HYDROMETEOROLOGICAL REPORT NO. 47

Meteorological Criteria For Extreme Floods For Four Basins in the Tennessee and Cumberland River Watersheds

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
TENNESSEE VALLEY AUTHORITY

Silver Spring, Md.
May 1973

HYDROMETEOROLOGICAL REPORTS

*No. 1. Maximum possible precipitation over the Ompompanoosuc Basin above Union Village, Vt. 1943.
*No. 2. Maximum possible precipitation over the Ohio River Basin above Pittsburgh, Pa. 1942.
*No. 3. Maximum possible precipitation over the Sacramento Basin of California. 1943.
*No. 4. Maximum possible precipitation over the Panama Canal Basin. 1943.
*No. 5. Thunderstorm rainfall. 1947.
*No. 6. A preliminary report on the probable occurrence of excessive precipitation over Fort Supply Basin, Okla. 1938.
*No. 7. Worst probable meteorological condition on Mill Creek, Butler and Hamilton Counties, Ohio. 1937. (Unpublished.) Supplement, 1938.
*No. 8. A hydrometeorological analysis of possible maximum precipitation over St. Francis River Basin above Wappapello, Mo. 1938.
*No. 9. A report on the possible occurrence of maximum precipitation over White River Basin above Mud Mountain Dam site, Wash. 1939.
*No. 10. Maximum possible rainfall over the Arkansas River Basin above Caddoa, Colo. 1939. Supplement, 1939.
*No. 11. A preliminary report on the maximum possible precipitation over the Dorena, Cottage Grove, and Fern Ridge Basins in the Willamette Basin, Oreg. 1939.
*No. 12. Maximum possible precipitation over the Red River Basin above Denison, Tex. 1939.
*No. 13. A report on the maximum possible precipitation over Cherry Creek Basin in Colorado. 1940.
*No. 14. The frequency of flood-producing rainfall over the Pajaro River Basin in California. 1940.
*No. 15. A report on depth-frequency relations of thunderstorm rainfall on the Sevier Basin, Utah. 1941.
*No. 16. A preliminary report on the maximum possible precipitation over the Potomac and Rappahannock River Basins. 1943.
*No. 17. Maximum possible precipitation over the Pecos Basin of New Mexico. 1944. (Unpublished.)
*No. 18. Tentative estimates of maximum possible flood-producing meteorological conditions in the Columbia River Basin. 1945.
*No. 19. Preliminary report on depth-duration-frequency characteristics of precipitation over the Muskingum Basin for 1- to 9-week periods. 1945.
*No. 20. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin above Garrison Dam site. 1945.
*No. 21. A hydrometeorological study of the Los Angeles area. 1939.
*No. 21A. Preliminary report on maximum possible precipitation, Los Angeles area, California. 1944.
*No. 21B. Revised report on maximum possible precipitation, Los Angeles area, California. 1945.
*No. 22. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin between Garrison and Fort Randall. 1946.
*No. 23. Generalized estimates of maximum possible precipitation over the United States east of the 105th meridian, for areas of 10,200, and 500 square miles. 1947.
*No. 24. Maximum possible precipitation over the San Joaquin Basin, Calif. 1947.
*No. 25. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 1947.
*No. 25A. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 2d edition. 1949.
*No. 26. Analysis of winds over Lake Okeeehobee during tropical storm of August 26–27, 1949. 1951.
*No. 27. Estimate of maximum possible precipitation, Rio Grande Basin, Fort Quitman to Zapata. 1951.
*No. 28. Generalized estimate of maximum possible precipitation over New England and New York. 1952.
*No. 29. Seasonal variation of the standard project storm for areas of 200 and 1,000 square miles east of 105th meridian. 1953.
*No. 30. Meteorology of floods at St. Louis. 1953. (Unpublished.)
*No. 31. Analysis and synthesis of hurricane wind patterns over Lake Okeechobee, Florida. 1954.
*No. 32. Characteristics of United States hurricanes pertinent to levee design for Lake Okeechobee, Florida. 1954.
No. 33. Seasonal variation of the probable maximum precipitation east of the 105th meridian for areas from 10 to 1,000 square miles and durations of 6, 12, 24, and 48 hours. 1956.
No. 34. Meteorology of flood-producing storms in the Mississippi River Basin. 1956.
No. 35. Meteorology of hypothetical flood sequences in the Mississippi River Basin. 1959.
*No. 36. Interim report—probable maximum precipitation in California. 1961. Also available is a supplement, dated October 1969.
No. 37. Meteorology of hydrologically critical storms in California. 1962.
No. 38. Meteorology of flood-producing storms in the Ohio River Basin. 1961.
No. 39. Probable maximum precipitation in the Hawaiian Islands. 1963.
No. 40. Probable maximum precipitation, Susquehanna River drainage above Harrisburg, Pa. 1965.
No. 41. Probable maximum and TVA precipitation over the Tennessee River Basin above Chattanooga. 1965.
No. 42. Meteorological conditions for the probable maximum flood on the Yukon River above Rampart, Alaska. 1966.
No. 43. Probable maximum precipitation, Northwest States. 1966.
No. 44. Probable maximum precipitation over South Platte River, Colorado, and Minnesota River, Minnesota. 1969.
No. 45. Probable maximum and TVA precipitation for Tennessee River Basins up to 3,000 square miles in area and durations to 72 hours. 1969.
No. 46. Probable maximum precipitation, Mekong River Basin. 1970.

---

* Out of print.

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

TENNESSEE VALLEY AUTHORITY

HYDROMETEOROLOGICAL REPORT NO. 47

Meteorological Criteria For Extreme Floods For Four Basins in the Tennessee and Cumberland River Watersheds

Prepared by
Francis K. Schwarz
Hydrometeorological Branch
Office of Hydrology
for the
TENNESSEE VALLEY AUTHORITY
(Contract TV-36522A)

Silver Spring, Md.
May 1973

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402.
Price $0.90 domestic postpaid or $0.65 G.P.O. Bookstore.

UDC 556.166:551.577.37(768)

551.5	Meteorology
.577	Precipitation
.37	Excessive rainfall in short or long periods
556	Hydrology
.166	Maximum floods
(768)	Tennessee

TABLE OF CONTENTS

TABLES

FIGURES

METEOROLOGICAL CRITERIA FOR EXTREME FLOODS FOR FOUR BASINS IN THE TENNESSEE AND CUMBERLAND RIVER WATERSHEDS

Chapter I

INTRODUCTION

Purpose of Present Estimates

This report summarizes studies to provide rainfall criteria which, when coupled with rain criteria contained in Hydrometeorological Report No. 41 (U. S. Weather Bureau 1965), permit definition of maximum flood levels along the Tennessee River from the mouth upstream to TVA's Browns Ferry Nuclear Plant at mile 294. These studies were made in two parts. In 1968 maximum rainfall depths were defined for the 16,170-sq-mi drainage area above the Browns Ferry plant and below TVA's major tributary dams. In 1970 the study was extended to include the 26,780-sq-mi drainage area above Kentucky Dam and below TVA's major tributary dams. This latter study included definition of concurrent rainfall expected on the Cumberland Basin as required to evaluate the effects of the canal which connects the two rivers just upstream of Kentucky Dam.

This report also summarizes studies made in 1971 to provide rainfall criteria for defining maximum flood levels along the Cumberland River above Old Hickory Dam. This required defining rainfall for both the 11,674-sq-mi drainage area above the dam and the 2,734-sq-mi watershed between Old Hickory and the next major upstream dams, Center Hill, Dale Hollow, and Wolf Creek.

Locations of the four basins are shown in figure 1-1. These studies extended over a 3-yr period, consequently developments and changing techniques resulted in a somewhat different analysis of each basin.

