at Falls St. at Houston	29°48'22"	95°19'50"	6	1979	1984	4.240	1.130	–.250	3.930	1.440	–.0954
167	85770	5770	HURP	Hunting Bayou at I–10	29°47'35"	95°16'04"	26	1964	1989	4.290	1.140	–.250	3.990	1.450	–.0954
168	85780	5780	HURP	Greens Bayou at Cutten Rd. near Houston	29°56'56"	95°31'10"	13	1977	1989	4.030	1.100	–.250	3.700	1.390	–.0954
169	85900	5900	HURP	Greens Bayou at US 75 near Houston	29°57'24"	95°25'04"	25	1965	1989	4.110	1.120	–.250	3.820	1.420	–.0954
170	86000	6000	HURP	Greens Bayou near Houston	29°55'05"	95°18'24"	25	1965	1989	4.210	1.140	–.250	4.000	1.440	–.0954
171	86200	6200	HURP	Halls Bayou at Deertrail St. at Houston	29°54'07"	95°25'21"	6	1979	1984	4.130	1.120	–.250	3.800	1.420	–.0954
172	86500	6500	HURP	Halls Bayou at Houston	29°51'42"	95°20'05"	11	1979	1989	4.210	1.130	–.250	3.950	1.440	–.0954
173	88011	11R	HURP	Linder Lake	29°49'00"	95°21'15"	3	1964	1966	4.220	1.130	–.250	3.890	1.440	–.0954
174	88014	14R	HURP	Sayer St.	29°49'54"	95°19'47"	7	1966	1972	4.230	1.130	–.250	3.940	1.440	–.0954
175	88021	21R	HURP	Brittmore St.	29°51'02"	95°33'46"	21	1964	1984	4.040	1.090	–.250	3.650	1.400	–.0954

Table 3. Stations for three precipitation-monitoring networks near Houston, Texas—Continued

Site no.	Current study station no.	Original station no.	Operator	Station name	Latitude	Longitude	Years of record	Beginning year of record	Ending year of record	Distribution parameters for determining recurrence interval of annual precipitation maxima (Asquith, 1998)					
										GLO ξ (in.)	GLO α (in.)	GLO κ (--)	GEV ξ (in.)	GEV α (in.)	GEV κ (--)
176	88025	25R	HURP	Jones Rd.	29°58'00"	95°34'12"	4	1965	1968	3.970	1.080	–0.250	3.660	1.380	–0.0954
177	88026	26R	HURP	Louedda St.	29°56'57"	95°33'58"	3	1968	1970	3.990	1.080	–.250	3.660	1.380	–.0954
178	88029	29R	HURP	Mills Rd.	29°57'29"	95°33'40"	11	1970	1980	3.990	1.090	–.250	3.660	1.380	–.0954
179	88031	31R	HURP	Stafford	29°36'43"	95°32'58"	21	1964	1984	4.170	1.110	–.250	3.760	1.420	–.0954
180	88039	39R	HURP	KHTV	29°43'25"	95°30'06"	13	1967	1980	4.150	1.110	–.250	3.740	1.420	–.0954
181	88041	41R	HURP	Gulf Palms	29°37'54"	95°12'32"	3	1964	1966	4.350	1.150	–.250	4.010	1.470	–.0954
182	88045	45R	HURP	Minnesota St.	29°37'35"	95°14'30"	5	1968	1972	4.340	1.150	–.250	3.970	1.470	–.0954
183	88101	101R	HURP	Liberty Rd.	29°47'19"	95°18'50"	2	1979	1980	4.260	1.140	–.250	3.940	1.450	–.0954
184	88203	203R	HURP	Mintz Ln.	29°59'53"	95°28'39"	5	1979	1983	4.040	1.100	–.250	3.750	1.400	–.0954
185	88204	204R	HURP	Breen St.	29°53'57"	95°27'28"	6	1979	1984	4.100	1.110	–.250	3.750	1.410	–.0954
186	88205	205R	HURP	Frontier St.	29°50'08"	95°31'22"	6	1979	1984	4.080	1.100	–.250	3.690	1.410	–.0954
187	88303	303R	HURP	Four Corners	29°40'07"	95°39'36"	4	1979	1982	4.050	1.080	–.250	3.650	1.400	–.0954
188	88304	304R	HURP	Chasewood	29°36'32"	95°29'57"	4	1979	1982	4.210	1.110	–.250	3.790	1.430	–.0954
189	88305	305R	HURP	Furman	29°37'45"	95°22'45"	6	1979	1984	4.270	1.130	–.250	3.860	1.450	–.0954
190	88308	308R	HURP	Public Health Department, City of Houston	29°42'27"	95°23'30"	6	1979	1984	4.230	1.130	–.250	3.840	1.440	–.0954
191	88401	401R	HURP	Llano St.	29°39'11"	95°12'07"	4	1979	1982	4.350	1.150	–.250	4.010	1.470	–.0954
192	88402	402R	HURP	Klondike	29°38'06"	95°15'04"	5	1979	1983	4.330	1.150	–.250	3.960	1.470	–.0954
193	88403	403R	HURP	Edgebrook	29°38'55"	95°13'23"	6	1979	1984	4.340	1.150	–.250	3.990	1.470	–.0954

Table 4. Abbreviated example of intra-network sample ratios surrounding any annual precipitation maxima near Dallas, Texas

[Unless otherwise noted, units are dimensionless. Vertical line indicates data available, but not shown. in., inches; mi, miles; w, winter season consisting of annual precipitation maxima October–March; s, summer season consisting of annual precipitation maxima April–September]

Central station (station with annual precipitation maxima)	Selected station (neighboring station with existing concurrent precipitation)	Annual precipitation maxima (in.)	Depth of concurrent precipitation (in.)	Season identifier	Date of annual precipitation maxima	Estimated cumulative annual probability of annual precipitation maxima	Calculated recurrence interval of annual precipitation maxima (years)	Ratio of annual precipitation maxima to concurrent precipitation	Separation distance (mi)
129	201	2.46	0	w	10/10/1961	0.2202	1.28	0	25.96
129	262	2.46	.47	w	10/10/1961	.2202	1.28	.191	77.64
129	337	2.46	1.59	w	10/10/1961	.2202	1.28	.646	26.30
│	│	│	│	│	│	│	│	│	│
5646	9522	2.36	.72	s	5/18/1952	.1836	1.22	.305	43.63
5646	9532	2.36	1.29	s	5/18/1952	.1836	1.22	.547	18.48
5646	9538	2.36	.50	s	5/18/1952	.1836	1.22	.212	25.20
│	│	│	│	│	│	│	│	│	│
47775	47725	4.06	3.15	w	12/20/1997	.6590	2.93	.776	4.92
47775	47725	4.06	3.52	w	12/20/1997	.6590	2.93	.867	3.56
47775	47725	4.06	3.31	w	12/20/1997	.6590	2.93	.815	2.06

Table 5. Abbreviated summary statistics of intra-network sample ratios surrounding any annual precipitation maxima near Dallas, Texas

