NOAA Technical Memorandum NWS HYDRO-35

FIVE- TO 60-MINUTE PRECIPITATION FREQUENCY FOR THE EASTERN AND CENTRAL UNITED STATES

Silver Spring, Md.
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NWS HYDRO 14 National Weather Service River Forecast System Forecast Procedures. December, 1972. COM-73-10517)

(Continued on inside back cover)

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FIVE-TO 60-MINUTE PRECIPITATION FREQUENCY FOR THE EASTERN AND CENTRAL UNITED STATES

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ABSTRACT. Precipitation-frequency values for durations of 5, 15, and 60 minutes at return periods of 2 and 100 years are presented in map form for 37 states from North Dakota to Texas and eastward. Equations are given to derive 10- and 30-min values from the maps. Equations are also given to compute values for selected return periods between 2 and 100 years.

The basic input data to the study are the maximum annual precipitation values for 5, 10, 15, 30, and 60 minutes at about 200 stations and the maximum annual 1-hr events at about 1900 stations with recording rain gages. Computer space-averaging techniques were used for interstation interpolation.

INTRODUCTION

The growing environmental awareness of the past few years has increased the demand for hydrologic planning and design for small area drainages having very short times of concentration. Examples of such drainage areas are cattle feedlots and urban shopping and parking areas. Hydrologic design practice and legal standards are generally expressed in terms of control of storm flow of specified frequency of recurrence. Precipitation frequencies for short durations are an essential input to evaluating the runoff frequencies from small drainage areas.

Since 1961, U. S. Weather Bureau Technical Paper No. 40 (Hershfield 1961), abbreviated TP-40, has been the standard for precipitation-frequency values for durations from 5 minutes to 24 hours over the Eastern United States. For durations of less than 1 hour, the TP-40 values are derived by using nationwide, return-period independent ratios of shorter duration values to 1-hr values. While these average ratios are valid in many specific sections of the country, they have an observed, describable geographic pattern. It has also been found that the ratios vary with return period.

The present publication analyzes the above variations and derives new 5- to 60-min precipitation frequencies for the 37 states, North Dakota to Texas and eastward. These are presented in the form of maps for the 5-, 15- and 60-min durations at the 2- and 100-yr return periods, together with equations and nomograms for intraduration and intrareturn period interpolations.

This report is the latest in the precipitation-frequency literature for the United States that began in the 1930's when David L. Yarnell (1935) first published generalized precipitation-frequency maps for durations of 5 minutes to 24 hours at return periods of 2 to 100 years. Since 1955, the National Weather Service (NWS, then the Weather Bureau) and the Soil Conservation Service, U. S. Department of Agriculture, have been engaged in a cooperative effort to define the depth-area-duration precipitation-frequency regime of the entire United States. This effort is reviewed in the introduction to the several volumes of NOAA Atlas 2, "Precipitation-Frequency Atlas of the Western United States" (Miller et al. 1973).

BASIC DATA

N-MINUTE DATA

The data for durations from 5 to 60 minutes are from recording rain gages at nearly 200 first-order NWS stations (fig. 1). The period of record averages nearly 60 years. The measurements are mostly from tipping bucket gages of 12-in. (305-mm) diameter which mark each 0.01 in. (0.25 mm) of rainfall as a step on a recording strip chart (Weather Bureau 1963). Rainfalls for 5, 10, 15, 30 and 60 minutes that exceed certain intensity thresholds have been tabulated for these stations since 1936 (1943 for 15-min durations). These data are published in U. S. Meteorological Yearbook (Weather Bureau 1936-49) and Climatological Data, National Summary, Annual (Environmental Data Service 1950-72). For the present study, annual maxima for each duration at each station were abstracted from these sources. For the period prior to 1936 (1943 for 15-min values), maximum annual values for the selected durations were transcribed manually several years ago from station records at each field station (or repository for stations closed), in response to a request from the office of the authors.

HOURLY DATA

A network of recording rain gages has been maintained by the NWS, with cooperation from many agencies, since the early 1940s. Data from about 1,900 of these stations in the study area were analyzed for this project, (fig. 1). The basic rain gage was originally an 8-in. (203-mm) diameter weighing rain gage in which the weight of precipitation collected in a bucket guides a pen arm recording on a clock-driven strip chart. During recent years, some of these gages have been replaced by the newer Fischer & Porter gage which records the accumulated precipitation by 0.10 in. (2.5 mm) increments at 15-min intervals on punched paper tape.

Hourly precipitation for clock hours (1:00 a.m. to 2:00 a.m., 2:00 a.m. to 3:00 a.m., etc.) is abstracted from the charts of these gages and published in the Hydrologic Bulletin (Weather Bureau 1940-48), Climatological Data (Weather Bureau 1948-51), and Hourly Precipitation Data (Environmental Data Service 1951-72). The National Climatic Center, Environmental Data Service, NOAA, which is responsible for abstracting and publishing the data, began current punching of the data on cards in 1948 and later transferred the information to magentic tape. This clock-hour data for 1948-72 is available on magnetic tape. Maximum annual clock-hour precipitation magnitudes

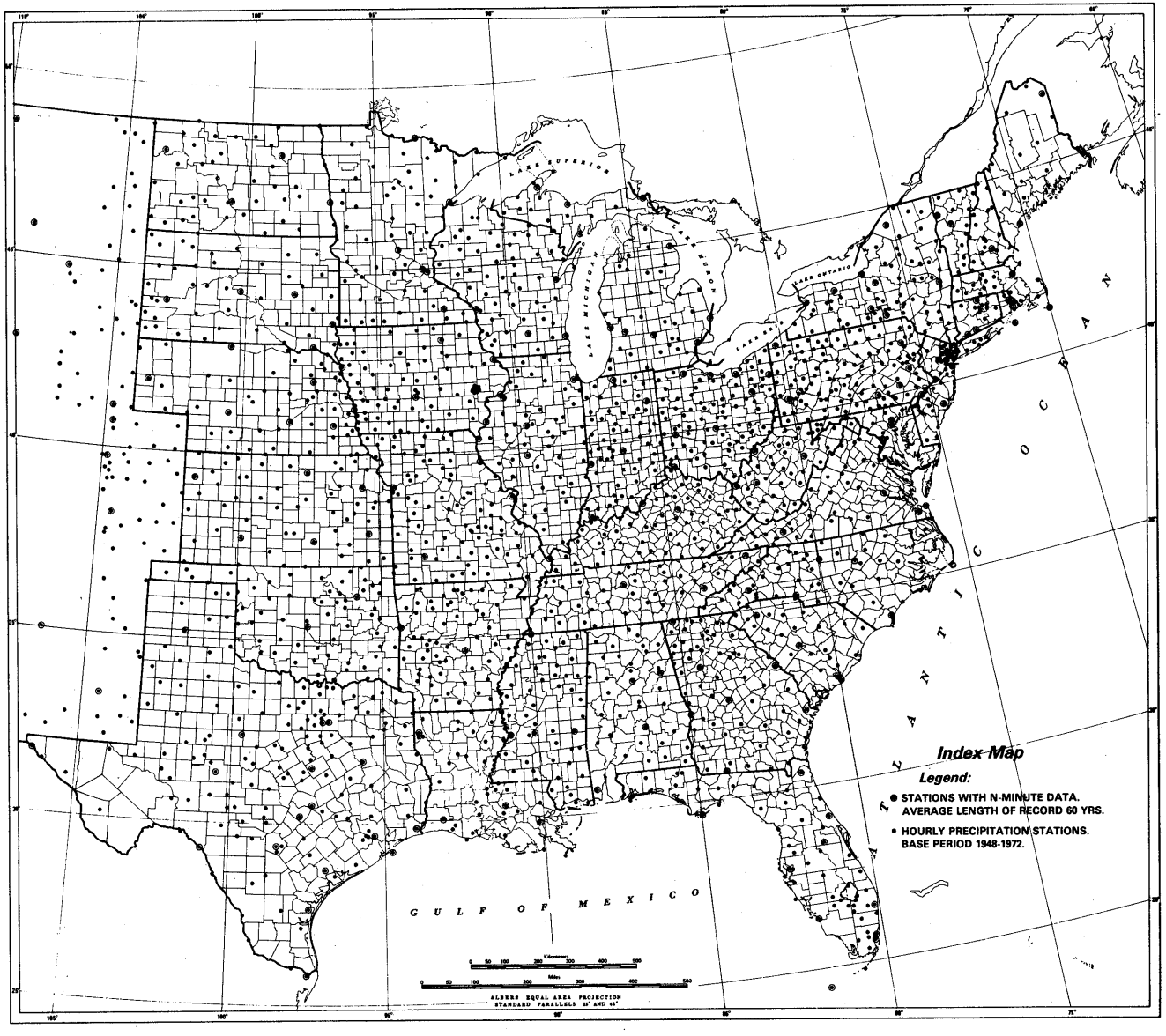

Figure 1.--Station index map.

extracted from this data set differ from, and may be smaller than, maximum 60-min magnitudes from the preceding data set. Statistical conversion of clock-hour precipitation frequencies to 60-min frequencies is discussed later. Stations with 15 or more years of data during the 1948-72 25-year period were processed. Many stations had a complete 25-yr record, most had more than 20 years and only a few as little as 15 years.