Background

Previous requests to the Hydrometeorological Branch by the Tennessee Valley Authority (TVA) for precipitation estimates for hydrologic design within the Tennessee Watershed have been summarized in Hydrometeorological Reports No. 41 (U. S. Weather Bureau 1965) and 45 (U. S. Weather Bureau 1969). Frequent references will be made to these studies in this report, and they will be referred to hereafter as HMR 41 and HMR 45.

In HMR 41, the problem of high flows on the Tennessee River at Chattanooga, Tenn., was of concern. That report presents estimates of design precipitation values for the total drainage of 21,400 sq mi above Chattanooga and for the 7,980-sq mi subbasin drainage immediately above Chattanooga and below TVA's major tributary dams. The spring (i.e., March) storm was established as the most likely to produce probable maximum precipitation (PMP) for the basin sizes concerned in HMR 41. The most likely summer threat was shown to result from a tropical storm. In HMR 41, a relation between rainfall amounts from tropical storms and distance from the coast was developed. This relation indicated that for large drainages, tropical storm precipitation in the Tennessee River Watershed was below that to be expected of a spring storm type. These same conclusions on controlling storm types apply to the precipitation estimates for the three larger basins of this report. For the 2,874-sq-mi drainage area between Old Hickory and Center Hill, Dale Hollow and Wolf Creek Dams, the warm season rainfall criteria were needed. All the basins for which estimates are given in this report adjoin or overlap one of the basins for which estimates were reported in HMR 41. The area covered by HMR 41 is shown in figure 1-2.

In HMR 41, the concept of a "TVA" level of precipitation criteria, less extreme than a PMP level, was defined, and separate estimates for each level were developed. The TVA values are defined as those resulting from transposition of outstanding storms that have occurred elsewhere. Adjustments are made only for regional differences in moisture. Some of the most extreme events are undercut.

One important innovation in HMR 41 consists of the development of antecedent and subsequent rainfall that can logically be combined with 3-day PMP and TVA precipitation. Previously, it had been customary for the user to pick a reasonably "wet" antecedent condition to combine with the PMP or TVA precipitation.

In HMR 45, generalized precipitation criteria were developed for drainages up to 3,000 sq mi for durations up to 24 hrs. The region covered is shown in figure 1-2. That report also contains precipitation estimates that were previously prepared for numerous specific basins. These basins range in size from 189 sq mi to 2,912 sq mi. As with HMR 41, HMR 45 presents estimates of both probable maximum and TVA precipitation. HMR 41 considers broad aspects of orographic effects only. HMR 45 considered more detailed orographic effects on intensity and distribution of rainfall. In addition, HMR 45 developed further the concept of antecedent rainfall.

Authorization

The authorization for these basin studies is in the form of agreements between the Tennessee Valley Authority and the National Weather Service (NWS).

Scope

The contents of this report fulfill specific needs of TVA. Two categories of precipitation, namely, probable maximum precipitation (PMP) and a standardized and less extreme rainfall called TVA precipitation (defined earlier), are included. Extensions of methods used in previous studies to larger drainages resulted in some slight modifications in the interrelation between PMP and TVA precipitation levels. This is discussed in chapter III.

Developmental work beyond that in HMR 41 and HMR 45 involved:

1. The extension of basic rainfall estimates to large areas;
2. Provision for various placements of isohyetal patterns;
3. Critical review of hypothetical storm sequences for comparison with long duration rainfall potential; and
4. Adjustments to rainfall volume based upon the orientation of the rainfall patterns.

Organization of the Report

Chapter II specifies the drainage area and consolidates the results of the studies in the form of PMP and TVA rainfall values for the four separate basins. The basic methods used in developing the estimates of PMP and TVA rainfall are covered in chapter III. Orographic considerations and adjustments to basic rainfall values for alternate location of rainfall centers are also covered in this chapter. Chapter IV deals with the relation between the TVA and probable maximum levels of rainfall with the variations in the relations that were developed in order to embrace the larger areas covered in this report. The topics of chapter V are areal and time distribution of the rainfall criteria. In addition, this chapter summarizes the practicability of providing multiple isohyetal patterns and discusses the results of an isohyetal-orientation rainfall-magnitude study. Chapter VI covers antecedent rainfall.

Chapter II

ADOPTED BASIN VALUES AND ADJUSTMENT FOR GEOGRAPHICAL RELOCATION

Drainage Areas

The drainage areas of concern in this report are outlined on figure 2-1. The first, the diagonally hatched and dotted region on figure 2-1, is for the 16,170-sq-mi drainage of the Tennessee Basin above Wheeler Dam and below the major tributary dams: Norris, Cherokee, Douglas, Fontana, and Hiwassee.

The second basin of concern includes the 16,170-sq-mi area above Wheeler Dam and below the tributaries, plus the additional area between Wheeler Dam and Kentucky Dam. Thus, it includes both the drainage area for the first basin and the additional dotted region on figure 2-1. Because the Tennessee drainage is connected with the Cumberland River drainage by a canal just upstream of Kentucky Dam, estimates of concurrent rainfall values are needed on the Cumberland River drainage during the extreme rainfall on the Tennessee. This region is also shown on figure 2-1 as the horizontally and diagonally hatched and cross-hatched area immediately to the north of the basin under consideration.

The watersheds for the Cumberland River studies are shown by the horizontally and diagonally hatched areas on figure 2-1. The diagonally hatched area is an uncontrolled 2,734-sq-mi drainage of the Cumberland River immediately above Old Hickory Dam.

Adopted PMP and TVA Precipitation Values

Tables 2-1 to 2-4 give accumulated PMP and TVA precipitation for the four drainages by 6-hr increments for durations from 6 to 72 hrs. These values are for rainfall centered as indicated for each specific estimate, but unadjusted for basin configuration.

Adjustments for Geographical Relocation

The values presented in tables 2-1 to 2-4 are applicable to the indicated centerings. Preliminary hydrologic trials conducted by TVA suggest that the indicated centerings were most critical for the first two basins; for the third and fourth basins, the approximate center of the basin was selected. Adjustment factors for other centerings of the PMP values were determined and are discussed in chapter III. These adjustments are applied to isohyetal pattern labels, discussed also in chapter III, rather than to the average depths given in tables 2-1 to 2-4.

Table 2-1.--Accumulated PMP and TVA precipitation for the 16,170-sq-mi drainage of the Tennessee River Watershed between Wheeler Dam and dams on the major tributaries

(For rainfall pattern centered at Nickajack Dam, 35°00'N, 85°38'W)

Duration (hr)											
6	12	18	24	30	36	42	48	54	60	66	72
Probable maximum precipitation (in)											
5.7	8.4	10.5	12.2	13.1	14.0	14.7	15.4	16.1	16.8	17.5	18.1
TVA precipitation (in)											
3.5	5.3	6.5	7.6	8.2	8.7	9.2	9.6	10.0	10.4	10.8	11.2

Table 2-2.--Accumulated PMP and TVA precipitation for the 26,780-sq-mi drainage of the Tennessee River Watershed between Kentucky Dam and dams on the major tributaries

(For rainfall pattern centered at Fayetteville, Tenn., 35°10'N, 86°33'W)

Duration (hr)											
6	12	18	24	30	36	42	48	54	60	66	72
Probable maximum precipitation (in)											
4.6	7.1	8.7	10.1	11.0	11.8	12.5	13.1	13.7	14.3	14.8	15.3
TVA precipitation (in)											
3.2	5.0	6.1	7.1	7.7	8.3	8.8	9.2	9.6	10.0	10.4	10.7

Table 2-3.--Accumulated PMP and TVA precipitation for the 11,674-sq-mi drainage of the Cumberland River Watershed above Old Hickory Dam

(For rainfall pattern centered near 36°38'N, 85°00'W)