[Unless otherwise noted, units are dimensionless. Vertical line indicates data available, but not shown. All table entries from Appendix II–1, except for column “Limits for each mile-wide window.” mi, miles]

Limits for each mile-wide window (mi)	Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	0	1	0	0	1	0	0	0
0–1	No data, less than 10 sample ratios available for 0 to 1 mi							
1–2	1.61	1.0537	.4960	.4707	.9280	182	6	.0319
2–3	2.55	.9179	.3251	.3542	.9010	368	7	.0187
│	│	│	│	│	│	│	│	│
18–19	19.53	.6660	.4424	.6643	.6200	427	20	.0447
19–20	20.56	.5617	.4421	.7870	.5120	684	87	.1128
20–21	21.67	.5375	.4208	.7828	.5000	599	72	.1073
│	│	│	│	│	│	│	│	│
47–48	47.53	.4501	.4093	.9093	.3450	1,516	190	.1114
48–49	48.41	.4808	.4218	.8774	.3720	576	81	.1233
49–50	49.52	.4191	.3990	.9518	.3220	1,039	148	.1247

Table 6. Summary of observed cumulative annual probabilities for each precipitation-monitoring network

[NWS, National Weather Service; AUS, City of Austin; DAL, City of Dallas; HAR, Harris County Office of Emergency Management; HURP, U.S. Geological Survey Houston Urban Program]

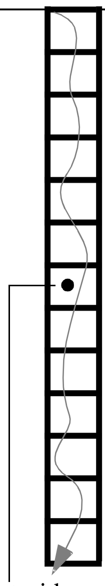
Location of data base/network	Recurrence interval (years)	Defined cumulative annual probability	Observed cumulative annual probability	No. of nonexceedance storms	No. of storms	Defined cumulative annual probability minus observed cumulative annual probability
Austin/NWS	1.111	0.10	0.120	68		–0.020
	1.25	.20	.252	143		–.052
	2	.50	.591	335	567	–.091
	5	.80	.857	486		–.057
	10	.90	.938	532		–.038
Austin/AUS	1.111	.10	.161	28		–.061
	1.25	.20	.333	58		–.133
	2	.50	.753	131	174	–.253
	5	.80	.954	166		–.154
	10	.90	.989	172		–.089
Dallas/NWS	1.111	.10	.134	224		–.034
	1.25	.20	.271	451		–.071
	2	.50	.601	1,000	1,664	–.101
	5	.80	.855	1,423		–.055
	10	.90	.931	1,549		–.031
Dallas/DAL	1.111	.10	.0977	13		.002
	1.25	.20	.203	27		–.003
	2	.50	.722	96	133	–.222
	5	.80	.977	130		–.177
	10	.90	1.000	133		–.100
Houston/NWS	1.111	.10	.147	294		–.047
	1.25	.20	.276	554		–.076
	2	.50	.604	1,211	2,004	–.104
	5	.80	.833	1,669		–.033
	10	.90	.910	1,824		–.010
Houston/HAR	1.111	.10	.245	141		–.145
	1.25	.20	.440	253		–.240
	2	.50	.741	426	575	–.241
	5	.80	.899	517		–.099
	10	.90	.944	543		–.044
Houston/HURP	1.111	.10	.0663	13		.034
	1.25	.20	.270	53		–.070
	2	.50	.663	130	196	–.163
	5	.80	.847	166		–.047
	10	.90	.949	186		–.049

Table 7. Equations that define the estimated 2-year or greater depth-distance relation and the areal-reduction factor for circular watersheds for Austin, Dallas, and Houston, Texas

City	Estimated 2-year or greater depth-distance relation (figs. 14–16) for distance (r), in miles	Areal-reduction factor for circular watersheds having radius (r), in miles	Equation limits
Austin	$S_2(r) = 1.0000 - 0.1400(r)$	$ARF_2(r) = 1.0000 - 0.0933(r)$	$0 \leq r \leq 1$
	$S_2(r) = 0.9490 - 0.0890(r)$	$ARF_2(r) = 0.9490 - 0.0593(r) + (0.0170 / r^2)$	$1 \leq r \leq 2$
	$S_2(r) = 0.8410 - 0.0350(r)$	$ARF_2(r) = 0.8410 - 0.0233(r) + (0.1610 / r^2)$	$2 \leq r \leq 3$
	$S_2(r) = 0.8080 - 0.0240(r)$	$ARF_2(r) = 0.8080 - 0.0160(r) + (0.2600 / r^2)$	$3 \leq r \leq 4.5$
	$S_2(r) = 0.7750 - 0.0167(r)$	$ARF_2(r) = 0.7750 - 0.0111(r) + (0.4828 / r^2)$	$4.5 \leq r \leq 9$
	$S_2(r) = 0.7420 - 0.0130(r)$	$ARF_2(r) = 0.7420 - 0.0087(r) + (1.3737 / r^2)$	$9 \leq r \leq 13$
	$S_2(r) = 0.7203 - 0.0113(r)$	$ARF_2(r) = 0.7203 - 0.0076(r)+ (2.5943 / r^2)$	$13 \leq r \leq 19$
	$S_2(r) = 0.6950 - 0.0100(r)$	$ARF_2(r) = 0.6950 - 0.0067(r) + (5.6427 / r^2)$	$19 \leq r \leq 28$
	$S_2(r) = 0.6502 - 0.0084(r)$	$ARF_2(r) = 0.6502 - 0.0056(r) + (17.3505 / r^2)$	$28 \leq r \leq 33$
	$S_2(r) = 0.6040 - 0.0070(r)$	$ARF_2(r) = 0.6040 - 0.0047(r) + (34.1211 / r^2)$	$33 \leq r \leq 41$
Austin	$S_2(r) = 0.3717 - 0.0013(r)$	$ARF_2(r) = 0.3717 - 0.0009(r) + (164.3052 / r^2)$	$41 \leq r \leq 50$
Dallas	$S_2(r) = 1.0000 - 0.0600(r)$	$ARF_2(r) = 1.0000 - 0.0400(r)$	$0 \leq r \leq 2$
	$S_2(r) = 0.9670 - 0.0435(r)$	$ARF_2(r) = 0.9670 - 0.0290(r) + (0.0440 / r^2)$	$2 \leq r \leq 4$
	$S_2(r) = 0.8910 - 0.0245(r)$	$ARF_2(r) = 0.8910 - 0.0163(r) + (0.4493 / r^2)$	$4 \leq r \leq 6$
	$S_2(r) = 0.8760 - 0.0220(r)$	$ARF_2(r) = 0.8760 - 0.0147(r) + (0.6293 / r^2)$	$6 \leq r \leq 8$
	$S_2(r) = 0.8460 - 0.0183(r)$	$ARF_2(r) = 0.8460 - 0.0122(r) + (1.2693 / r^2)$	$8 \leq r \leq 12$
	$S_2(r) = 0.8130 - 0.0155(r)$	$ARF_2(r) = 0.8130 - 0.0103(r) + (2.8533 / r^2)$	$12 \leq r \leq 16$
	$S_2(r) = 0.7650 - 0.0125(r)$	$ARF_2(r) = 0.7650 - 0.0083(r) + (6.9493 / r^2)$	$16 \leq r \leq 18$
	$S_2(r) = 0.7200 - 0.0100(r)$	$ARF_2(r) = 0.7200 - 0.0067(r) + (11.8093 / r^2)$	$18 \leq r \leq 24$
	$S_2(r) = 0.6880 - 0.0087(r)$	$ARF_2(r) = 0.6800 - 0.0058(r) + (17.9533 / r^2)$	$24 \leq r \leq 27$
	$S_2(r) = 0.6228 - 0.0063(r)$	$ARF_2(r) = 0.6228 - 0.0042(r) + (33.8091 / r^2)$	$27 \leq r \leq 31$
Dallas	$S_2(r) = 0.5563 - 0.0041(r)$	$ARF_2(r) = 0.5563 - 0.0027(r) + (55.1070 / r^2)$	$31 \leq r \leq 50$
Houston	$S_2(r) = 1.0000 - 0.1200(r)$	$ARF_2(r) = 1.0000 - 0.0800(r)$	$0 \leq r \leq 1$
	$S_2(r) = 0.9400 - 0.0600(r)$	$ARF_2(r) = 0.9400 - 0.0400(r) + (0.0200 / r^2)$	$1 \leq r \leq 2$
	$S_2(r) = 0.8800 - 0.0300(r)$	$ARF_2(r) = 0.8800 - 0.0200(r) + (0.1000 / r^2)$	$2 \leq r \leq 4$
	$S_2(r) = 0.8667 - 0.0267(r)$	$ARF_2(r) = 0.8667 - 0.0178(r) + (0.1711 / r^2)$	$4 \leq r \leq 7$
	$S_2(r) = 0.8078 - 0.0183(r)$	$ARF_2(r) = 0.8078 - 0.0122(r) + (1.1334 / r^2)$	$7 \leq r \leq 11$
	$S_2(r) = 0.7363 - 0.0118(r)$	$ARF_2(r) = 0.7363 - 0.0078(r) + (4.0173 / r^2)$	$11 \leq r \leq 15$
	$S_2(r) = 0.6800 - 0.0080(r)$	$ARF_2(r) = 0.6800 - 0.0053(r) + (8.2360 / r^2)$	$15 \leq r \leq 20$
Houston	$S_2(r) = 0.6187 - 0.0049(r)$	$ARF_2(r) = 0.6187 - 0.0033(r) + (16.4138 / r^2)$	$20 \leq r \leq 50$