Canadian Data

The Canadian Atmospheric Environment Service (AES) recently prepared frequency distributions of short-duration precipitation (Atmospheric Environment Service, Canada, 1974). AES methods are similar to those used in this study. There are about 20 Canadian stations within about 100 miles of the United States border with frequency distributions of 5- to 60-min rainfalls based on records of 15 years or longer, and many additional stations with frequencies based on shorter records. The Canadian frequency values were used in the analysis without additional testing or investigation, giving the most weight to the longer record stations.

DATA PROCESSING AND TESTING

Computer Processing of Data Tapes

The data tapes containing hourly precipitation values for the period 1948 through 1972 were computer analyzed to select the maximum hourly value for each month for each station/year. From these monthly values, the computer selected the largest as the maximum hourly value for each year. During processing, the computer also tabulated the number of hours each month listed as missing and the number which contained accumulated amounts. All data (maximum monthly and annual values and number of missing or accumulated values) were listed on the computer output and checked by technicians. Errors sought included: (1) mispunched data still on the tapes and (2) a maximum value chosen from an incomplete station year. The inspected data sets used in the analysis are believed to be as reasonable and correct as can be expected when dealing with data sets of this magnitude.

Frequency Analysis

There are two methods of selecting data for analysis of extreme values. The first method selects the largest single event that occurred within each year of record. For this annual series, the year may be calendar year, water year, or any other consecutive 12-mo period. The second method recognizes that large amounts are not calendar bound and that more than one large event may occur within the time unit used as a year. In the latter, the partial-duration series, all values above a base (frequently the smallest maximum annual event) are used regardless of how many occur in the same year; the only restriction is that independence of individual events be maintained. The partial-duration series is not a complete series (Chow 1950) and thus is difficult to handle mathematically.

One requirement in the preparation of this publication is that the results be expressed in terms of partial-duration frequencies. To avoid the complexities of handling the partial-duration series, the annual series data for calendar years were collected and analyzed; and the resulting statistics were transformed to partial-duration statistics.

Conversion Factors Between Annual and Partial-Duration Series

Table 1 gives the empirical factors used to multiply annual series values to obtain the equivalent partial-duration series values. It is based on a sample of about 200 geographically well-distributed first-order NWS stations (Hershfield 1961). The factors shown in table 1 are reciprocals of the factors in table 2 of TP-40.

Table 1.--Factors for converting annual series to equivalent partial-duration series

Return period (yr)	Factor
2	1.13
5	1.04
10	1.01
25	1.00
50	1.00
100	1.00

The rainfall frequency maps in this publication are for partial duration occurrences, and are based on analysis of station annual series, adjusted by factors from table 1.

Frequency Distribution

The Fisher-Tippett Type I frequency distribution is used in this study. The fitting procedure is that developed by Gumbel (1958). This distribution and fitting procedure were used by the NWS in previous studies of short-duration precipitation values (U. S. Weather Bureau 1953, 1954a, 1954b, 1955a, 1955b, 1956, 1957-60, Hershfield 1961, and Miller et al. 1973). Studies by Hershfield and Kohler (1960) and Hershfield (1962) have demonstrated the applicability of this distribution to precipitation extremes. Recently, in conjunction with another study (Miller et al. 1973), a comparison of the values obtained by the Gumbel technique, the Lieblein fitting of the Fisher-Tippett Type I, the Pearson Type III, and the Log Pearson Type III distributions was performed. The data were for durations of 1, 6, and 24 hours. Several thousand station years of data were examined by determining the percent of observations that equaled or exceeded the calculated values for certain return periods. Results of the four computation procedures did not differ significantly. Therefore, there is no reason to use another technique; and by continuing the Gumbel fitting procedure, the study is compatable with previous studies.

The Gumbel procedure uses the method of moments. The 2-yr value measures the first moment, or central tendency. The relation of the 2-yr to the 100-yr value is a measure of the second moment, or dispersion. Values for other return periods can be derived mathematically from the 2- and 100-yr rainfalls.

DATA TESTING

Test for Climatological Trend

The aim of this study is to depict the frequency of N-min precipitation values in a population extending over a long period of time. A large share of the data is from a 25-yr record, but longer records are also used. To test the hypothesis that there was no recent climatological trend that would make different record lengths incompatible, 68 geographically well-distributed first-order NWS stations within the study area were selected. These stations had complete and concurrent records of maximum annual 5- and 60-min rainfalls for the 50-yr period 1923-72.

For the 68 stations, the data sample was divided into two 25-yr segments, 1923-47 and 1948-72, and means and standard deviation for the 2- and 100-yr 5- and 60-min values were computed. For each duration a t-test of the two

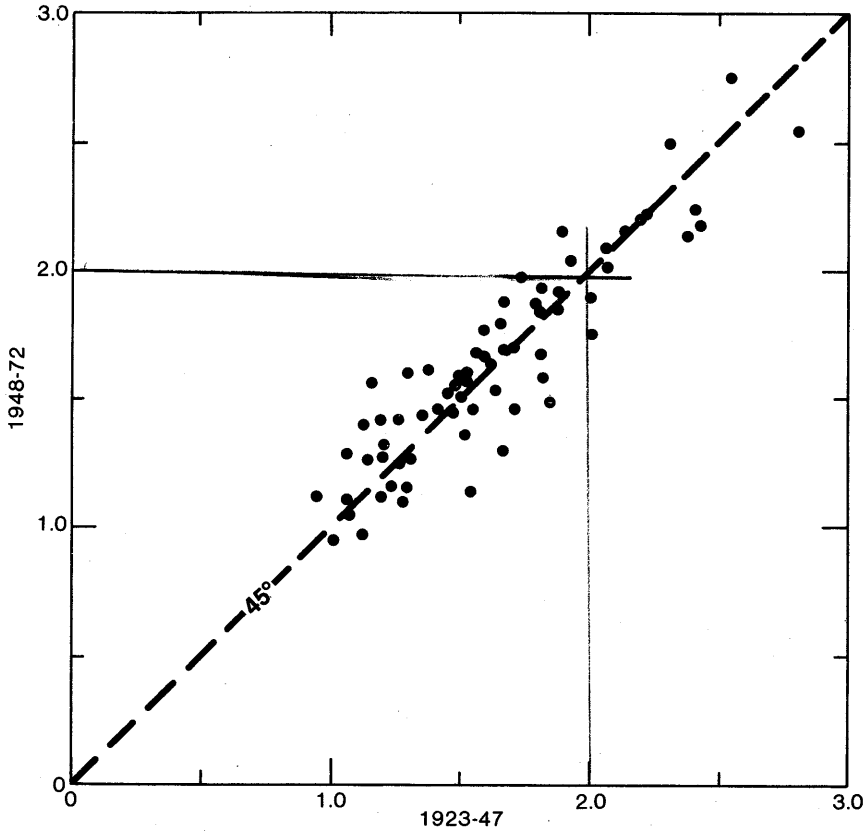

Figure 2.--Comparison of 2-yr 60-min precipitation values for 1923-47 and 1948-72, at 68 stations.

sample means (one mean for each data period) indicated a probability greater than 0.90 that samples from the two periods were from the same populations at the 5- and 60-min durations. Figure 2 is a plot of the 2-yr 60-min values from the two different record periods.

Adjustment of Clock-Hour Data to 60-Min Values

A factor to adjust statistical 1-hr values to 60-min values was determined empirically by NWS several years ago (Weather Bureau 1953, 1954a). It was found that, on the average, the N-yr 60-min value derived from the series of annual maximum 60-min events is 1.13 as great as the N-yr clock-hour value estimated from the series of annual maximum clock-hour values. This does not say that an annual maximum clock-hour event multiplied by 1.13 will give the maximum annual 60-min event in a particular case. This adjustment applies only to the results of a statistical analysis of a series of events.

Using probability theory, Weiss (1964) confirmed this adjustment. Nonetheless, an investigation was undertaken to insure that the adjustment of clock-hour to 60-min data, as previously used, was applicable to the present data set. Thirty first-order NWS stations, geographically well distributed over the study area and possessing complete and concurrent records of both maximum clock-hour and maximum 60-min precipitation for the period 1948-72, were chosen as a data sample. The series of annual maxima of the two types for each station was analyzed using the Gumbel fitting of the Fisher-Tippett Type I distribution. The ratios of the 60-min/1-hr values at the 2- and 100-yr return periods both confirmed the 1.13 factor.

The geographical variability of the adjustment factor, if any, was also investigated. A plot of the individual station ratios of the 2- and 100-yr return period clock-hour to 60-min values showed no discernible pattern. The 1.13 factor to adjust clock-hour values to comparable 60-min values was therefore adopted and used throughout this study.

ISOPLUVIAL MAPS

METHODOLOGY

The project objective is to define 2- to 100-yr precipitation at durations from 5 to 60 minutes. The usual approach to such a task is to draw maps for the enveloping durations and return periods and mathematically compute values for intermediate durations and return periods (e.g., Miller et al. 1973). For the present study, this would have meant drawing 5- and 60-min maps for the 2- and 100-yr return periods and developing equations to estimate 10-, 15- and 30-min values. To investigate the feasibility of this, data for the stations having N-min data were grouped geographically. Duration formulas for each such group for return periods of 2 and 100 years were computed in the following form:

$$R_n = C_n \ (R_{m2}) + (1-C_n) \ (R_{m1}) \qquad (1)$$

where R_n is the required frequency value for N minutes, R_{m1} and R_{m2} are mapped values for a lesser and longer duration, and C_n is the interpolation

constant. C_n was found to vary both geographically and by return period when the 10-, 15- and 30-min values were related to the 5- and 60-min values. For instance, interpolating the 15-min values between 5 and 60 minutes showed C_n ranging from 0.35 to 0.43 in different regions and for different return periods. 15-min values computed using an average C_n and analyzed 5- and 60-min values differed by over 10 percent from values obtained by statistical analysis of the station data. However, by interpolating 10-min between 5- and 15-min and 30-min between 15- and 60-min values, C_n stabilized with negligible geographic and return period differences. Thus, the decision was made to prepare the six maps named in the introduction.