Duration (hr)											
6	12	18	24	30	36	42	48	54	60	66	72
Probable maximum precipitation (in)											
5.7	8.3	10.3	11.7	12.9	13.8	14.6	15.3	15.9	16.5	17.1	17.6
TVA precipitation (in)											
3.5	5.1	6.4	7.3	8.0	8.6	9.1	9.5	9.9	10.3	10.6	10.9

Table 2-4.--Accumulated PMP and TVA precipitation for the 2,734-sq-mi drainage of the Cumberland River Watershed above Old Hickory Dam

(For rainfall pattern centered near 36°18'N, 85°46'W)

Duration (hr)											
6	12	18	24	30	36	42	48	54	60	66	72
Probable maximum precipitation (in)											
11.0	13.9	15.7	17.1	18.0	18.9	19.7	20.4	21.0	21.6	22.2	22.8
TVA precipitation (in)											
6.6	8.3	9.4	10.3	10.8	11.3	11.8	12.2	12.6	13.0	13.4	13.7

Chapter III

BASIC METHOD OF DEVELOPMENT OF ESTIMATES

Underpinning by HMR 41 and HMR 45

Transposition and adjustment of observed storm rainfall, as explained in HMR 41 and HMR 45, is the basic method used to obtain the estimates in this report. Depth-area-duration (DAD) relations of PMP were implicit from a series of generalized charts developed in these earlier reports. The adopted generalized March TVA precipitation and PMP values for 10,000 sq mi and 24 hrs are shown in figures 3-1 and 3-2, respectively. These figures were taken from HMR 41. They were developed specifically to provide PMP and TVA precipitation estimates for the Tennessee Valley. Only storms that were considered transposable to this region or the immediately surrounding area were considered. Charts prepared for a generalized study to prepare PMP estimates for a much larger region would show differences from these charts outside the Tennessee Valley.

The distinction between PMP and TVA precipitation estimates is attributable directly to the maximization for moisture used for estimating PMP but not used for estimating TVA values. The moisture maximization is the ratio of the precipitable water content associated with the maximum 12-hr persisting dew point for the month and place of the storm to that associated with the storm.

The two generalized charts shown (figs. 3-1 and 3-2) represent a series of such charts for range of durations from 6 to 72 hrs and for areas from 1,000 to 20,000 sq mi. Some charts were also drawn for the other 11 months. The degree of envelopment of the precipitation values plotted on any individual chart is dependent not only on the data for that chart but also on the data for other charts for the same month for other durations and areas and is also influenced by similar charts for adjoining months. The precipitation values shown on figures 3-1 and 3-2 are plotted at the location of the rainfall center of the storm. In preparing these two charts, the precipitation amounts were transposed to a series of grid points. The precipitation amounts for each storm were transposed to every grid point within a region where it was considered that the storm could have occurred without significant modifications to the storm mechanism. In each case, the storm value was adjusted to take into account the variation in moisture supply between the storm location and the grid point.

Orographic Considerations

Using various types of rainfall data, evaluation was made of the overall effects of topography on the total volume of rainfall over large areas in the mountainous East. For the large basins of concern in HMR 41, the conclusion was reached that orographic increases tend to be compensated for by decreases behind barriers and other sheltered areas. Therefore, there is no net change in the total volume of precipitation. Orographically controlled rainfall patterns, however, were prepared for the 21,400-sq-mi drainage area of the Tennessee River above Chattanooga. The patterns provide for the effect orography has on the distribution of rainfall in the mountainous eastern portion of the Tennessee Watershed.

In HMR 45, since small basins up to 3,000 sq mi were involved, much more detailed evaluations of orography had to be made. For basins up to 100 sq mi, the various orographic factors were reflected in the 5-sq-mi PMP and TVA precipitation charts, reproduced here as figures 3-3 and 3-4 from HMR 45 figures 2-21A and 2-22A, respectively.

In the present report, the basins are 2,734 sq mi or larger in area. It was necessary to investigate precipitation indices to determine whether there were any orographic effects on total precipitation volume over these basins. Certain indices of highest monthly precipitation values were part of the data used as guides to determine if orographic effects should be incorporated into the precipitation estimates.

The basic data evaluated was monthly precipitation on selected watersheds with drainage areas between 300 and 2,200 sq mi located in the western part of the Tennessee River Basin. The period of record investigated was 1935-64. One index was the geographic distribution of the highest monthly value. A second was the variation in the average of the three highest monthly values. Allowing for the climatological variations to be expected over the western half of the Tennessee Watershed, there did appear to be some evidence of a slight orographic intensification in the Cumberland Plateau region. This substantiates what was shown in the small-basin PMP for the western half of the Tennessee River Watershed, figure 3-3.

Intensification shown in figure 3-3 will be in excess of what would be expected for large basins, since in determination of the increase in precipitation values depicted in this figure we were concerned with essentially thunderstorm precipitation rather than with large-area general storms.

For rainfall intensification over small areas, inflow to each point must be considered separately and many wind directions are important. For maximum precipitation amounts over large areas, one inflow direction is usually optimum.

Because the above-mentioned investigations of monthly precipitation over subbasins of the western Tennessee River Watershed indicated some increase in rainfall on larger areas, resulting from orographic influences, it was necessary to examine the topography in more detail. The nature of the terrain in the 16,170-sq-mi Tennessee River Watershed above Wheeler Dam and below the major tributary dams, suggests some slight orographic effect on the rainfall. The storm type producing large precipitation amounts is important in determining the orographic factor. Examination of the location of rainfall centers of major large-area spring storms in this region indicates that meteorological factors are more important than orographic factors.

The decision was made to incorporate any orographic effects in the form of a correction to the total volume of nonorographic rainfall.

Winds from a south or southwesterly direction are prevalent in large-area rainstorms. Thus, we started with an assumed storm inflow wind direction from the southwest in evaluating the orographic effect. Generalized contours were constructed on a 1:1,000,000-scale topographic chart, and areas with significant southwest-facing slopes were outlined. The assumption was made that "triggering" and upslope effects would prevail (or persist) for a distance of 20 miles downwind from the tops of significant upslopes. The outlines for all such areas were then transferred to figures 3-3 and 3-4. The initial orographic intensification factor was determined from consideration of these areas. This intensification factor was the average increase of the precipitation within these regions over that shown on the smooth curve of figure 2-15 of HMR 45. These computations show a net orographic increase of approximately 5 percent in total rainfall volume over the 16,170-sq-mi drainage above Wheeler Dam. This net orographic increase in total rainfall volume was determined by distributing over the entire basin the greater percentage increase obtained from restricted portions of the basin.

A similar examination of the terrain factor over the total area above Kentucky Dam and below the major tributary dams in the Tennessee River Watershed suggested that the increase on favorably oriented slopes would be essentially compensated by the orographic decrease on other slopes and in sheltered areas. Examination of the terrain above Old Hickory Dam on the Cumberland River drainage suggested the same simplifying assumption--that the orographic increases and orographic decreases would cancel and no net orographic effect would be present for either the total basin or the smaller 2,734-sq-mi uncontrolled drainage.

Estimates for Tennessee River Watersheds

Generalized charts of PMP and TVA precipitation such as figures 3-1 and 3-2 are useful in preparing sets of DAD curves for specific locations. Such PMP curves for areas up to 5,000 sq mi, and applicable to the location of Knoxville Airport, were developed in the preparation of HMR 45 and are shown in that report as figure 3-11. A similar set of DAD curves was prepared in the development of the estimates of probable maximum and TVA precipitation for the Tennessee River Watershed above Chattanooga (HMR 41). These curves cover the range from 10,000 to slightly above 20,000 sq mi.