Table 8. Example areal-reduction factor calculation for a hypothetical, linear watershed in the Austin area

[mi, miles; mi^2, square miles; --, dimensionless; (5), column number]

Cell no.	Watershed map (each cell represents 1 mi^2)	Distance (r) from centroid, cell 7 (mi)	Applicable equation from table 7, with distance substituted for distance (r) (--)	(5) Estimated 2-year or greater depth-distance relation (--)	(6) Cell area (mi^2)	Areal-reduction factor for cell (5) * (6)
1		6	0.775 – 0.0167(6) =	0.675	1	0.675
2		5	0.775 – 0.0167(5) =	0.692	1	0.692
3		4	0.808 – 0.024(4) =	0.712	1	0.712
4		3	0.841 – 0.035(3) =	0.736	1	0.736
5		2	0.949 – 0.089(2) =	0.771	1	0.771
6		1	1.0 – 0.14(1) =	0.860	1	0.860
7		0	1.0 – 0.14(0) =	1.00	1	1.00
8		1	1.0 – 0.14(1) =	0.860	1	0.860
9		2	0.949 – 0.089(2) =	0.771	1	0.771
10		3	0.841 – 0.035(3) =	0.736	1	0.736
11		4	0.808 – 0.024(4) =	0.712	1	0.712
12		5	0.775 – 0.0167(5) =	0.692	1	0.692
13		6	0.775 – 0.0167(6) =	0.675	1	0.675
	Centroid			**Column total**	13	9.892
				Areal-reduction factor	9.892 / 13	**0.76**

For comparison, an areal-reduction factor for a circular watershed having the same drainage area as this example can be calculated. The radius of a 13-mi^2 circular watershed is 2.03 mi. The areal-reduction factor is calculated from equation in table 7.

The areal-reduction factor for a 13-mi^2 circular watershed **0.83**

APPENDIX I—
Summary Statistics of Intra-Network Sample Ratios for Austin, Texas

Appendix I–1. Summary statistics of intra-network sample ratios surrounding any annual precipitation maxima near Austin, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 17,242. mi, miles]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
.83	.9018	.2326	.2579	.9580	74	4	.0513
1.50	.8288	.3776	.4556	.8930	399	36	.0828
2.50	.8364	.3577	.4277	.8790	675	52	.0715
3.48	.8292	.3494	.4214	.8630	837	37	.0423
4.50	.7884	.3534	.4482	.8290	1011	46	.0435
5.47	.7929	.3694	.4659	.8100	932	48	.0490
6.52	.7760	.3845	.4955	.7970	1012	42	.0398
7.50	.7593	.3700	.4873	.7820	974	45	.0442
8.50	.7329	.3786	.5165	.7510	934	49	.0498
9.50	.6990	.4130	.5908	.6990	951	66	.0649
10.50	.7077	.4027	.5691	.6930	884	41	.0443
11.51	.7015	.4174	.5950	.7000	789	56	.0663
12.54	.6603	.4157	.6296	.6480	743	46	.0583
13.53	.6631	.4303	.6489	.6310	663	50	.0701
14.44	.6229	.4141	.6647	.5990	465	30	.0606
15.41	.6417	.4273	.6659	.6360	476	23	.0461
16.46	.6045	.4311	.7131	.5790	498	27	.0514
17.46	.5918	.3891	.6575	.5680	310	27	.0801
18.45	.5006	.4383	.8756	.4260	278	44	.1366
19.54	.5330	.4209	.7897	.4780	285	24	.0777
20.39	.5807	.4310	.7422	.5680	195	19	.0888
21.39	.6412	.4408	.6875	.6040	112	7	.0588
22.40	.5030	.4510	.8967	.4290	272	43	.1365
23.27	.4207	.3906	.9285	.3310	141	22	.1350