In this study, the ratio of number of stations providing hourly values to N-minute stations is about 10 to 1 and precipitation-frequency patterns can be most accurately defined at the 60-min duration. Similarly, the period of record is several multiples of two years, but only a fraction of 100 years. Frequency pattern depiction is most accurate at the 2-yr return period. The 2-yr 60-min isopluvial pattern therefore was constructed first and used as a guide in constructing maps for longer return periods and for shorter durations.

Space-Averaging of Precipitation-Frequency Values

Individual station frequency values are necessarily derived from a small sample of the entire precipitation population. In areas without strong orographic influences on precipitation, as in most of the study area, the occurrence of heavy rainfall has a random component and the computed frequencies at individual stations are variable due to sampling error. The random component is especially pronounced at the short durations with which this study is concerned. Some stations are expected to experience more extreme events during the data period than others in the same climatic regime. For these reasons, all precipitation-frequency maps are constructed through use of space-averaging techniques. The techniques may be either computationally explicit or implicit in the drawing of the isopluvials by an analyst.

In this project, computerized space-averaging (or smoothing) techniques were adapted from those used by the National Meteorological Center (NMC) of NWS for the objective analysis of a variety of weather maps, and from some experimental work in analyzing storm isohyets. The NMC methods described by Cressman (1959) are designed to eliminate erroneous values and to compute a smoothed data field closely fitting widely spaced observed data. Isohyetal analysis, using techniques similar to those described by Barnes (1963) and Greene (1971), is designed to produce a smoothed data field still retaining detailed features of individual storm cells. The problem of precipitation-frequency analysis in an area free of marked orographic influences is somewhat different from both these problems. The climatological precipitation-frequency field sought is smoother than individual storm isohyets and, compared with the NMC problem, is based on a greater density of data points. Both differences suggest stronger areal averaging.

The smoothing program employed the following steps to estimate precipitation-frequency values at grid points spaced at each half degree of latitude and longitude:

1. Precipitation-frequency values from all stations within a given latitude-longitude rectangle surrounding each grid point were averaged, weighted by a function of distance from the grid point, giving the first estimate of the grid point value, $GP_{N=1}$:

$$GP_{N=1} = \sum_{j=1}^{k} PF_j W_j \Big/ \sum_{j=1}^{k} W_j \tag{2}$$

where k is the number of stations within the chosen latitude-longitude rectangle, PF_j a station precipitation frequency value, and W_j a weight for that station derived from a distance weighting function.

2. The first estimates at the four grid points surrounding each station are in turn used in double linear interpolation to estimate a new value at each station, PF_{ADJ}:

$$PF_{ADJ} = \left[GP_{NW}(1 - DI) + GP_{NE}\ DI\right] (1 - DJ) + \left[GP_{SW}(1 - DI) + GP_{SE}\ DI\right] DJ \tag{3}$$

GP_{NW}, GP_{NE}, GP_{SW}, and GP_{SE} are the closest grid points northwest, northeast, southwest, and southeast of a station and DI and DJ delineate station location in fractional latitude and longitude grid intervals.

The difference is computed between the original station value and this interpolated value:

$$\Delta PF = PF - PF_{ADJ} \tag{4}$$

3. Each grid point first estimate from step 1 is adjusted by the average of the differences from step 2, weighted by the distance function, for all stations within a given distance (called the scan radius) of the grid point:

$$GP_N = GP_{N-1} + \sum_{j=1}^{k} \Delta PF_j\ W_j \Big/ \sum_{j=1}^{k} W_j \tag{5}$$

GP_N is the Nth grid point iteration and ΔPF_j and W_j are precipitation frequency difference from (4) and distance weighting factors for k number of stations within a given scan radius.

Steps 2 and 3 are repeated to progressively adjust the grid point estimates.

The degree of smoothing of a data field by this technique is a decision of the analyst exercised through the choice of constants and weighting functions and based on a combination of professional judgment and any independent statistical evidence, and is not inherent in the objective smoothing technique. The role of the objective technique is to carry out the subjectively determined degree of smoothing in a uniform, systematic and economical manner. The scan radius, number of iterations, and form of weighting function determine the degree of smoothing.

Using a test area in the midwest, the smoothing program was run on 60-min 2-yr data with various scan radii, number of repeats of steps 2 and 3, and linear and exponential weighting functions. In all cases the first grid point estimate (step 1) was the weighted average of the station values in a 2° latitude X 2° longitude box centered on the grid point. A 2° latitude and longitude scan radius (defining an ellipse with longest axis north-south) 3 iterations, and a linear weighting function ranging from a weight of 1.0 at zero distance to zero at the scan radius, produced the degree of smoothing illustrated in figure 3. This is judged appropriate to the 60-min data and the factors indicated were adopted. Additional iterations after the third in the test runs produced little additional change in the variance of differences between original station values and interpolated values.

Table 2 illustrates the frequency distribution of the number of stations which were used for estimation of the individual grid point values in step 3. The grid points with the fewest influencing stations are, naturally, located along the border of the study area and in such protrusions as the Florida peninsula, Maine and West Texas. Grid point values in such areas tend to be overly influenced by values inward of the grid field with no opportunity for influence from a gradient outside the grid field. In drawing lines in such areas, the analyst kept this in mind and made adjustments to compensate for it.

Table 2.--Frequency of number of station values used to estimate grid point values for 60 minutes.

No. stations	No. grid point	No. stations	No. grid point
0-9	38	100-109	189
10-19	132	110-119	136
20-29	218	120-129	93
30-39	283	130-139	43
40-49	334	140-149	57
50-59	220	150-159	43
60-69	131	160-169	30
70-79	161	170-179	23
80-89	187	180-189	5
90-99	196		

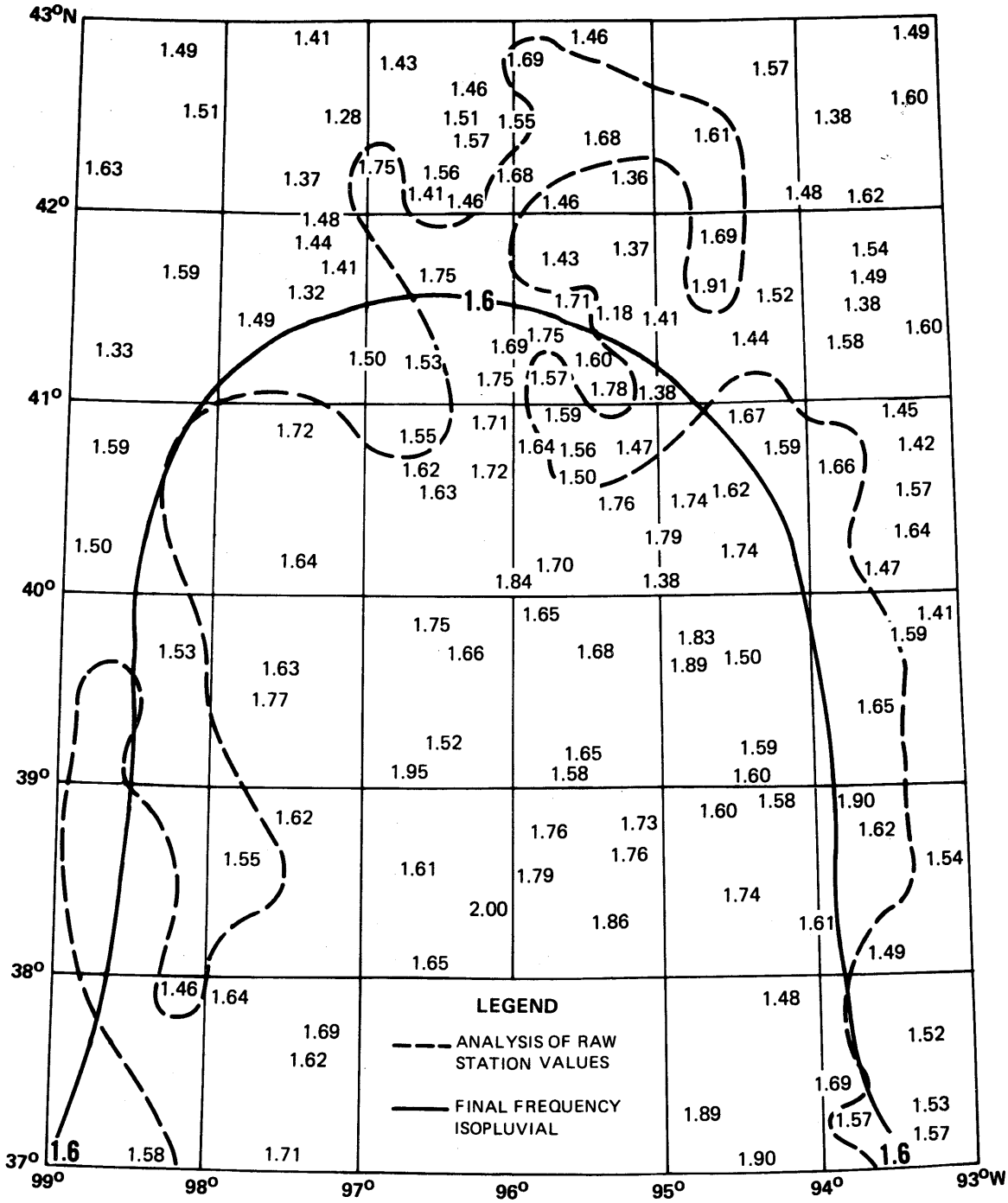

Figure 3.--Example of space-averaging of 2-yr 60-min precipitation values.