To obtain PMP and TVA precipitation estimates for the Tennessee River Watershed between Wheeler Dam and the major tributary dams and between Kentucky Dam and the major tributary dams, two additional families of DAD curves were prepared--one for PMP values and one for TVA precipitation values. That only these two were required is evidenced by the orientation of the isohyets on enveloping precipitation charts which indicated that the same PMP or TVA precipitation curves are applicable to both watersheds. Figures 3-5 and 3-6 show the adopted PMP and TVA precipitation DAD curves appropriate for the selected centerings in each watershed, Nickajack Dam and Fayetteville, Tenn., respectively. The PMP and TVA precipitation values for the Tennessee River Watershed above Wheeler Dam and below the major tributary dams are given in table 2-1. These values have been increased by 5 percent over values read from the curves of figure 3-5 or 3-6 for the orographic increase discussed in the previous section. They have not been adjusted for the basin configuration. The PMP and TVA precipitation values for the Tennessee River Watershed above Kentucky Dam and below the major tributary dams are given in table 2-2. These also have not been adjusted for basin configuration.

Extension to Larger Areas

Since the estimate for the 26,780-sq-mi area above Kentucky Dam requires concurrent rainfall over the adjacent Cumberland drainage while PMP is occurring in the primary study region, it was necessary to develop estimates of PMP and TVA rainfall for areas larger than 100,000 sq mi. Storm rainfalls were transposed and moisture maximized, and additional generalized charts for areas larger than 25,000 sq mi for both PMP and TVA precipitation were prepared. Such generalized charts were required to provide the needed consistency of estimates over the large region. Figures 3-7 and 3-8 show the generalized charts and supporting data for a duration of 72 hrs and for an area of 100,000 sq mi. Many other such charts (not shown) were developed for other areas and durations with varying degrees of completeness. Again, as with the smaller areas, PMP and TVA precipitation values were taken from these generalized charts and sets of DAD curves were prepared for centering at Fayetteville, Tenn. These DAD curves are shown in figure 3-9 and are extensions of the curves of figure 3-5.

Transposition of Storms to Fayetteville, Tenn.

A check was made by transposing key storms to Fayetteville, Tenn., center of adopted values of table 2-2. These transpositions helped us to obtain a better perspective on controlling storms in relation to the extended set of DAD curves of figure 3-9. The largest general cool season storms that occurred in the eastern half of the United States were transposed. Table 3-1 lists the maximum storm precipitation values adjusted for maximum moisture. The table also shows the storm designation from Storm Rainfall (Corps of Engineers, U. S. Army 1945-.) and the adjustment factor in parentheses. For example, 141 means a 41-percent increase of the observed rainfall to the amount that would have occurred under maximum moisture conditions. The locations of these storms are shown in figures 3-7 and 3-8.

The controlling values of table 3-1 are plotted on figure 3-9 to show the resulting relation to the smoothed adopted set of DAD curves applicable to the location of Fayetteville. A more liberal transposition limit was used in the preparation of table 3-1 than is customary in the preparation of such arrays of maximum precipitation. This was done for the purpose of comparing the transposed values with curves prepared from generalized charts in which the regional and seasonal smoothing provides implicit transposition that usually results in maximization not obtained by transposing storms to a particular location. Therefore, it is to be expected that some moisture-

Table 3-1.--Maximized storm precipitation values applicable to a centering at Fayetteville, Tenn.

Area (sq mi)	Duration (hr)					
	6	12	18	24	48	72
	Rainfall (in)					
10,000	5.9(105) LMV 2-20	9.3(141) LMV 2-5	11.3(141) LMV 2-5	12.6(105) LMV 2-20	16.0(105) LMV 2-20	17.9(105) LMV 2-20
20,000	4.4(141) LMV 2-5	8.1(141) LMV 2-5	9.8(141) LMV 2-5	11.0(141) LMV 2-5	13.9(141) LMV 2-5	15.0(105) LMV 2-20
50,000	3.1(141) LMV 2-5	5.9(141) LMV 2-5	7.2(141) LMV 2-5	8.3(141) LMV 2-5	11.0(141) LMV 2-5	*11.7(141) LMV 2-5
75,000	2.5(141) LMV 2-5	4.9(141) LMV 2-5	6.1(141) LMV 2-5	7.1(141) LMV 2-5	9.5(141) LMV 2-5	10.1(141) LMV 2-5
100,000	1.7(105) LMV 2-20	2.7(134) OR 1-15	3.7(105) LMV 2-20	4.5(105) LMV 2-20	8.2(164) MR 1-1	9.3(164) MR 1-1

Storm Identification	Date	Location of Center
LMV 2-20	March 11-16, 1929	Elba, Ala.
LMV 2-5	April 15-18, 1900	Eutaw, Ala.
OR 1-15	March 23-27, 1913	Bellefontaine, Ohio
MR 1-1	December 16-20, 1895	Phillipsburg, Mo.

Notes: 1. Values in parentheses after rainfall are storm adjustments.
2. Storm identification, under rainfall, from Storm Rainfall (Corps of Engineers, U. S. Army 1945-.).

*Other storms showed 11.6 (MR 1-1, 12/16-20/95); 10.6 (SW 2-20, 5/6-12/43); 11.0 (LMV 2-20, and 3/11-16/29), signifying strong support for the 50,000-sq-mi - 72-hr value.

adjusted and transposed precipitation values will exceed the results obtained from the generalized charts (see 12- and 18-hr values for 20,000 sq mi).

The closeness of the transposed storm values to the smooth set of DAD curves adopted from the generalized map procedure lends support to the estimates. For areas of a few thousand sq mi and less, the curves are controlled by the DAD curves that were developed for HMR 45.

As can be seen from table 3-1 and figure 3-9, the shape and magnitude of DAD relations for the three large basins of concern in this report are controlled primarily by spring and late winter storms. The two most important storms are the Elba, Ala., storm of March 11-16, 1929 (LMV 2-20), and the Eutaw, Ala., storm of April 15-18, 1900 (LMV 2-5). These two storms also provide some controlling values for the generalized charts, such as those of figures 3-7 and 3-8. Although the Bellefontaine, Ohio, storm of March 23-27, 1913 (OR 1-15) apparently provides the controlling value for 100,000 sq mi and 12-hr duration, actually, the Eutaw, Ala., storm controls. DAD data were available for this latter storm only for areas as large as 75,000 sq mi; but even assuming no rain beyond 75,000 sq mi (a minimum assumption), the estimated average depth over an area of 100,000 sq mi for the Eutaw, Ala., storm would be 3.7 in. or 1 in. more than that from the Bellefontaine, Ohio, storm.

Estimates for the Cumberland River Watersheds

The generalized TVA precipitation and PMP charts of figures 3-1 and 3-2 were not restricted to the Tennessee Valley. These charts were prepared to encompass a region of Southeastern United States surrounding that region. It was possible, therefore, to develop sets of DAD relations for the Cumberland River Watershed above Old Hickory Dam from these same generalized charts. These DAD curves are shown in figure 3-10, and PMP and TVA precipitation values are given for the total basin area in table 2-3.

Summertime Rainfall Potential for the Uncontrolled 2,734-sq-mi Drainage Above Old Hickory Dam

Hydrologic trials using rainfall estimates for the total 11,674-sq-mi drainage area above Old Hickory Dam suggested the possibility that the warm-season extreme storm rainfall concentrating over the lower uncontrolled portion of the basin immediately above Old Hickory Dam might be more critical. This drainage is a local area below the major tributary dams (Center Hill, Dale Hollow, and Wolf Creek) and above Old Hickory Dam. Warm-season PMP and TVA precipitation estimates were made, therefore, for this uncontrolled 2,734-sq-mi drainage. This set of curves was developed from generalized warm-season PMP and TVA precipitation maps. The maps used were part of the set of generalized charts examples of which are shown as figures 3-1, 3-2, 3-7, and 3-8 of this report and figure 3-10 of HMR 45. The estimates were made for rainfall centered at 36°18'N and 85°46'W (table 2-4). Procedures for centering the rainfall patterns at other geographical points are developed later in this chapter.