Appendix I–1. Summary statistics of intra-network sample ratios surrounding any annual precipitation maxima near Austin, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.64	0.4668	0.4242	0.9087	0.3880	231	31	0.1183
25.48	.5424	.4169	.7687	.4580	77	8	.0941
26.57	.4510	.4281	.9492	.3040	171	27	.1364
27.32	.4592	.4089	.8904	.4120	181	25	.1214
28.61	.4716	.4535	.9616	.3720	178	25	.1232
29.41	.4226	.4162	.9850	.2900	144	27	.1579
30.50	.3127	.3191	1.0205	.2220	152	34	.1828
31.52	.5242	.4287	.8178	.4310	151	14	.0848
32.44	.3368	.3651	1.0842	.2030	144	31	.1771
33.37	.4391	.4026	.9169	.3720	90	15	.1429
34.76	.4793	.4448	.9280	.3530	87	10	.1031
35.53	.4803	.3892	.8105	.4480	138	12	.0800
36.64	.4244	.4132	.9737	.3310	158	22	.1222
37.81	.3953	.3833	.9696	.2690	238	38	.1377
38.46	.2960	.3193	1.0788	.1350	122	24	.1644
39.44	.2587	.3228	1.2478	.0910	46	16	.2581
40.51	.5615	.5074	.9037	.4090	100	11	.0991
41.47	.5381	.4611	.8569	.4240	71	5	.0658
42.16	.2428	.2747	1.1312	.1150	74	19	.2043
43.60	.3415	.3706	1.0852	.1720	125	22	.1497
45.22	.4526	.4248	.9386	.3540	107	15	.1230
46.71	.3695	.3493	.9455	.2510	49	4	.0755
47.48	.4465	.4168	.9335	.3310	254	33	.1150
48.08	.4125	.3939	.9550	.3020	133	17	.1133
49.87	.3634	.3595	.9891	.2290	111	12	.0976

Appendix I–2. Summary statistics of intra-network sample ratios surrounding the 2-year or greater annual precipitation maxima near Austin, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 5,226. mi, miles]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
.84	.8714	.1786	.2050	.9020	17	1	.0556
1.48	.7549	.3513	.4653	.8590	103	17	.1417
2.50	.7288	.3374	.4629	.8110	186	22	.1058
3.50	.7441	.3312	.4450	.8090	232	21	.0830
4.53	.6732	.3282	.4875	.7440	269	19	.0660
5.46	.7144	.2888	.4042	.7490	245	11	.0430
6.49	.6669	.3326	.4987	.6660	251	16	.0599
7.51	.6361	.3375	.5306	.6420	253	22	.0800
8.51	.6356	.3485	.5483	.6480	242	21	.0798
9.48	.5896	.3636	.6167	.5880	250	21	.0775
10.49	.6394	.3708	.5798	.6150	231	11	.0455
11.51	.5789	.3721	.6428	.5480	215	25	.1042
12.57	.5129	.3538	.6897	.5270	203	19	.0856
13.51	.5896	.3839	.6511	.5600	190	14	.0686
14.46	.5099	.3454	.6773	.5340	118	8	.0635
15.39	.5259	.3824	.7271	.5000	147	8	.0516
16.48	.5410	.3691	.6823	.5290	150	9	.0566
17.47	.5919	.3763	.6358	.5800	95	8	.0777
18.49	.4582	.4073	.8889	.4100	79	10	.1124
19.57	.5585	.4362	.7810	.5300	91	10	.0990
20.34	.5786	.4321	.7468	.5230	60	6	.0909
21.35	.6036	.4264	.7064	.5560	39	2	.0488
22.37	.4446	.3915	.8805	.3640	112	14	.1111
23.24	.4022	.3873	.9629	.3400	62	12	.1622

Appendix I–2. Summary statistics of intra-network sample ratios surrounding the 2-year or greater annual precipitation maxima near Austin, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.65	0.4128	0.3832	0.9284	0.3110	100	10	0.0909
25.48	.5011	.3329	.6644	.3650	24	1	.0400
26.57	.4558	.4096	.8986	.3230	64	7	.0986
27.31	.3633	.3142	.8647	.3070	77	11	.1250
28.60	.3921	.3780	.9641	.2960	73	11	.1310
29.40	.3540	.3433	.9698	.2360	58	10	.1471
30.47	.3339	.3057	.9156	.2910	69	9	.1154
31.54	.4528	.3343	.7383	.4070	56	5	.0820
32.45	.2936	.3001	1.0222	.2100	59	9	.1324
33.37	.3616	.3384	.9358	.3150	40	6	.1304
34.77	.4017	.3587	.8930	.3060	35	4	.1026
35.55	.3652	.3266	.8942	.2640	61	6	.0896
36.65	.3618	.3470	.9592	.2720	67	8	.1067
37.80	.3518	.3225	.9166	.2500	97	14	.1261
38.46	.2276	.2433	1.0692	.1270	58	13	.1831
39.45	.3406	.4109	1.2064	.0940	25	7	.2188
40.51	.4223	.3280	.7766	.3640	43	4	.0851
41.46	.4575	.3322	.7262	.4010	30	2	.0625
42.16	.2140	.2501	1.1685	.0780	36	9	.2000
43.60	.3083	.3169	1.0279	.1710	49	5	.0926
45.21	.3176	.2625	.8267	.2820	46	6	.1154
46.71	.3458	.3466	1.0020	.2170	20	1	.0476
47.48	.3511	.3311	.9431	.2430	104	11	.0957
48.08	.3663	.3394	.9267	.2620	48	4	.0769
49.87	.2897	.3012	1.0397	.1330	47	4	.0784

Appendix I–3. Summary statistics of intra-network sample ratios surrounding the 5-year or greater annual precipitation maxima near Austin, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 1,293. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1.53	.5271	.4524	.8583	.7090	20	8	.2857
2.51	.6616	.3278	.4955	.7980	40	8	.1667
3.43	.5398	.3723	.6897	.6000	41	10	.1961
4.55	.5323	.3690	.6932	.5700	61	12	.1644
5.46	.6118	.3039	.4966	.7440	50	7	.1228
6.51	.5735	.3865	.6739	.7350	42	7	.1429
7.45	.4787	.3720	.7772	.6300	48	14	.2258
8.50	.4236	.3687	.8705	.5650	48	14	.2258
9.46	.4514	.3692	.8180	.5490	48	13	.2131
10.49	.5727	.3136	.5476	.6280	50	5	.0909
11.50	.4538	.3648	.8038	.4980	43	10	.1887
12.54	.4339	.3384	.7798	.5040	43	5	.1042
13.52	.5502	.3846	.6991	.5280	45	2	.0426
14.43	.3996	.2845	.7121	.4600	19	2	.0952
15.34	.5486	.4144	.7554	.5050	27	2	.0690
16.45	.4682	.3178	.6787	.4890	31	2	.0606
17.47	.5296	.3386	.6393	.4580	25	1	.0385
18.52	.3142	.3013	.9591	.1640	24	3	.1111
19.60	.4042	.3956	.9788	.2160	31	6	.1622
20.25	.6229	.3095	.4969	.6150	14	0	.0000
21.31	.6562	.4284	.6528	.6040	12	1	.0769
22.38	.3886	.3569	.9183	.2450	35	6	.1463
23.28	.2707	.2141	.7910	.2770	19	1	.0500