Because data for the 5- and 15-min durations are one tenth as dense as data for 60 minutes, the first estimate for these durations was made using all stations within 2° of latitude or longitude of the grid point and the adjustments using 4° scan radius. The first estimates plus three iterations was continued. In practice, this means that despite using a scan area four times as large as that used with 60-min data the number of stations bearing on a given data point is only about 40 percent of the number shown in table 2. This is not, however, a serious problem since areal variability decreases as duration decreases: i.e., the data field for the 5-min duration shows less variation than does the 60-min data field. To illustrate this point, four data sets consisting of all 2- and 100-yr 5-min values and 2- and 100-yr 60-min values in the area bounded by the Gulf Coast on the south, 45°N on the north, and 85°W and 95°W on the east and west sides were analyzed. At the 5-min duration the coefficient of variation of the 2-yr data set was 0.126 and at the 100-yr return period it was 0.121. The corresponding coefficients of variation for 60 minutes were 0.245 and 0.207.

MAP CONSTRUCTION

2-Yr 60-Min (Fig. 4)

The individual station frequency values, calculated as previously described, were plotted on a map. Most of these are derived from maximum annual clock-hour values adjusted to 60 minutes by the 1.13 factor. Also plotted on the half-degree latitude-longitude grid system were the values obtained from the computer smoothing program. The final precipitation-frequency isopluvials were derived by small additional manual smoothing of the grid point values in areas with little or no orographic influence, with constant concurrent reference to the unsmoothed station data. In the vicinity of the Appalachian Mountains, there are believed to be substantial orographic influences on precipitation frequency at a scale finer than the station density available for this study. In NOAA Atlas 2 (Miller et al. 1973), this characteristic was recognized in the 11 Western States by developing statistical relations between precipitation-frequency and topographic parameters. The latter can be defined by elevations read from topographic maps in whatever detail is relevant. However, NOAA Atlas 2 was developed for longer durations (6 and 24 hours) than the present study and for 24 hours was able to use the more numerous data available from the NWS network of nonrecording rain gages to estimate isopluvial variations. The development of similar statistical relations for the Appalachians was beyond the scope of the present study. The precipitation-frequency isopluvials in the mountainous regions in the Eastern United States were shaped subjectively to the topography depicted on 1:1,000,000 scale World Aeronautical Charts with some guidance from valley vs. higher elevation data at a few places.

Isopluvial variations due to topographic influences are probably present in the Black Hills region and in the vicinity of the Ozark Mountains. The station precipitation-frequency data were closely scrutinized for such influences in these areas but no consistent, explainable variations could be detected and no nearby valley vs. mountain contrasts were found in the available station data. Thus, the final isopluvials in the Black Hills and Ozark Mountains are based on station data without regard to topography.

In addition, the isopluvials were tied into values calculated from or implied by the precipitation-frequency maps for Montana, Wyoming, Colorado, and New Mexico in NOAA Atlas 2 and the frequency values at nearby Canadian stations.

100-Yr 60-Min (Fig. 5)

No matter what distribution or fitting method is used in extreme value analysis, the sampling error at the 100-yr return period is greater than at the 2-yr return period. The general form of the equation for any return period is $Y_t = \overline{X} + KS$, where Y_t is the value for the return period, $\overline{X}$ is the annual series sample mean, and S its standard deviation. K is a factor that differs with distribution assumed and the fitting method used, but K values have a common trait no matter what the distribution or fitting method--they increase with increasing return period.

For example, using Gumbel's method on a data sample of 25 items, at the 2-yr return period, K = -0.1506; while at the 100-yr level, K = 3.7283--in absolute value the 100-yr K is about 25 times the 2-yr K. The noise component brought about by the difference between S and the population standard deviation, σ, is much greater at the 100-yr return period than at the shortest return periods.

Over the years, it has been found that the ratio of 100-yr to 2-yr precipitation-frequency values is conservative over large contiguous areas and varies less than the 100-yr values themselves. For example, the ratio of the 100- to 2-yr 60-min values gradually increases northward.

The construction of the 100-yr 60-min map used the following aids: 1) station data and smoothed grid point data developed from the station data by computer smoothing as previously described; 2) station 100-yr/2-yr ratios and smoothed grid point values of that ratio; and 3) the isopluvial pattern of the 2-yr 60-min map.

5-Min Maps (Figs. 6 and 7)

It was hypothesized that the maximum annual 5-min values at adjacent stations are mostly from different storms and may be treated as statistically independent. This hypothesis was examined by comparing data from all stations in a 240-mi (385-km) square centered on Iowa. The period of record was 1907-72, but not all stations had data for all years. There was a total of 264 station years at seven stations. About 11 percent of the 5-min annual maxima occurred on the same date as an annual maximum at another of the seven stations. However, only about a quarter of these equaled or exceeded the 2-yr return period value. Essential independence of the more significant maximum annual 5-min rainfalls was considered established.

In view of the above, new data series were constructed, consisting of all maximum annual 5-min events at all the stations within overlapping 4° latitude-longitude boxes. This new series was analyzed by the Gumbel fitting of the Fisher-Tippett Type I distribution, as previously discussed. The resulting 0.5 and 0.01 probability events (equivalent to 2-yr and 100-yr

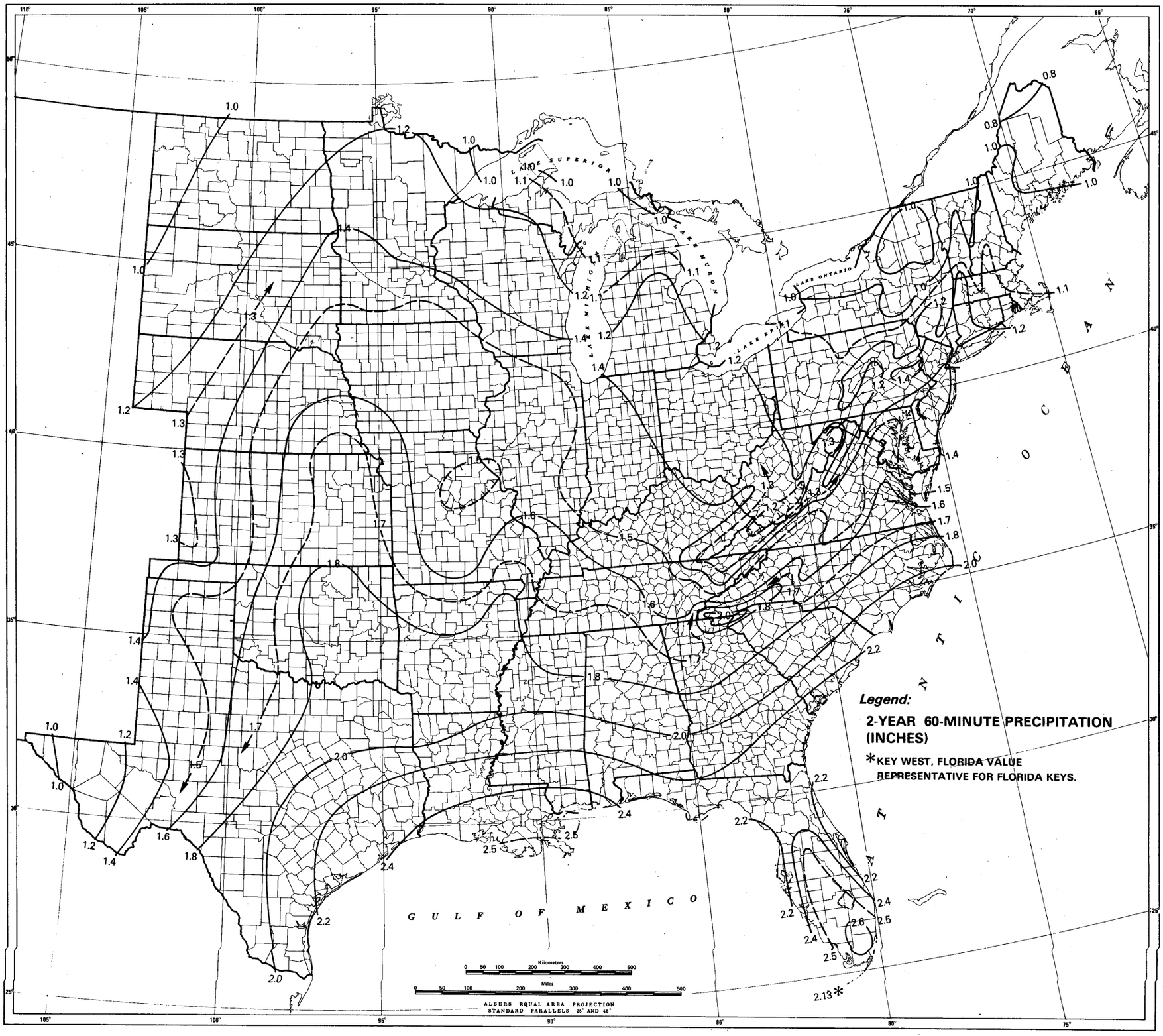

Figure 4.--2-year 60-min precipitation (inches)--adjusted to partial duration series.