Adjustment in Depth-Duration Relation Based Upon Recent Work on Generalized Estimates for the Eastern United States

A slight adjustment was made in the basic DAD values for the Cumberland River Watersheds as interpolated from the generalized charts discussed in the preceding paragraphs. This was based upon the preliminary results of a project to prepare generalized estimates of PMP for areas from 1,000 up to 20,000 sq mi for the Eastern United States. These changes amounted to a 4- to 5-percent increase at the 48- and 72-hr durations. There were no differences for the durations of 24 hrs and less.

Geographical Relocation Adjustments

The PMP and TVA precipitation estimates shown in tables 2-1 to 2-4 are for specific centerings of the isohyetal patterns. A brief mention of the geographic relocation adjustments was made in chapter II. Figures 3-12 to 3-14 show the geographical relocation adjustments for the Tennessee River Watershed above Kentucky Dam, the Cumberland River Watershed above Old Hickory Dam, and the uncontrolled portion of the Cumberland River Watershed above Old Hickory Dam, respectively. On each of these charts, the 100-percent line passes through the location indicated in tables 2-1, 2-3, and 2-4. These geographical relocation adjustments were based on the generalized PMP and TVA precipitation lines of figures 3-1 and 3-2.

Previous flood studies by TVA using data from HMR 41 indicated the most critical centering for a storm over the 16,170-sq-mi drainage above Wheeler Dam and below the major tributary dams was near Nickajack Dam. No large departures from such a centering were deemed necessary. Consequently, it was decided the user would be given the option of shifting the isohyetal pattern within the radius of 35 mi of Nickajack Dam without requiring any adjustment to the basin rainfall values.

Chapter IV

TVA LEVEL OF PRECIPITATION

Historical Development

A less intense precipitation criterion than PMP is often required for design of certain type hydrologic structures. The TVA uses a storm that is termed a TVA storm. This is defined as a storm "resulting from transposition and adjustment to the Tennessee Watershed without maximization of appropriate storms that have occurred elsewhere." This basic definition was used in HMR 41 and HMR 45 and is also used in this report.

In accordance with this basic definition, in HMR 41, independent estimates were made of PMP and TVA precipitation, including seasonal variations through the warmer months. Generalized maps of precipitation for durations of up to 72 hrs and areas to 20,000 sq mi form the basis of these estimates. Examples of such maps are those shown in figures 3-1 and 3-2 of the present report. From such maps, a comparison of the two sets of estimates indicates that the TVA precipitation is 64 percent of the PMP for March, with lower percentages indicated for the summer months. Cool-season percentages, other than in March, are somewhat higher than 64 percent.

The same basic concept used in HMR 45 for the relation between TVA precipitation and PMP is carried forward into the present report. However, a variable depth-duration relation is introduced for the TVA level of precipitation. This, of course, results in increased variability in the ratio between TVA precipitation and PMP.

TVA Precipitation Estimates for Basins in the Present Study

TVA precipitation estimates were prepared by computing ratios between the TVA precipitation and PMP shown on the generalized charts developed for this study, such as figures 3-1, 3-2, 3-7, and 3-8. The adopted ratio of TVA precipitation to PMP for the basin above Wheeler Dam, and that above Old Hickory Dam, was 0.62. This ratio is applicable to the all-season PMP and provides the all-season TVA precipitation, which will occur in the spring season for these two basins. It is equivalent to the average ratio adopted for spring storms in HMR 41 for the 7,980- and 21,400-sq-mi basins of concern in that report.

For the smaller uncontrolled drainage area, 2,734 sq mi above Old Hickory Dam, the maximum precipitation would be from a warm season situation. The generalized charts show a lower ratio would be appropriate for this summer-type storm. Consequently, a ratio of 0.60 between TVA precipitation and PMP was adopted for this basin.

For the area above Kentucky Dam, embracing both the Tennessee and Cumberland Watersheds, it was necessary to consider the ratio of TVA precipitation and PMP over much larger areas than for the previous studies. This was also done using the generalized-chart technique, as was explained in the first paragraph of this section. Consideration of these generalized charts for many durations suggested that a ratio of 0.70 between TVA precipitation and PMP was appropriate for this basin. Additional support for this ratio for larger areas is suggested by a comparison of large-area precipitation volume in hypothetical storm sequences. These kinds of data are discussed in chapter VI of this report.

Chapter V

AREAL AND TIME DISTRIBUTIONS

Areal Distribution

Enveloping DAD curves, such as those of figures 3-5 and 3-9, or estimates of average depth of precipitation over the total basin, such as those provided by tables 2-1 to 2-4, provide only a portion ot the precipitation criteria necessary for determining the flood potential of a basin. It is also necessary to specify the areal distribution of the precipitation over the basin. Two features of the areal distribution within the basin are considered in this section. One of these is the shape of a meteorologically reasonable isohyetal pattern that minimizes the volume of rainfall that falls outside the basin. The other feature is the concentration of the rainfall within the basin. Values assigned to individual isohyets and the isohyetal gradient determine this concentration or peakedness.

Isohyetal Patterns

Historically, before the advent of computer methods, custom and time requirements ordinarily dictated that a single isohyetal pattern be chosen for distributing the rainfall over a basin. Currently, it is more feasible to experiment with several isohyetal patterns to determine which is more hydrologically critical. Four isohyetal patterns are provided in figures 5-1 to 5-4 for use in the drainage above Wheeler Dam.

Two patterns are ellipses and have major-to-minor axis ratios of 2:1 (fig. 5-1) and 5:2 (fig. 5-3). The pattern of figure 5-1 was developed in HMR 40 (U. S. Weather Bureau 1965). This isohyetal pattern for probable maximum precipitation storms was developed considering many storms from Eastern United States and is considered applicable to this region. Figure 5-3 is a slight modification of figure 5-1, and it is based on a major-to-minor axis ratio of 5:2. A 2:1 ratio is commonly used for an isohyetal pattern. In order to allow for more possibilities, another pattern with the 5:2 ratio was provided. A summary of many rains in and near the Tennessee showed such variability to be realistic.

To determine additional likely areal patterns for distribution of the precipitation from the probable maximum storm over the basin, major storms in the Tennessee River Watershed were studied. Figures 5-2 and 5-4 were developed from figures 5-1 and 5-3, respectively, and show a recommended geographical location of the rainfall centers for each pattern and the additional isohyetal patterns for the Tennessee River Watershed between Wheeler Dam and the major tributary dams. This centering was within the area determined by hydrologic trials conducted by the Tennessee Valley Authority as providing the hydrologically critical centerings of the rainfall potential. (See section, "Adjustments for Geographical Relocation").

This centering places most of isohyets "A" through "G" within the basin area between Wheeler Dam and Chickamauga Dam. Isohyets "H" and "I" were shifted or warped. The warping was done so as to minimize the rainfall that occurs outside the basin and to preserve the correct total volume of PMP.

For the three other drainages considered in this report, the Tennessee River between Kentucky Dam and the major tributary dams, the Cumberland River above Old Hickory Dam, and the uncontrolled drainage of the Cumberland River between Old Hickory Dam and the major tributary dams, the basic elliptical pattern with a major-to-minor axis ratio of 2:1 is recommended (fig. 5-1). For application to these drainages, no warping of the isohyetal pattern is recommended.

Adjustments in Isohyetal Patterns for Orographic Effect

While some orographic increases in the foothills of the mountainous eastern portion of the Tennessee River Watershed may be reasonable, as indicated in chapter III under the section, "Orographic Considerations," the increases would be small for the Tennessee River Watershed above Kentucky Dam. In addition, the inclusion of the area of the Cumberland drainage would further decrease the net orographic effect resulting from the mountainous eastern portion of the basin. One factor supporting this contention is the inability of a particular wind direction to produce orographic increases in both the Tennessee and the adjoining Cumberland Watershed simultaneously. For example, a southwest upslope wind in the Tennessee drainage becomes a downslope wind in the bordering Cumberland River Watershed.