Appendix I–3. Summary statistics of intra-network sample ratios surrounding the 5-year or greater annual precipitation maxima near Austin, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.47	0.4666	0.4472	0.9584	0.3110	36	3	0.0769
26.61	.3289	.2666	.8107	.2640	22	1	.0435
27.38	.3673	.3212	.8743	.2720	26	2	.0714
28.57	.3974	.2300	.5787	.4100	23	1	.0417
29.40	.3597	.3005	.8353	.2850	26	3	.1034
30.38	.3660	.3595	.9823	.2670	22	3	.1200
31.57	.3942	.3051	.7740	.3570	18	1	.0526
32.41	.2162	.1926	.8909	.2100	22	4	.1538
33.37	.3787	.3167	.8363	.3150	15	0	.0000
35.52	.2951	.2838	.9619	.2130	28	4	.1250
36.65	.3601	.2920	.8108	.2720	27	1	.0357
37.78	.3613	.3522	.9749	.2500	36	5	.1220
38.42	.2060	.2235	1.0845	.1070	25	4	.1379
40.48	.4020	.3198	.7955	.3640	21	3	.1250
41.48	.6205	.4023	.6483	.5500	11	1	.0833
42.14	.1210	.1508	1.2464	.0410	13	5	.2778
43.62	.2628	.2667	1.0150	.0970	15	0	.0000
45.23	.3764	.2762	.7338	.4180	13	1	.0714
46.71	.3865	.3951	1.0221	.1480	11	1	.0833
47.51	.3065	.3170	1.0343	.2190	38	5	.1163
48.07	.4418	.3479	.7875	.3020	13	0	.0000
49.87	.2598	.2697	1.0383	.1170	16	1	.0588

APPENDIX II—
Summary Statistics of Intra-Network Sample Ratios for Dallas, Texas

Appendix II–1. Summary statistics of intra-network sample ratios surrounding any annual precipitation maxima near Dallas, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 41,786. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1.61	1.0537	.4960	.4707	.9280	182	6	.0319
2.55	.9179	.3251	.3542	.9010	368	7	.0187
3.56	.8307	.3119	.3754	.8300	499	9	.0177
4.52	.7956	.3515	.4419	.7890	593	25	.0405
5.49	.8368	.3325	.3973	.8130	555	5	.0089
6.49	.7866	.3700	.4703	.7750	800	25	.0303
7.47	.7891	.3596	.4558	.7660	783	18	.0225
8.58	.7493	.3851	.5140	.7350	780	21	.0262
9.53	.6709	.4165	.6208	.6460	873	54	.0583
10.58	.7052	.4048	.5740	.6970	705	31	.0421
11.44	.7091	.4052	.5714	.6810	817	33	.0388
12.43	.6963	.4141	.5948	.6950	975	55	.0534
13.60	.6795	.4318	.6356	.6770	1,000	56	.0530
14.48	.6111	.4341	.7103	.5820	1,076	100	.0850
15.53	.6133	.4335	.7069	.5630	643	53	.0761
16.48	.5928	.4343	.7327	.5470	835	72	.0794
17.65	.5833	.4227	.7245	.5650	655	56	.0788
18.53	.5596	.4351	.7775	.5000	816	95	.1043
19.53	.6660	.4424	.6643	.6200	427	20	.0447
20.56	.5617	.4421	.7870	.5120	684	87	.1128
21.67	.5375	.4208	.7828	.5000	599	72	.1073
22.55	.5471	.4220	.7713	.4790	955	80	.0773
23.46	.5399	.4318	.7996	.4780	886	92	.0941

Appendix II–1. Summary statistics of intra-network sample ratios surrounding any annual precipitation maxima near Dallas, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.39	0.5014	0.4336	0.8649	0.4210	823	114	0.1217
25.50	.5621	.4580	.8147	.4940	958	110	.1030
26.53	.5197	.4153	.7990	.4650	1,144	122	.0964
27.54	.5114	.4132	.8079	.4520	610	59	.0882
28.56	.5085	.4182	.8224	.4460	1,050	118	.1010
29.40	.5198	.4488	.8634	.4240	475	55	.1038
30.47	.4934	.4312	.8739	.3980	1,131	147	.1150
31.46	.5041	.4471	.8870	.4020	793	99	.1110
32.62	.4723	.4261	.9023	.3820	1,106	155	.1229
33.58	.4596	.4042	.8794	.3770	926	122	.1164
34.51	.4722	.4152	.8792	.3820	911	118	.1147
35.41	.4838	.4144	.8566	.3950	980	122	.1107
36.56	.4794	.4156	.8668	.3990	1,046	119	.1021
37.53	.4498	.4151	.9229	.3540	1,545	223	.1261
38.54	.4912	.4098	.8343	.4120	933	89	.0871
39.53	.4352	.4185	.9617	.3250	945	153	.1393
40.57	.4946	.4243	.8579	.4150	1,202	137	.1023
41.41	.4449	.4122	.9265	.3430	589	87	.1287
42.40	.4136	.3965	.9587	.2980	758	122	.1386
43.50	.4403	.3952	.8976	.3610	1,047	157	.1304
44.51	.4238	.4050	.9555	.3110	1,363	193	.1240
45.56	.3714	.3668	.9878	.2570	603	111	.1555
46.38	.4150	.3876	.9340	.3270	1,211	200	.1417
47.53	.4501	.4093	.9093	.3450	1,516	190	.1114
48.41	.4808	.4218	.8774	.3720	576	81	.1233
49.52	.4191	.3990	.9518	.3220	1,039	148	.1247

Appendix II–2. Summary statistics of intra-network sample ratios surrounding the 2-year or greater annual precipitation maxima near Dallas, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 15,775. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1.60	.9155	.1967	.2148	.9260	53	1	.0185
2.59	.8599	.2642	.3073	.8720	111	1	.0089
3.55	.7821	.2676	.3421	.8180	165	3	.0179
4.55	.7575	.2984	.3940	.7700	195	6	.0299
5.51	.7688	.2782	.3618	.7770	159	2	.0124
6.48	.7135	.3233	.4532	.6930	261	8	.0297
7.48	.7340	.3054	.4161	.7320	259	6	.0226
8.58	.6733	.3441	.5111	.6630	253	7	.0269
9.54	.6068	.3660	.6032	.5740	310	16	.0491
10.60	.6672	.3653	.5475	.6740	205	7	.0330
11.47	.6265	.3640	.5811	.5940	286	14	.0467
12.43	.6486	.4010	.6183	.6420	343	14	.0392
13.61	.6186	.4007	.6477	.5810	373	18	.0460
14.50	.5815	.3871	.6657	.5530	402	21	.0496
15.53	.5501	.3830	.6962	.5260	247	14	.0536
16.47	.5574	.3772	.6768	.4980	310	15	.0462
17.64	.5314	.3888	.7316	.4840	235	18	.0711
18.50	.4945	.3805	.7696	.4290	281	27	.0877
19.55	.5784	.3946	.6823	.5220	162	8	.0471
20.59	.5018	.3567	.7109	.4910	266	23	.0796
21.67	.4752	.3606	.7589	.4000	218	19	.0802
22.56	.4852	.3807	.7846	.4120	369	30	.0752
23.48	.4772	.3813	.7990	.4110	332	24	.0674