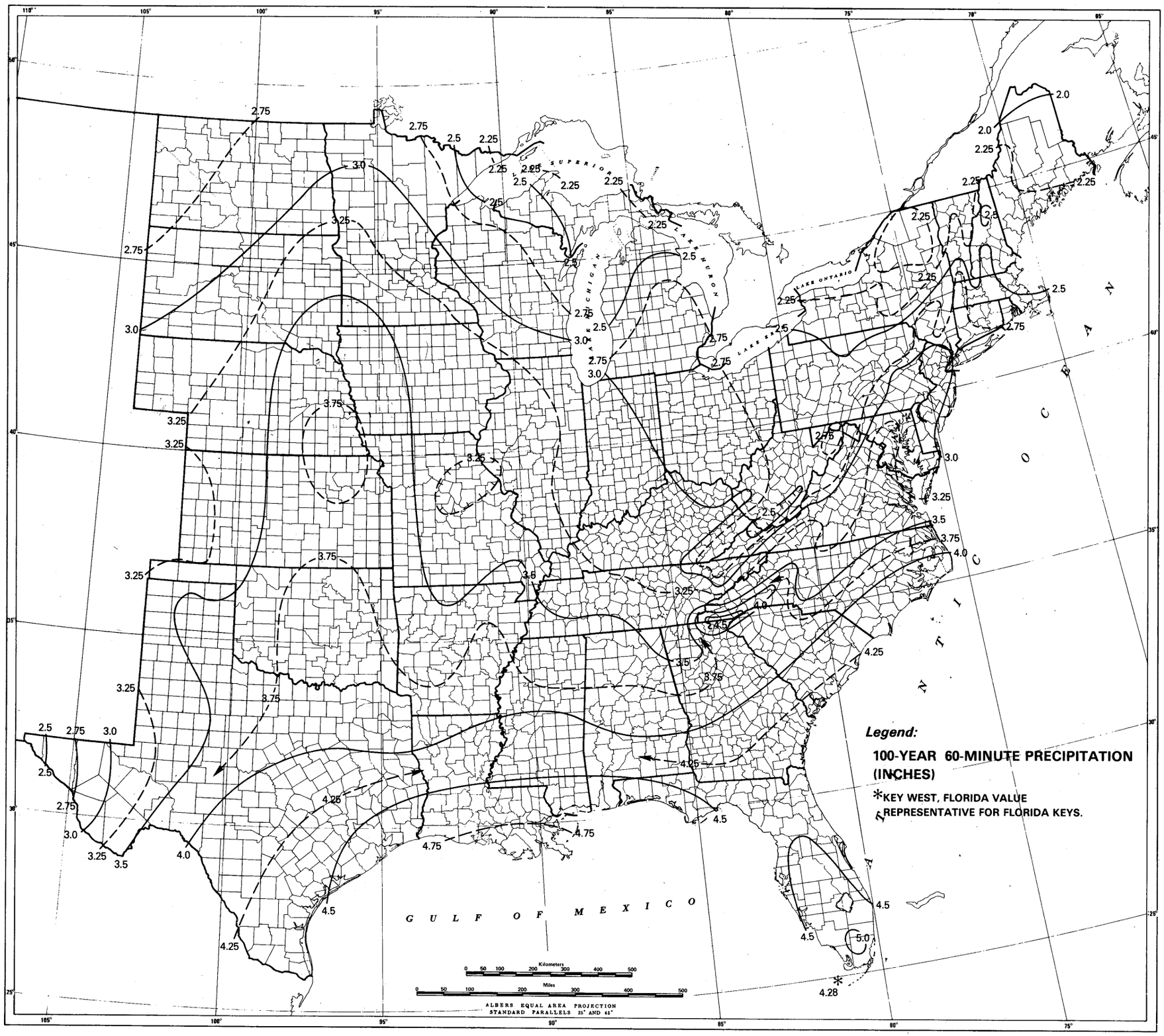

Figure 5.--100-year 60-minute precipitation (inches)--adjusted to partial duration series.

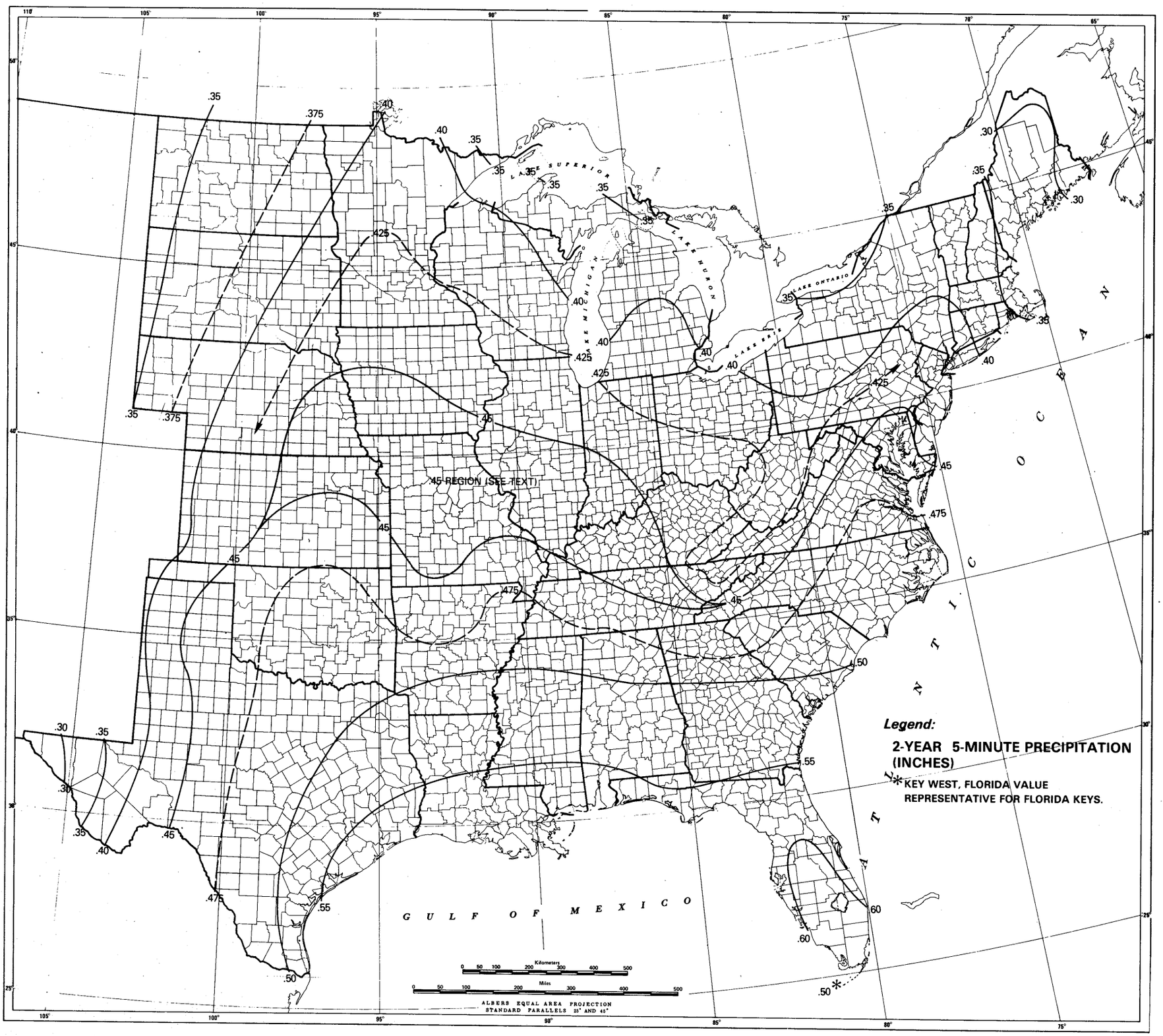

Figure 6.--2-year 5-minute precipitation (inches)--adjusted to partial-duration series.