For the drainages above Old Hickory Dam (both total and smaller uncontrolled), as in the estimate for the Tennessee River above Kentucky Dam, no warping of the pattern for orography is permitted. The general paralleling of the ridges (within the relatively small, more rugged headwater portions of the basin) with the orientation of the recommended isohyetal pattern would result in terrain increases in rainfall that would be compensated for by decreases at other locations. Consequently, no net change in the isohyetal pattern or total volume of rainfall for the basin due to orography is necessary. Similarly, the conclusion of no net orographic effect is reasonable for the smaller uncontrolled portion of the basin above Old Hickory Dam.

Isohyetal Labels

The PMP estimate (or TVA precipitation estimate) for a particular basin for any duration determines the total volume of rainfall over that size area for that duration. The distribution of rainfall within the basin is defined by depth-area relations and isohyetal patterns. In the previous section, the shapes of typical isohyetal patterns were described for the four basins of concern within this report. The next step is to determine the labels that will be placed upon the isohyetal pattern to maintain the correct total volume of precipitation.

The basic procedures for determining the within-basin concentration of rainfall were handled by an adaptation of the generalized methods developed in HMR 40 (U. S. Weather Bureau 1965). Comparison of the isohyetal gradients in large storms that could affect the Tennessee River Watershed with those used in the development of these procedures verified their applicability. The initial nomograms for developing isohyetal labels for pattern storms were published in HMR 45 as figures 3-24 to 3-26. In an addendum to HMR 45 (in press) the figures were further smoothed and extended. These revised figures provide the basis for the development of the isohyetal labels shown in tables 5-1 to 5-7.

Isohyetal labels for the two basins within the Tennessee River Valley are given in tables 5-1 to 5-4. Table 5-1 provides labels for isohyets "A" to "I" for PMP and table 5-2 for TVA precipitation for the 16,170-sq-mi area of the Tennessee River above Wheeler Dam and below the major tributary dams. Tables 5-3 and 5-4 give similar information for isohyets "A" to "P" for the 26,780-sq-mi drainage of the Tennessee River above Kentucky Dam and below the major tributary dams. Tables 5-5 to 5-7 provide the PMP and TVA precipitation isohyetal labels for the Cumberland River Watershed. Tables 5-5 and 5-6 provide isohyetal labels for the total 11,674-sq-mi drainage of the Cumberland River above Old Hickory Dam. Table 5-7 provides both the PMP and TVA precipitation isohyetal labels for the uncontrolled 2,734-sq-mi drainage area above Old Hickory Dam. Labels are provided for isohyets "A" to "I."

The within-basin relation developed for the area above Kentucky Dam provides PMP (and TVA precipitation) values for area sizes from about 10,000 sq mi up to areas a little larger than the key 26,780-sq-mi area. For areas less than 10,000 sq mi for the maximum 6-hr increment, the greatest departure is at the smallest area where it is about two-thirds of PMP. This is in accordance with present meteorological judgment that a single storm would not produce the PMP for all durations and sizes of area over a particular basin.

The canal connecting the Tennessee and Cumberland River Watersheds near Kentucky Dam on the Tennessee River requires consideration of rainfall on the Cumberland drainage when PMP is centered on the Tennessee drainage. Meteorological judgment indicates that storms which produce PMP over the Tennessee drainage would not concurrently produce PMP over the adjoining Cumberland drainage. Therefore, depths are less than PMP for areas significantly larger than the basin size. The greatest departures for 100,000 sq mi was 8 percent below PMP.

Rotation of Isohyetal Patterns

Historically, the rotation of isohyetal patterns in PMP estimates has been restricted to meteorological limits that do not require a change in the rainfall magnitude. We may turn to hypothetical storm sequences for large

Table 5-1.--Values of PMP isohyets for the 16,170-sq-mi Tennessee River Watershed between Wheeler Dam and the major tributary dams

	Isohyet								
	A	B	C	D	E	F	G	H	I
	Isohyet values (in)								
1st 6 hrs	12.7	11.0	9.2	8.1	6.9	6.1	5.3	4.1	2.7
2d 6 hrs	4.0	3.7	3.5	3.3	3.0	2.8	2.6	2.1	1.6
3d 6 hrs	3.0	2.8	2.6	2.4	2.2	2.1	1.9	1.7	1.3
4th to 12th 6-hr period	Uniform areal distribution								
	Accumulative area (sq mi)								
	60	265	740	1,625	3,185	5,190	7,725	14,450	25,545

Table 5-2.--Values of TVA precipitation isohyets for the 16,170-sq-mi Tennessee River Watershed between Wheeler Dam and the major tributary dams

	Isohyet								
	A	B	C	D	E	F	G	H	I
	Isohyet values (in)								
1st 6 hrs	7.9	6.8	5.7	5.0	4.3	3.8	3.3	2.5	1.7
2d 6 hrs	2.5	2.3	2.2	2.0	1.9	1.7	1.6	1.3	1.0
3d 6 hrs	1.9	1.7	1.6	1.5	1.4	1.3	1.2	1.1	0.8
4th to 12th 6-hr period	Uniform areal distribution								
	Accumulative area (sq mi) (See table 5-1)								

Table 5-3.--Values of PMP isohyets for the 26,780-sq-mi Tennessee River Watershed between Kentucky Dam and the major tributary dams

	Isohyet								
	A	B	C	D	E	F	G	H	I
	Isohyet values (in)								
1st 6 hrs	13.5	11.6	10.1	8.5	7.0	5.9	5.0	3.7	2.5
2d 6 hrs	4.1	3.6	3.5	3.3	3.1	2.5	2.3	2.2	2.1
3d 6 hrs	3.2	2.8	2.5	2.3	2.0	1.8	1.7	1.6	1.5
4th to 12th 6-hr period	Uniform areal distribution								
	Accumulative area (sq mi)								
	60	265	740	1,625	3,185	5,190	7,725	14,450	25,545

	Isohyet--Continued						
	J	K	L	M	N	O	P
	Isohyet values (in)						
1st 6 hrs	2.2	1.8	1.6	1.3	1.1	0.9	0.7
2d 6 hrs	1.8	1.6	1.3	1.2	1.1	0.8	0.6
3d 6 hrs	1.4	1.3	1.2	1.1	0.9	0.7	0.5
4th to 12th 6-hr period	Uniform areal distribution						
	Accumulative area (sq mi)						
	35,315	46,200	58,420	70,940	82,920	98,350	118,960

Table 5-4.--Values of TVA precipitation isohyets for the 26,780-sq-mi Tennessee River Watershed between Kentucky Dam and the major tributary dams

	Isohyet								
	A	B	C	D	E	F	G	H	I
	Isohyet values (in)								
1st 6 hrs	9.4	8.1	7.1	6.0	4.9	4.1	3.5	2.6	1.7
2d 6 hrs	2.9	2.5	2.4	2.3	2.2	1.8	1.6	1.5	1.5
3d 6 hrs	2.2	2.0	1.8	1.6	1.4	1.3	1.2	1.1	1.0
4th to 12th 6-hr period	Uniform areal distribution								
	Accumulative area (sq mi) (See table 5-3)								

	Isohyet--Continued						
	J	K	L	M	N	O	P
	Isohyet values (in)						
1st 6 hrs	1.5	1.3	1.1	0.9	0.8	0.6	0.5
2d 6 hrs	1.3	1.1	0.9	0.8	0.8	0.6	0.4
3d 6 hrs	1.0	0.9	0.8	0.8	0.6	0.5	0.4
4th to 12th 6-hr period	Uniform areal distribution						
	Accumulative area (sq mi) (See table 5-3)						