Appendix II–2. Summary statistics of intra-network sample ratios surrounding the 2-year or greater annual precipitation maxima near Dallas, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.36	0.4844	0.3968	0.8191	0.4130	316	30	0.0867
25.50	.5130	.3987	.7771	.4480	399	36	.0828
26.54	.4703	.3815	.8112	.4040	469	42	.0822
27.55	.4508	.3591	.7965	.3860	236	15	.0598
28.57	.4142	.3484	.8411	.3500	404	37	.0839
29.39	.4191	.3420	.8160	.3620	186	14	.0700
30.47	.4182	.3662	.8757	.3340	456	50	.0988
31.45	.4299	.3747	.8717	.3450	305	23	.0701
32.63	.4143	.3712	.8960	.3220	421	49	.1043
33.60	.4220	.3627	.8593	.3170	362	38	.0950
34.52	.4269	.3548	.8311	.3520	384	41	.0965
35.42	.4352	.3561	.8181	.3640	377	30	.0737
36.56	.4244	.3569	.8409	.3410	393	26	.0621
37.54	.4063	.3708	.9126	.3110	630	75	.1064
38.55	.4175	.3462	.8293	.3430	370	30	.0750
39.51	.3727	.3381	.9071	.2960	342	41	.1070
40.56	.4353	.3804	.8739	.3510	476	45	.0864
41.40	.3669	.3323	.9057	.2640	232	29	.1111
42.41	.3630	.3229	.8893	.2800	310	36	.1040
43.53	.3762	.3248	.8635	.3070	399	50	.1114
44.50	.3582	.3354	.9364	.2620	551	64	.1041
45.56	.3059	.2904	.9494	.2010	234	32	.1203
46.37	.3658	.3385	.9256	.2800	480	63	.1160
47.53	.3818	.3280	.8591	.2980	616	55	.0820
48.43	.4008	.3498	.8728	.3220	237	33	.1222
49.55	.3275	.2949	.9006	.2500	395	49	.1104

Appendix II–3. Summary statistics of intra-network sample ratios surrounding the 5-year or greater annual precipitation maxima near Dallas, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 5,146. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1–2	--	--	--	--	--	--	--
2.76	.7003	.2935	.4191	.6430	14	0	.0000
3.85	.6089	.3929	.6452	.6520	13	1	.0714
4.56	.6697	.2642	.3946	.6650	27	0	.0000
5.54	.7054	.2860	.4055	.6930	14	0	.0000
6.48	.5765	.2783	.4828	.5310	50	2	.0385
7.50	.6812	.3218	.4724	.6000	45	0	.0000
8.64	.5840	.3595	.6156	.5000	47	0	.0000
9.52	.5331	.3544	.6649	.4440	82	5	.0575
10.63	.6344	.3227	.5086	.5450	54	1	.0182
11.50	.5573	.3386	.6076	.4760	69	2	.0282
12.44	.6577	.3903	.5935	.6670	100	2	.0196
13.62	.5280	.3272	.6197	.5160	114	4	.0339
14.47	.5901	.3667	.6213	.5370	115	4	.0336
15.56	.5012	.3725	.7434	.4830	92	5	.0515
16.44	.5100	.3560	.6980	.4470	102	4	.0377
17.66	.5653	.3970	.7022	.5930	85	7	.0761
18.54	.4733	.3640	.7691	.3950	99	7	.0660
19.55	.4652	.2566	.5515	.4370	58	0	.0000
20.58	.4844	.3651	.7537	.3760	79	6	.0706
21.67	.4301	.3065	.7126	.3930	79	8	.0920
22.58	.4485	.3321	.7405	.3780	144	9	.0588
23.51	.4367	.3576	.8188	.3780	114	6	.0500

Appendix II–3. Summary statistics of intra-network sample ratios surrounding the 5-year or greater annual precipitation maxima near Dallas, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.38	0.4895	0.3546	0.7244	0.4200	96	2	0.0204
25.47	.4497	.3332	.7408	.3920	133	9	.0634
26.53	.4728	.3484	.7368	.4370	156	9	.0545
27.57	.3900	.2993	.7674	.3250	87	4	.0440
28.55	.3750	.3205	.8546	.2680	139	9	.0608
29.38	.3738	.3380	.9043	.2650	67	6	.0822
30.48	.3768	.3294	.8742	.2970	155	11	.0663
31.45	.4305	.3602	.8368	.3410	113	7	.0583
32.62	.3889	.3372	.8671	.3070	141	12	.0784
33.62	.3789	.2705	.7139	.3020	112	6	.0508
34.50	.3953	.3122	.7896	.3360	133	8	.0567
35.43	.3836	.3121	.8136	.3090	150	9	.0566
36.59	.3983	.3349	.8409	.2930	159	7	.0422
37.54	.3699	.3130	.8462	.3030	220	15	.0638
38.55	.3810	.3107	.8154	.3070	141	6	.0408
39.52	.2785	.2456	.8819	.2010	131	11	.0775
40.60	.3736	.3080	.8244	.3210	181	10	.0524
41.42	.3085	.2565	.8313	.2480	79	9	.1023
42.43	.3153	.2589	.8210	.2540	102	10	.0893
43.53	.3503	.3008	.8585	.2890	139	12	.0795
44.55	.2941	.2478	.8425	.2550	207	15	.0676
45.57	.2849	.2480	.8705	.1910	81	7	.0795
46.39	.3315	.3091	.9326	.2000	164	16	.0889
47.54	.3559	.2859	.8032	.2760	229	10	.0418
48.47	.4096	.3342	.8159	.3350	92	8	.0800
49.53	.2718	.2339	.8608	.2270	143	13	.0833

APPENDIX III—
Summary Statistics of Intra-Network Sample Ratios for Houston, Texas

Appendix III–1. Summary statistics of intra-network sample ratios surrounding any annual precipitation maxima near Houston, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 69,370. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1.68	1.4273	1.3440	.9416	.8810	111	2	.01770
2.54	.8688	.4027	.4635	.8410	224	5	.0218
3.50	.8314	.4132	.4970	.8080	516	15	.0282
4.51	.8070	.4102	.5082	.7990	487	11	.0221
5.57	.7616	.4168	.5473	.7430	1,016	32	.0305
6.48	.6963	.4593	.6597	.6810	1,284	87	.0635
7.51	.6903	.4446	.6441	.6700	1,221	68	.0528
8.55	.7100	.4469	.6294	.6740	1,334	85	.0599
9.47	.6923	.4578	.6613	.6520	1,405	64	.0436
10.47	.6767	.4310	.6369	.6450	1,651	85	.0490
11.52	.6390	.4500	.7042	.5940	1,538	86	.0530
12.51	.6146	.4447	.7235	.5550	2,240	166	.0690
13.49	.6382	.4465	.6996	.5970	1,700	106	.0587
14.45	.6134	.4250	.6928	.5590	1,634	97	.0560
15.47	.6045	.4278	.7077	.5560	2,173	142	.0613
16.47	.6272	.4491	.7161	.5620	1,761	110	.0588
17.50	.6021	.4334	.7198	.5410	2,064	123	.0562
18.48	.5894	.4440	.7534	.5300	2,182	169	.0719
19.47	.5829	.4406	.7560	.5080	2,189	155	.0661
20.48	.5711	.4315	.7556	.4940	2,179	147	.0632
21.52	.5359	.4131	.7708	.4700	1,690	126	.0694
22.46	.5561	.4255	.7653	.4880	1,771	118	.0625
23.55	.5504	.4287	.7789	.4750	2,244	178	.0735