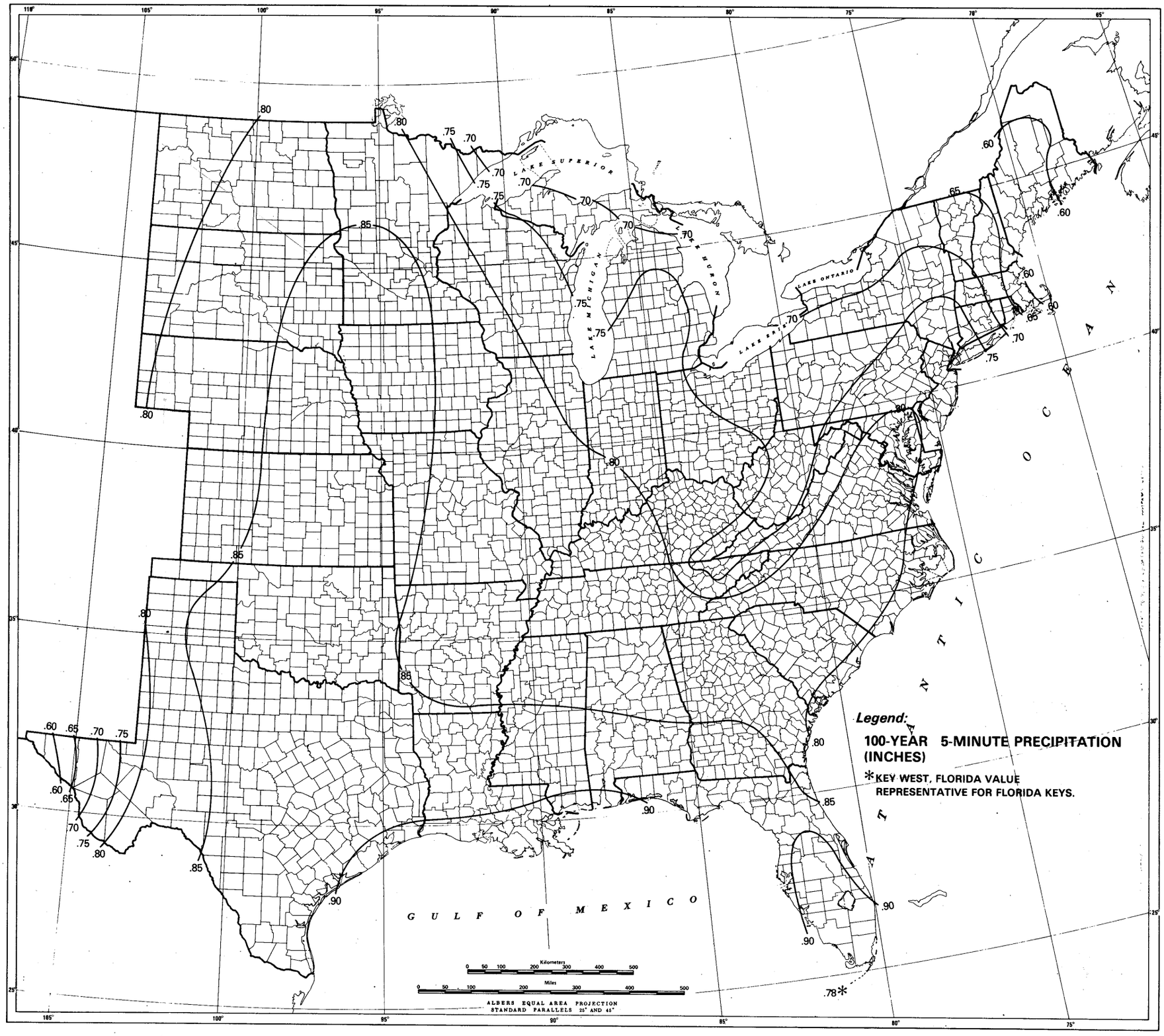

Figure 7.--100-year 5-minute precipitation (inches)--adjusted to partial-duration series.

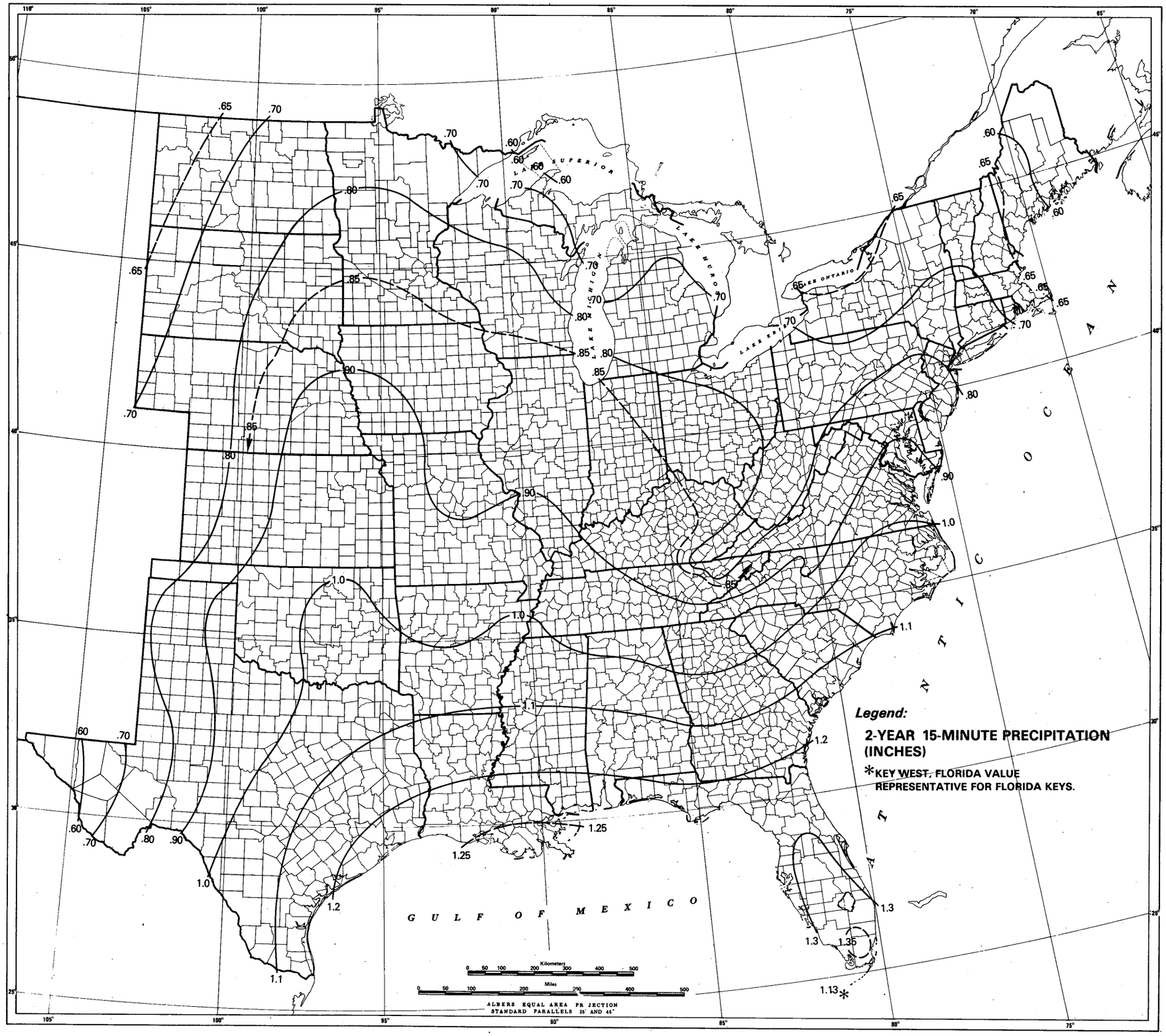

Figure 8.--2-year 15-min precipiatatation (inches)--adjusted to partial-duration series.