Table 5-5.--Values of PMP isohyets for the 11,674-sq-mi Cumberland River Watershed above Old Hickory Dam

	Isohyet								
	A	B	C	D	E	F	G	H	I
	Isohyet values (in)								
1st 6 hrs	13.0	10.5	9.2	7.9	6.6	5.3	4.3	2.9	2.2
2d 6 hrs	4.1	3.3	3.0	2.8	2.7	2.7	2.6	2.4	2.2
3d 6 hrs	3.2	2.7	2.6	2.3	2.0	2.0	2.0	1.9	1.1
4th to 12th 6-hr period	Uniform areal distribution								
	Accumulative area (sq mi) (See table 5-1)								

Table 5-6.--Values of TVA precipitation isohyets for the 11,674-sq-mi Cumberland River Watershed above Old Hickory Dam

	Isohyet								
	A	B	C	D	E	F	G	H	I
	Isohyet values (in)								
1st 6 hrs	8.1	6.5	5.7	4.9	4.1	3.3	2.7	1.8	1.4
2d 6 hrs	2.5	2.0	1.9	1.7	1.7	1.7	1.6	1.5	1.4
3d 6 hrs	2.0	1.7	1.6	1.4	1.3	1.2	1.2	1.2	.7
4th to 12th 6-hr period	Uniform areal distribution								
	Accumulative area (sq mi) (See table 5-1)								

Table 5-7.--Values of PMP and TVA precipitation isohyets for the uncontrolled 2,734-sq-mi drainage above Old Hickory Dam

	Isohyet								
	A	B	C	D	E	F	G	H	I
	Isohyet values (in)								
1st 6 hrs									
PMP	16.4	13.8	11.8	10.3	7.0	5.2	4.0	2.8	2.1
TVA	9.8	8.3	7.1	6.2	4.2	3.1	2.4	1.7	1.3
2d to 12th 6-hr period	Uniform areal distribution								
	Accumulative area (sq mi) (see table 5-1)								

areas to see what has been done with the rotation of large isohyetal patterns. For example, in the Cumberland report (U. S. Weather Bureau 1955), rotations of isohyetal patterns of 10° to 20° were suggested for the various storms comprising the hypothetical sequences. Rotations of 4° to 10° were generally used in the hypothetical sequences in the Ohio report (U. S. Weather Bureau 1961). It is possible to have such limited variations in storm orientations without postulating any significant changes in the storm mechanism.

One hypothesis is that the orientation of rainfall patterns for very large areas may be significantly tied to major atmospheric controls. This was shown to be true in former studies (U. S. Weather Bureau 1956, 1965). These studies showed that large-area rains in Eastern United States formed isohyetal patterns that were roughly in accordance with stationary or quasi-stationary patterns of wind flow aloft. In other words, the flow through the total atmosphere controls the path of rain-producing mechanisms. Since this is true with the largest storms, we hypothesize that the optimum rainfall efficiency would exist with a particular fixing of the broad-scale atmospheric controls. Patterns aloft that do not conform to this optimum broad-scale pattern ought, therefore, to produce concentrated rains of lesser magnitude than those that would occur with the optimum flow pattern.

To quantify the variation of rainfall depths as the flow pattern departs from the optimum in the region of the Tennessee and Cumberland drainages, an empirical study was conducted of the orientation of isohyetal patterns of large storms in this region reported in "Storm Rainfall in the United States" (Corps of Engineers, U. S. Army 1945-.). All 72-hr storms within a broad region (fig. 5-5), which extended through areas of 20,000 to 50,000 sq mi, were investigated. The storms considered were those in which the rainfall center occurred within the solid lines surrounding the Tennessee

River Watershed in the figure. In addition to the rainfall center occurring within this rather broad geographic area, a significant portion of the isohyetal pattern had to occur within the hatched area of figure 5-5. Eighty-two storms occurred within these geographical limits. Ten of these were tropical storms and were excluded from the data sample since an adjustment was desired appropriate to cool-season storm characteristics.

After the isohyetal pattern orientations were determined for the remaining 72 storms, rainfall magnitude was plotted versus isohyetal pattern orientation. Means and 80-percent envelopments of the rainfall data, within orientation intervals of 20°, were analyzed. Figure 5-6 shows a plot of the 20,000-sq-mi 72-hr data. Also shown on this figure are curves for means and 80-percent envelopments of these data combined with similar data for 50,000 sq mi and 72 hrs. Definite trends with orientation resulted and were then subjectively smoothed. Heaviest rains were suggested for patterns with the major axis orientation aligned between 185° and 205°. The adopted curve (in terms of rainfall corrections) is shown in both figure 5-6 and figure 5-7.

No significant seasonal or geographical trends were noted in the data. In addition, moisture-maximized storm rainfall did not suggest a consistent departure from the adopted curve. The percentage adjustments from the adopted curve are given in table 5-8. These adjustments are applied to isohyetal values. It should be noted that the data sample was somewhat restricted and contained primarily those orientations within the range shown in figure 5-7.

Physically, the result shown in figure 5-7 can be interpreted to mean the average steering current aloft for the most efficient storms would be oriented approximately along 195°-15°. Large-area storms typically stem from low-pressure systems moving along a zone between air masses with contrasting temperatures. Successive waves (low-pressure systems) following along approximately the same track, controlled by the direction of the steering currents of the total atmosphere, result in the elongation of the precipitation pattern. Furthermore, over the Eastern United States, where the Gulf of Mexico is a major moisture source in situations producing significant rainfall, the most favorable persistent rain-producing situation is where a sustained flow of moist air exists, particularly in the low levels, with pronounced components from the south or southwest. When these winds swing around too much to a westerly direction, reducing the flow of air from the moisture source, rainfall decreases.

Thus, the results of this empirical study support the reasonable physical hypothesis that within the Tennessee and Cumberland River Watersheds rainfall magnitude and orientation of the isohyetal pattern should be related.

Table 5-8.--Adjustments of rainfall for isohyetal orientation

Major axis orientation (degrees from north)	Rainfall adjustment (%)
195	0
205	0
215	-1
225	-3
235	-5
245	-8
255	-11
265	-14
275	-17
285	-21

Time Distribution

Six-hr increments of PMP and TVA precipitation are obtained by taking differences of the accumulated rainfalls in tables 2-1 to 2-4 for the various basins. Certain guidelines are recommended for time arrangements of these increments. The user may select a critical sequence in accordance with the guidelines given below.

1. Group the four heaviest 6-hr increments of the 72-hr PMP or TVA precipitation in a 24-hr period, the middle four increments in a 24-hr period, and the smallest four increments in a 24-hr period.

2. Arrange the three 24-hr periods with the second highest next to the highest, with the third highest (actually lowest) at either end. Any of the possible arrangements of the three 24-hr periods is acceptable, with the exception of placing the lowest 24-hr period in the middle.

3. Arrange the 6-hr increments within each 24-hr period such that the highest two and the highest three adjoin.

These suggestions cover the time distribution of precipitation within the 72-hr PMP and TVA precipitation storms. Recommendations on areal and time distribution of antecedent rain are covered in chapter VI.

Chapter VI

ANTECEDENT RAINFALL

Introduction

In HMR 41, antecedent rainfall and its seasonal variation were given for the 7,980- and 21,400-sq mi basins. The concept involved the use of rainfall values that could "readily occur." Summer antecedent rainfall for small basins was covered in HMR 45. In this latter report, emphasis was on the "equal probability" concept for TVA antecedent rainfall. The rainfalls antecedent to TVA precipitation are intended to be close to what normally occurs. They are selected with the intent that the probability of the total event does not change. Thus, if a 3-day antecedent rain is added to a 3-day TVA rain with three intervening rainless days, the 9-day event should have about the same probability as that of the 3-day TVA precipitation event. The magnitude of antecedent rain to TVA precipitation for this "equal probability" concept was derived from a joint consideration of rainfall and streamflow data from flooding situations and was determined to be 20 percent of the main storm. This proved to be 50 percent of the 40 percent value used to determine the antecedent storm for the PMP event.