Appendix III–1. Summary statistics of intra-network sample ratios surrounding any annual precipitation maxima near Houston, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.43	0.5537	0.4326	0.7813	0.4710	2,094	152	0.0677
25.49	.5441	.4499	.8269	.4540	1,724	155	.0825
26.50	.5583	.4400	.7881	.4770	1,717	123	.0668
27.56	.5212	.4123	.7912	.4360	2,012	164	.0754
28.54	.5015	.4252	.8479	.4100	1,646	146	.0815
29.45	.5145	.4352	.8459	.4210	1,396	116	.0767
30.46	.5229	.4275	.8175	.4350	1,769	132	.0694
31.46	.4935	.4154	.8417	.3970	1,374	119	.0797
32.51	.4809	.4068	.8457	.4000	1,143	112	.0892
33.50	.4688	.4108	.8764	.3630	1,335	121	.0831
34.48	.4703	.4272	.9084	.3550	1,407	170	.1078
35.51	.4517	.4193	.9283	.3320	1,526	190	.1107
36.57	.4823	.4108	.8518	.4000	1,613	153	.0866
37.49	.4773	.4359	.9131	.3560	1,105	107	.0883
38.46	.4461	.4143	.9286	.3320	1,070	136	.1128
39.39	.4815	.4274	.8877	.3740	1,438	130	.0829
40.61	.4537	.4201	.9260	.3420	1,735	223	.1139
41.56	.4262	.4020	.9433	.2970	790	98	.1104
42.48	.4797	.4374	.9118	.3550	1,479	146	.0898
43.40	.4299	.4216	.9806	.2960	878	133	.1316
44.50	.4171	.3830	.9182	.3180	1,021	119	.1044
45.51	.4680	.4447	.9501	.3590	1,195	152	.1128
46.49	.4219	.4265	1.0108	.2810	903	125	.1216
47.47	.4026	.4073	1.0115	.2740	975	148	.1318
48.62	.4280	.4283	1.0008	.2890	862	147	.1457
49.44	.3932	.4023	1.0231	.2440	549	91	.1422

Appendix III–2. Summary statistics of intra-network sample ratios surrounding the 2-year or greater annual precipitation maxima near Houston, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 21,392. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1.70	.8237	.3461	.4202	.8830	31	1	.0312
2.57	.7792	.3896	.5000	.7620	61	3	.0469
3.49	.7918	.3894	.4918	.7630	135	7	.0493
4.51	.7501	.3745	.4993	.7800	119	4	.0325
5.57	.7191	.3820	.5312	.6910	264	8	.0294
6.46	.6264	.4383	.6996	.6260	367	33	.0825
7.50	.6535	.4138	.6331	.6540	362	17	.0449
8.55	.6597	.3974	.6024	.6350	400	21	.0499
9.45	.6488	.3924	.6049	.6140	380	18	.0452
10.45	.6321	.3802	.6014	.5910	468	19	.0390
11.51	.5671	.4165	.7344	.5030	443	26	.0554
12.52	.5456	.3923	.7191	.4970	631	42	.0624
13.49	.5769	.4183	.7251	.5210	482	27	.0530
14.45	.5535	.3766	.6805	.4750	424	19	.0429
15.44	.5534	.3943	.7126	.4920	611	34	.0527
16.47	.5526	.3949	.7146	.4690	520	27	.0494
17.50	.5654	.3995	.7066	.4990	626	34	.0515
18.49	.5253	.3958	.7533	.4470	652	46	.0659
19.48	.5212	.3836	.7359	.4450	646	39	.0569
20.47	.5028	.3913	.7782	.4100	633	34	.0510
21.52	.4750	.3795	.7988	.3900	470	33	.0656
22.47	.5041	.3848	.7634	.4300	500	22	.0421
23.56	.5467	.4117	.7531	.4560	672	34	.0482

Appendix III–2. Summary statistics of intra-network sample ratios surrounding the 2-year or greater annual precipitation maxima near Houston, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.42	0.4913	0.3965	0.8071	0.3990	638	45	0.0659
25.50	.4703	.3964	.8429	.3660	526	45	.0788
26.51	.5141	.4136	.8046	.4300	528	25	.0452
27.56	.4912	.3956	.8054	.3810	622	41	.0618
28.54	.4701	.4065	.8647	.3560	508	29	.0540
29.45	.4630	.4063	.8776	.3400	415	34	.0757
30.46	.5174	.4271	.8255	.4090	554	29	.0497
31.46	.4245	.3547	.8355	.3260	429	27	.0592
32.52	.4535	.3965	.8743	.3430	351	23	.0615
33.48	.4144	.3660	.8832	.2850	432	30	.0649
34.49	.4268	.3891	.9118	.3300	453	53	.1047
35.51	.4153	.3814	.9183	.3200	536	61	.1022
36.57	.4516	.3751	.8307	.3620	532	33	.0584
37.48	.4231	.3721	.8794	.3040	337	27	.0742
38.47	.4219	.3953	.9368	.2970	392	43	.0989
39.37	.4416	.3699	.8376	.3400	481	27	.0531
40.63	.3982	.3746	.9406	.2670	627	62	.0900
41.55	.3752	.3406	.9079	.2580	277	25	.0828
42.48	.4543	.4108	.9042	.3190	534	41	.0713
43.40	.3918	.3774	.9633	.2800	340	41	.1076
44.49	.3453	.3259	.9439	.2380	382	45	.1054
45.50	.4662	.4294	.9209	.3590	439	48	.0986
46.48	.3872	.3957	1.0220	.2280	314	38	.1080
47.47	.3416	.3438	1.0065	.2370	349	42	.1074
48.63	.3850	.3834	.9959	.2520	298	43	.1261
49.43	.3627	.3764	1.0377	.2150	201	25	.1106

Appendix III–3. Summary statistics of intra-network sample ratios surrounding the 5-year or greater annual precipitation maxima near Houston, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 8,536. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1–2	--	--	--	--	--	--	--
2.54	.7417	.3351	.4518	.7620	21	1	.0455
3.49	.7392	.3806	.5149	.7500	51	3	.0556
4.48	.7380	.4288	.5810	.8290	46	3	.0612
5.60	.7613	.3756	.4935	.7190	97	3	.0300
6.44	.5705	.3869	.6783	.5810	155	17	.0988
7.53	.6320	.4029	.6374	.6170	137	5	.0352
8.56	.6288	.3888	.6184	.6260	147	12	.0755
9.43	.6916	.4042	.5844	.6940	149	7	.0449
10.39	.6650	.4045	.6082	.6210	164	6	.0353
11.52	.5437	.4359	.8018	.5010	183	16	.0804
12.49	.5602	.4189	.7478	.5220	240	20	.0769
13.48	.5313	.3899	.7338	.4970	192	12	.0588
14.47	.5854	.3663	.6258	.5220	165	4	.0237
15.43	.5448	.4018	.7375	.5080	237	17	.0669
16.47	.5401	.3835	.7102	.4550	199	12	.0569
17.51	.5537	.3996	.7216	.4970	252	15	.0562
18.50	.5282	.4137	.7832	.4090	257	21	.0755
19.49	.4937	.3738	.7571	.4040	255	14	.0520
20.44	.4762	.3567	.7489	.3610	239	15	.0591
21.52	.4522	.3942	.8717	.3250	193	15	.0721
22.47	.5014	.3833	.7644	.4300	185	8	.0415
23.56	.5205	.3786	.7273	.4470	295	12	.0391