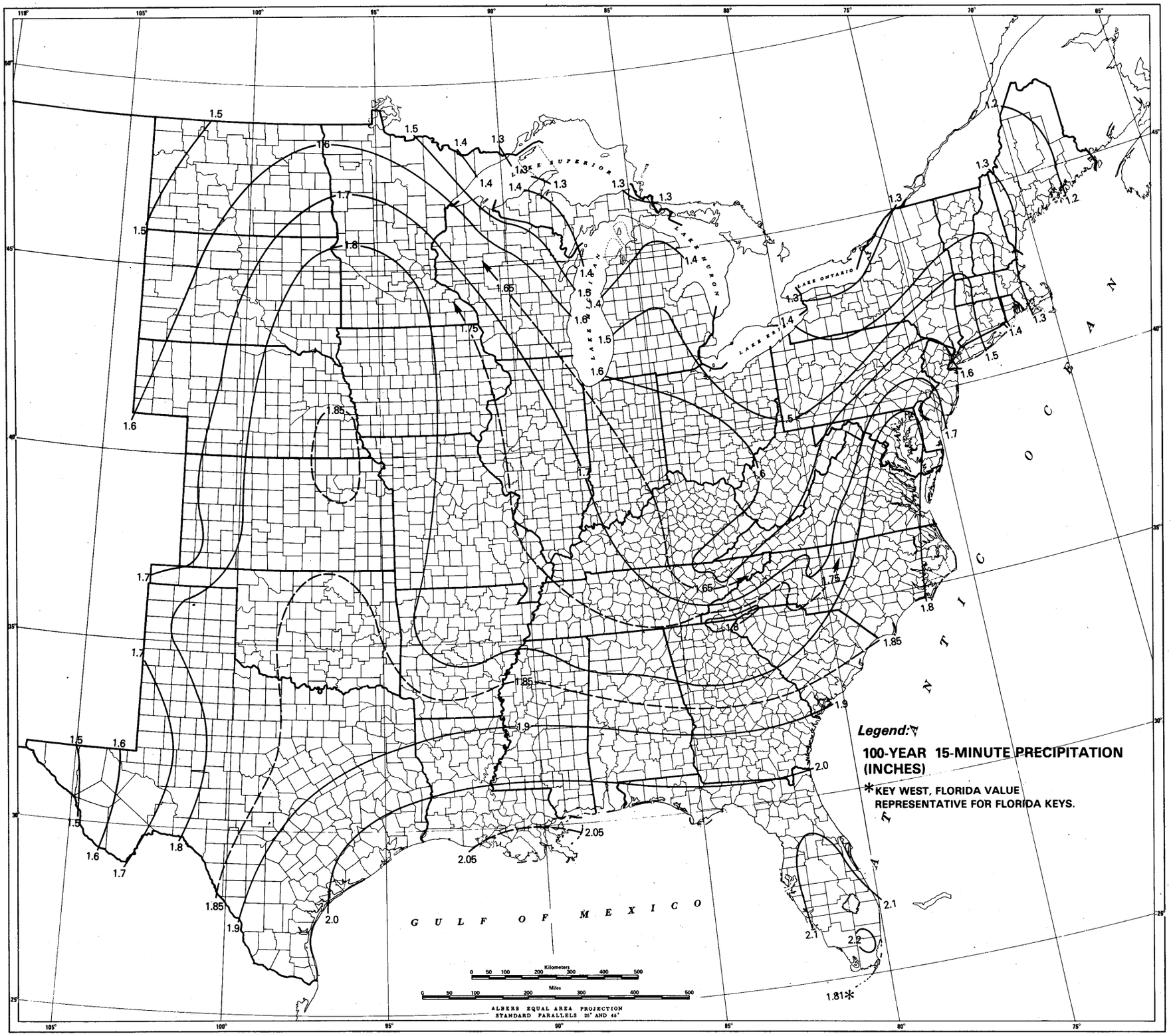

Figure 9.--100-year 15-minute precipitation (inches)--adjusted to partial-duration series.

return period) for each box were plotted at positions within the box determined by weighting the latitude and longitude of each contributing station by its length of record. In some regions of sparse data, only one station was available within a 4° box, but more generally the station years per box exceeded 100. The computer smoothing program was also run on the station 5-min values within the scan radius increased to 4°. Station ratios of 5- to 60-min values were similarly smoothed.

In summary, data used in construction of the 5-min maps included: 1) frequency values computed from all station data within each 4° latitude-longitude box and centered according to station location and length of record, 2) the computed frequency values and 5-min to 60-min ratio for the individual stations, 3) computer smoothed grid values for both frequency values and ratios, and 4) the isopluvial pattern developed for the 2-yr 60-min map.

The character of the 2-yr 5-min data (fig. 6) (and the climate) required an unorthodox analysis in the central part of the country, the shaded area labeled 0.45 region. All points within the area are to be considered to have a 2-yr 5-min frequency value of 0.45 in. (11.4 mm), with values gradually increasing southward and decreasing northward beyond this region. Considerable time and effort were spent attempting to define a precise location for the 0.45-in. isopluvial. The station data and the several forms of grid point data indicated that within this area values were equal to or within a few hundredths of an inch of 0.45, with no definable gradient. Since the placement of the line is a subjective judgment, the decision was made to treat the area as one broad line with all values equal to the value of the isoline.

15-Min Maps (Figs. 8 and 9)

As previously mentioned in the section "Methodology, Isopluvial Maps," the relationship between the 5-, 15- and 60-min precipitation frequencies was found to vary both geographically and by return period. Therefore, as an aid in the drawing of 15-min maps, the computer smoothing program was run on station values of the coefficient C_{15}:

$$R_{15} = C_{15} R_{60} + (1 - C_{15}) R_5 \qquad (6)$$

separately for the 2- and 100-yr return periods to obtain grid point values. Successive iterations of computer smoothing followed by manual adjustment were made to obtain consistent smooth fields of both C_{15} and R_{15}, holding R_{60} and R_5 fixed.

MAINTENANCE OF INTERNAL CONSISTENCY

Once preliminary 5-, 15- and 60-min isopluvial frequency maps for the 2- and 100-yr durations were completed, values were read from the analyzed maps at 0.5° latitude-longitude grid points. These values were used to produce maps showing ratios at the grid points between the various durations and return periods. The ratio fields were then scanned for consistency and correspondence to ratios from the station data. The preliminary isopluvial maps were adjusted to remove any inconsistencies in the ratio fields. Next,

differences between adjacent grid points on the six maps were compared to discover any places where one map or set of maps showed increasing values where other maps or sets of maps were indicating decreasing values. This does not imply that values on all maps must move parallel to each other, but that nonparallel movement be examined to insure that the trends are intended by the analyst. A case of validated nonparallelism is illustrated in the Northern Plains States, where the ridge in the isopluvials shifts westward with increasing return period.

Intermediate Durations and Return Periods

10- and 30-Min Relations

The procedure discussed under "Methodology" was used to derive equations to estimate the 10-min values from 5- and 15-min, and 30-min values from 15- and 60-min values. The station data were first grouped geographically, and separate equations derived for each area and for the 2- and 100-yr return period. Neither geographical nor return period differences were significant, and one equation for the 10-min estimation and one equation for 30-min estimation were adopted. They are:

$$\text{10-min value} = 0.59\ (\text{15-min value}) + 0.41\ (\text{5-min value}) \tag{7}$$

$$\text{30-min value} = 0.49\ (\text{60-min value}) + 0.51\ (\text{15-min value}) \tag{8}$$

The graphical solution to these equations is shown in figure 10. The ordinate scale is linear. It is left unlabeled so that the user can label as appropriate for the range of data being used.

Intermediate Return Periods

A mathematical solution of the Gumbel equations for the partial duration series results in the following equations to compute values for selected return periods intermediate to the 2- and 100-yr values.

$$\text{5-yr} = 0.278\ (\text{100-yr}) + 0.674\ (\text{2-yr}) \tag{9}$$

$$\text{10-yr} = 0.449\ (\text{100-yr}) + 0.496\ (\text{2-yr}) \tag{10}$$

$$\text{25-yr} = 0.669\ (\text{100-yr}) + 0.293\ (\text{2-yr}) \tag{11}$$

$$\text{50-yr} = 0.835\ (\text{100-yr}) + 0.146\ (\text{2-yr}) \tag{12}$$

INTERPRETATION OF RESULTS

Physiographic and Meteorological Effects

The center of low precipitation frequencies depicted in Northern Missouri is validated by the fact that this is also a center of low frequency of tornadoes (Fujita 1976) compared to the surrounding regions. High-intensity, short-duration rainfalls and tornadoes are both associated with convective storms. We do not know whether this anomaly is a shadow effect of the

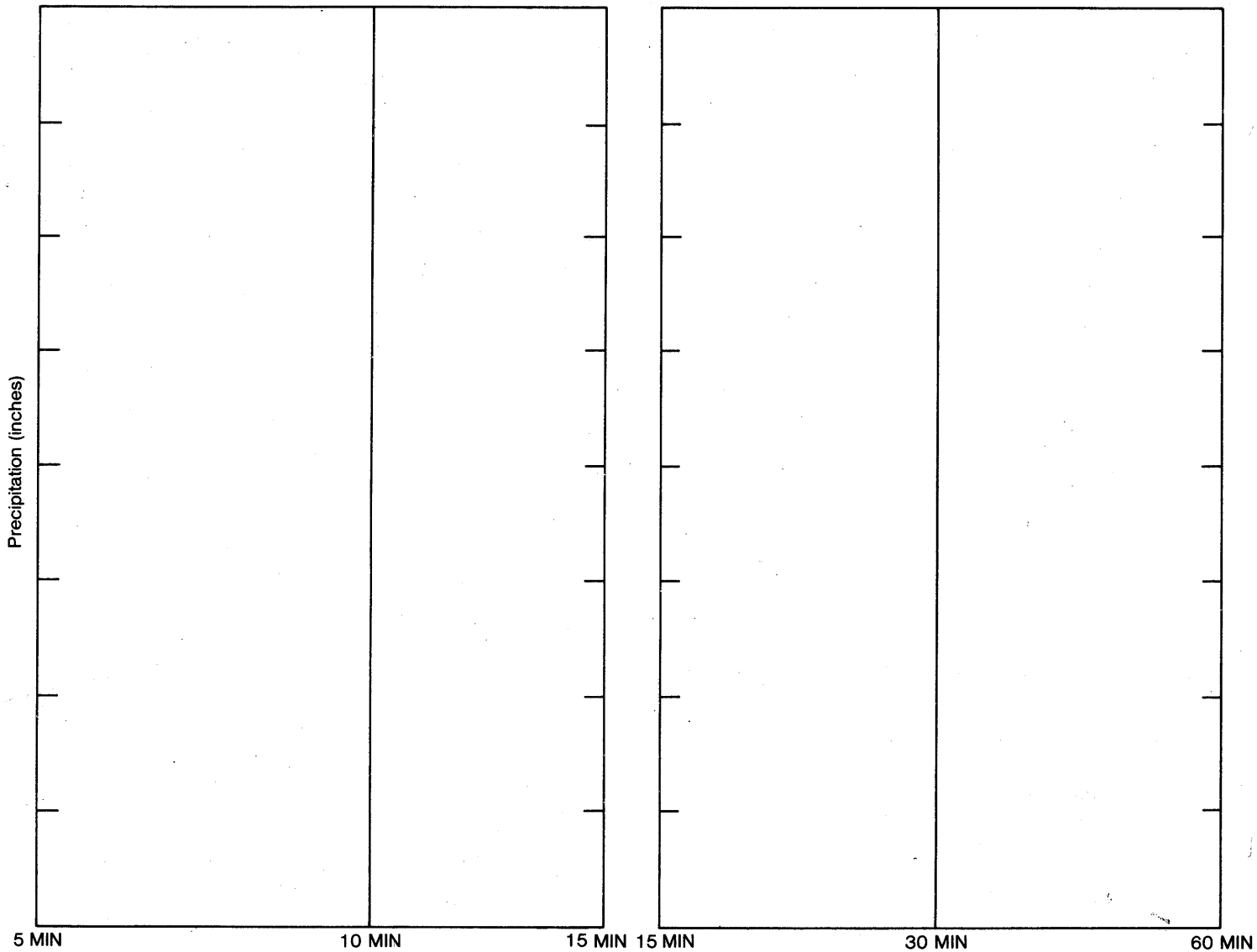

Figure 10.--Duration-interpolation diagram for 10- and 30-min estimates.