Appendix III–3. Summary statistics of intra-network sample ratios surrounding the 5-year or greater annual precipitation maxima near Houston, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.42	0.4793	0.4069	0.8490	0.3780	236	18	0.0709
25.52	.4596	.3952	.8598	.3480	216	20	.0847
26.51	.5156	.4024	.7804	.4350	186	9	.0462
27.57	.4776	.3667	.7677	.3760	232	7	.0293
28.57	.4742	.4006	.8447	.3590	215	8	.0359
29.43	.4084	.3652	.8942	.3000	167	14	.0773
30.46	.4919	.4167	.8472	.4060	230	13	.0535
31.45	.3681	.3266	.8875	.2660	172	10	.0549
32.51	.4345	.3816	.8783	.3120	136	6	.0423
33.50	.3893	.3448	.8857	.2360	174	7	.0387
34.50	.4293	.3805	.8865	.3340	184	16	.0800
35.50	.3675	.3286	.8941	.2960	234	27	.1034
36.60	.4062	.3315	.8162	.3330	208	13	.0588
37.48	.3786	.3436	.9074	.2700	159	17	.0966
38.50	.3776	.3617	.9581	.2370	142	16	.1013
39.35	.4055	.3549	.8752	.2810	205	9	.0421
40.64	.3507	.3392	.9673	.2230	270	25	.0847
41.53	.3646	.3560	.9764	.2150	115	12	.0945
42.48	.3871	.3368	.8701	.2810	204	14	.0642
43.39	.4076	.4105	1.0072	.2590	144	13	.0828
44.49	.2922	.2761	.9450	.2090	164	18	.0989
45.50	.4121	.3961	.9612	.2970	187	24	.1137
46.46	.2984	.3058	1.0249	.1730	137	16	.1046
47.46	.2828	.2946	1.0418	.1770	151	18	.1065
48.64	.3607	.3691	1.0232	.2300	121	17	.1232
49.43	.3274	.3370	1.0295	.2020	88	8	.0833

Appendix III–4. Summary statistics of intra-network sample ratios surrounding the 10-year or greater annual precipitation maxima near Houston, Texas

[Unless otherwise noted, units are dimensionless. Total number of samples for separation distances up to 50 miles equals 4,654. mi, miles; --, no data available]

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
0	1	0	0	1	0	0	0
0–1	--	--	--	--	--	--	--
1–2	--	--	--	--	--	--	--
2–3	--	--	--	--	--	--	--
3.45	.6831	.3546	.5191	.7060	30	2	.0625
4.44	.7259	.4350	.5992	.7820	25	1	.0385
5.56	.7325	.2940	.4014	.7140	56	2	.0345
6.46	.5286	.3659	.6921	.5770	79	10	.1124
7.54	.6358	.4016	.6316	.6260	75	3	.0385
8.59	.6105	.3518	.5762	.6350	85	7	.0761
9.42	.7116	.3720	.5227	.7250	90	1	.0110
10.41	.6062	.3585	.5915	.5870	82	5	.0575
11.54	.5385	.4228	.7851	.5110	105	9	.0789
12.50	.5601	.4147	.7405	.5230	135	12	.0816
13.48	.5198	.3505	.6744	.5280	98	3	.0297
14.47	.6172	.3797	.6151	.5390	87	3	.0333
15.44	.5664	.3787	.6686	.5920	130	6	.0441
16.46	.5128	.3576	.6973	.4550	104	6	.0545
17.51	.5110	.3628	.7099	.4640	138	12	.0800
18.48	.5449	.4049	.7431	.4700	142	10	.0658
19.47	.4710	.3545	.7528	.4040	131	8	.0576
20.45	.4389	.3281	.7474	.3500	122	7	.0543
21.52	.4450	.3895	.8751	.3240	112	6	.0508
22.48	.5340	.3941	.7380	.4970	102	3	.0286
23.58	.5024	.3709	.7383	.4480	162	8	.0471

Appendix III–4. Summary statistics of intra-network sample ratios surrounding the 10-year or greater annual precipitation maxima near Houston, Texas—Continued

Mean separation distance for each mile-wide window (mi)	Mean sample ratio, mean empirical $S_T(r)$	Standard deviation of sample ratios	Coefficient of variation of sample ratios	Median sample ratio, median empirical $S_T(r)$	No. of sample ratios	No. of zero sample ratios	Probability of zero sample ratio
24.41	0.4897	0.3733	0.7624	0.4170	121	3	0.0242
25.51	.4458	.3870	.8681	.3190	127	10	.0730
26.52	.5096	.3826	.7508	.4590	99	6	.0571
27.55	.4922	.3444	.6996	.4200	116	4	.0333
28.57	.4251	.3563	.8382	.3130	118	5	.0407
29.44	.3583	.2921	.8153	.3010	90	8	.0816
3.47	.4404	.3783	.8592	.3450	135	7	.0493
31.43	.3536	.2598	.7348	.2710	79	3	.0366
32.52	.3821	.3483	.9116	.2890	68	4	.0556
33.49	.3436	.3054	.8887	.2170	98	6	.0577
34.49	.3749	.3360	.8962	.2640	107	11	.0932
35.49	.3146	.2642	.8398	.2500	133	15	.1014
36.57	.3482	.3048	.8751	.2610	106	11	.0940
37.48	.3204	.3001	.9366	.2250	96	15	.1351
38.49	.3289	.3282	.9977	.2260	69	11	.1375
39.32	.3610	.3206	.8881	.2320	100	5	.0476
40.63	.2897	.2711	.9358	.1930	151	16	.0958
41.52	.3081	.2749	.8923	.2290	59	6	.0923
42.45	.3048	.2496	.8191	.2490	115	9	.0726
43.38	.2967	.2942	.9917	.1920	78	8	.0930
44.46	.2436	.2254	.9251	.1720	96	10	.0943
45.51	.4200	.3763	.8958	.3240	111	11	.0902
46.46	.2349	.2391	1.0176	.1310	80	11	.1209
47.48	.2711	.2819	1.0398	.1700	91	9	.0900
48.65	.2703	.2627	.9720	.2150	70	12	.1463
49.39	.2335	.2161	.9255	.1620	51	4	.0727