Ozark Mountains impeding the low-level moist inflow from the Gulf of Mexico or is due to some other cause.

The isopluvial discontinuities appearing across the Great Lakes occur because warm land surfaces to the windward enhance the development of summer thunderstorms, while the cool lake water surfaces tend to inhibit this type of weather. The data confirm this and suggest higher values on the upwind (west and south) shores of the Great Lakes than on the downwind (east and north) shores. A similar effect is noticeable in Florida, with the lowest values near the coast, especially the east coast in the summer easterlies, with higher values inland. Coastal effects are also noted along the middle Atlantic coast, being most prominent on the 5-min and 15-min 100-yr maps. The tongue of high values aligned north-south in the Western Plains coincides with the well-known nocturnal maximum of thunderstorms in the region, and with the frequent development of a band of strong winds from the south, called the low-level jet (Pitchford and London 1962). The trough of lower values paralleling, and northwest of, the Appalachians suggests that shielding by that mountain chain in a south to southwest flow has more impact on frequencies than does orographic simulation that might be expected with a west-southwest to west flow.

Comparison With Previous Studies

In both this study and TP-40, the 60-min map is the anchor map upon which precipitation-frequency values for shorter durations are based. Comparing the 60-min maps in the two reports at the 2-yr return period shows good correspondence with no overall trend to higher or lower values or pronounced regional differences.

The major difference is the greater detail with which the later map has been constructed, especially in the Appalachians. The largest increase in values, somewhat in excess of 20 percent, is at the triple point intersection of the borders of North Carolina, South Carolina, and Georgia, on the south-east flank of the Appalachians. An increase of less than 20 percent in northern Minnesota results from more northward penetration of the midwestern tongue of high values on the later analysis. Decreases of about 15 percent occur at points on the western shore of Chesapeake Bay, resulting from cutting back a tongue of high values east of the Appalachians. Most other changes are less than 10 percent and tend to average out over a given region. On the Florida peninsula, the general level of values is unchanged, but the later analysis gives more recognition to the stimulation of intense thunderstorms by solar heating of land (supported by the data) and places higher values in the interior of the peninsula than over the adjacent sea. For similar reasons, the north-south gradient is reduced in southern Louisiana.

Differences in the 60-min 100-yr maps are similar, with larger percentagewise changes in the Appalachians. This is expected, since more variation of both the mean of the annual series and its standard deviation have been introduced.

The largest differences between the new study and TP-40 exist at the 5-min duration. The present study shows values in Maine and parts of the northern plains 30 to 40 percent greater than values derived by use of the duration table in TP-40. Along the Gulf coast, on the other hand, the new values are about 20 percent less than those derived from TP-40 at the 2-yr return period and 30 percent less at the 100-yr return period. Values are also lowered along the Atlantic coast.

Yarnell (1935) published pioneering rainfall frequency maps for the United States based on data through 1933. He had available essentially the same network of first-order NWS stations available to this study for N minutes (fig. 1) but 40 years less record. The overall patterns and levels of values on Yarnell's charts and the maps of the present report are similar and are a testimony to the stability of the climate with respect to short-duration rainfalls. It has been possible to attain a finer scale of subregion detail in the later work, as well as provide the more detailed analysis in the Appalachians, which has been referred to. Values have been raised substantially in the Northeast in the present study compared to Yarnell. Identifying the reason for this would require repetition of Yarnell's analysis. Coastal patterns have been modified and the north-south axis of high values in the Plains States, prominent in all studies, is depicted farther to the west in the new study.

ILLUSTRATION OF THE USE OF PRECIPITATION-FREQUENCY MAPS, DIAGRAMS, AND EQUATIONS

1. Two-yr and 100-yr values for the duration of 5, 15, and 60 min are read from the six maps (figs. 4-9). Example: for the point at 37°N and 93°W, these values read by interpolation are entered in table 3.

2. Intermediate return period values are calculated using equations 9-12. The calculation for the 25-yr 15-min value (using eq. 11) is:

$$\text{25-yr 15-min} = 0.669\ (1.79) + 0.293\ (0.94) = 1.47$$

3. Values for intermediate durations are calculated using equation 7 or 8 or by plotting as in figure 11. The 100-yr 10-min value (using eq. 7) is:

$$\text{100-yr 10-min} = 0.59\ (1.79) + 0.41\ (0.85) = 1.40$$

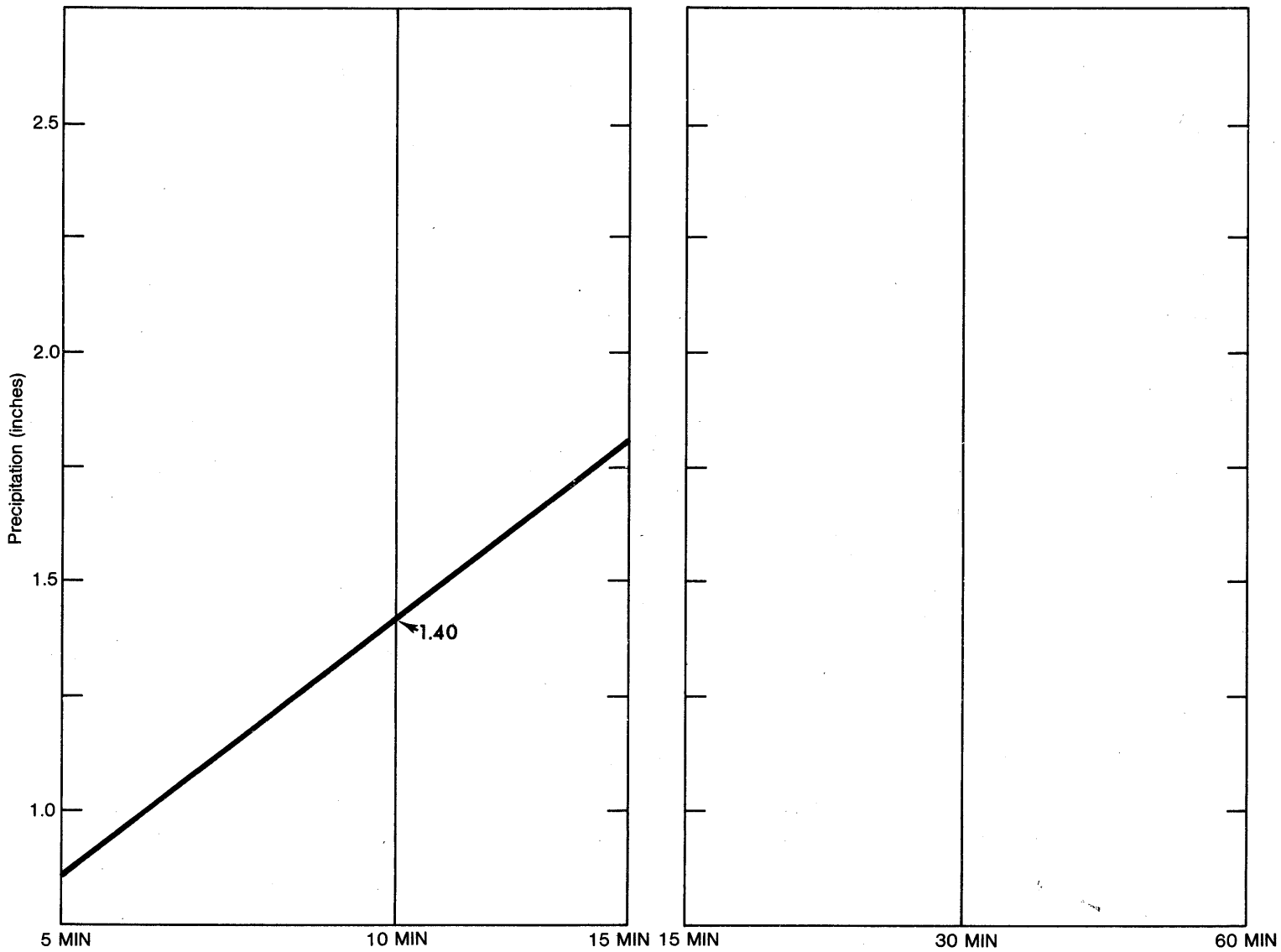

Figure 11.--Illustrative example using figure 10.

Table 3.--Precipitation frequency values (in.) for 93°00'W, 37°00'N)

	5-min	10-min	15-min	30-min	60-min
2-yr	0.45		0.94		1.59
5-yr					
10-yr					
25-yr			1.47		
50-yr					
100-yr	0.85	1.40	1.79		3.43

Note: Circled values are computed from the other values.

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