Antecedent PMP and TVA Precipitation Percentages for the Tennessee River Above Wheeler Dam and the Cumberland River Above Old Hickory Dam

The basic concepts and antecedent percentages developed in HMR 41 and HMR 45 were applied to the 16,170-sq-mi drainage of the Tennessee River Watershed above Wheeler Dam and the 11,674-sq-mi total drainage above Old Hickory Dam on the Cumberland River. Thus, for both these total drainages, which are akin to the size areas of concern in HMR 41, rainfall antecedent to PMP with three intervening rainless days is equal to 40 percent of the PMP. Maintaining the concept of "equal probability" developed in HMR 45, the adopted antecedent rainfall to TVA precipitation for these two basins is 50 percent of the percentage adopted for the antecedent conditions prior to PMP, or 20 percent of the 3-day TVA rainfall.

Antecedent Rainfall Conditions for PMP and TVA Precipitation for the Tennessee River Watershed Above Kentucky Dam

In order to form judgments as to the general level of antecedent plus PMP or TVA rainfall for this large drainage, a review and summarization was made of previously accepted hypothetical storm sequences. Hypothetical sequences were used because the event that could produce peak discharge or peak volume of runoff in a basin of the size of the combined Cumberland-Tennessee drainage would have to be of a longer duration than what is usually regarded as a single storm (72-hr interval). Furthermore, downstream progression of rainfall as can be simulated by hypothetical sequences would likely produce the most severe hydrologic sequence. Historically, the hypothetical sequence technique was developed for very large drainages where just a single 3-day storm event cannot produce a major flood. A recent summarized discussion of this technique is covered in WMO Technical Note No. 98 (World Meteorological Organization 1969).

Conclusions From Former Hypothetical Sequences

The review of earlier hypothetical sequences concentrated on seven sequences used in the Cumberland report (U. S. Weather Bureau 1955). Evaluations of long-duration rain potential were made of two cases: 1) where no storms were maximized for moisture and 2) where one storm in each sequence was maximized. Both upstream and downstream progression of rainfall with time were involved in these sequences.

Comparisons of hypothetical sequence rainfall (mean of the seven cases and the maximum and minimum values of these cases) and the proposed antecedent plus PMP or TVA precipitation are shown in figure 6-1. A base 9-day period is used for comparison. For the criteria of this report, the 9-day period includes 3 days of antecedent rainfall, a 3-day dry interval, and 3 days of PMP or TVA rainfall. The 3-day PMP comes from the adopted set of DAD curves of figure 3-5. The antecedent rainfalls are based upon the assumption of 50 percent of the PMP and 25 percent of the TVA precipitation, respectively. The 25-percent TVA antecedent precipitation is in line with meeting the "equal probability" criteria developed in HMR 45. TVA precipitation values result from using the 0.7 ratio of TVA precipitation to PMP adopted for large-area storms.

Figure 6-1 shows that the adoption of a 50-percent figure for the PMP antecedent precipitation results in a 9-day rainfall volume, which comes close to enveloping most of the individual hypothetical sequence data. It is considered appropriate that the adopted PMP and antecedent rainfall be above the mean values from the hypothetical sequences since downstream progression in some of the hypothetical sequences may introduce additional severity to resulting downstream floods.

Evidence From Long-Duration Actual Storms

An additional study was made of rain ratios (11- to 3-day and 15- to 3-day) in significant actual storms of record to detect trends, if any, in antecedent rains with varying area sizes. These storms, unlike the hypothetical sequences, involve events that did occur consecutively.

The outstanding storms used were of January 5-25, 1937, and the famous sequence of "Warner," and "Mounds," Oklahoma, storms covering the period of May 6-20, 1943 (Corps of Engineers, U. S. Army 1945-.). Figure 6-2 is a plot of the 11- to 3- and 15- to 3-day rain ratios from these storms versus area size. This represents an extension of some earlier work done in preparation of HMR 41, where areas of only up to around 20,000 sq mi were of concern. A mean line is drawn through the data of figure 6-2. For areas of less than 20,000 sq mi, there is no discernible variation, although above this area a definite trend exists for larger rain ratios. Based upon the trend in ratios shown in figure 6-2, the adopted 50-percent antecedent precipitation for PMP for areas larger than 25,000 sq mi appears reasonable in comparison to the 40 percent used in HMR 41 and HMR 45 for smaller areas.

Support From Precipitable Water Study

The adopted 50-percent antecedent percentage also appears reasonable based upon a separate study involving precipitable water and storm efficiency. Since all rainfall reduces basically to two factors, moisture and mechanism, it is possible to select a meteorological variable as an index to both mechanism and moisture. Surface vapor pressure (or dew point) is indicative of moisture only. However, when we consider an index of moisture through depth, such as precipitable water, we are implicitly obtaining an index to mechanism also. That is, with similar surface moisture conditions, one period may show a higher precipitable water than another with a similar surface moisture condition. The case with the higher total amount of precipitable water, then, can be looked upon as having some "mechanism" that distributes moisture through depth rather than restricting it through a lower layer. This upward movement of moisture is necessary for significant rainfall. Also, high values of moisture through depth cases can be associated with a broad, deep flow of moisture, which usually occurs in advance of frontal systems, or a flow above the immediate surface layer bringing moisture in and distributing it through the atmosphere. These types of cases indicate some mechanism that can cause precipitation as well as indicating higher moisture.

With the above in mind, a survey was made of persisting precipitable water values as an index of long-duration rainfall potential. Precipitable water data for Nashville (1946-65) were surveyed and periods where the total precipitable water in the atmosphere was in excess of 1 in. were selected. Long enough time intervals surrounding these periods were considered in order to evaluate antecedent plus basic PMP and TVA precipitation sequences. The precipitable water does not necessarily have to be consistently above the threshold value since antecedent rainfall periods may be separated by several essentially rainless days. March and the first half of April were chosen for this investigation because this is the season when the proposed large-area PMP would occur. All studies were based upon one observation a day at either 1200 or 1500 GMT.

Mean precipitable water was first determined for each peak of 1 in. or more of precipitable water for 2 or 3 days duration. The 3 preceding and 3 following days were alloted as drying intervals, and precipitable water means (expressed in percent of the peak 2- or 3-day mean values) were determined centered 5 days before and after the peak period. Interpolated values were used for missing data.

A total of 17 peak precipitable water cases with both antecedent and subsequent values were evaluated. Figure 6-3 shows plots of precipitable water for three March-April periods with some of the selected runs of high precipitable water indicated. Although there was much scatter, both the secondary antecedent and subsequent moisture peaks averaged 59 percent of the primary moisture peak. This study suggests that if precipitable water were used to maximum efficiency,* as in the PMP case, centered 5 days before the PMP (allowance for 3 dry days), the antecedent rainfall could readily be about 60 percent of the PMP. There are no known studies to indicate the efficiency of antecedent storms relative to PMP storms. The above results suggest that the previously adopted cool-season antecedent criteria of 40 percent of the PMP (HMR 41) is representative of storm conditions about two-thirds as efficient as the PMP. This seems to be realistic.

As the size of the drainage area increases from small areas of 100 sq mi or smaller to large areas of 10,000 to 20,000 sq mi or larger, the importance of thunderstorms in producing the PMP becomes less, although it does not completely disappear. For the larger areas, therefore, sequences of large-area storms, such as those described in Hydrometeorological Report Nos. 34 and 38 (U. S. Weather Bureau 1956, 1961) should be a major factor. For these sequences, an intense temperature gradient that can maintain itself in a nearly fixed geographic location becomes increasingly important. Thus, it is realistic to surmise that the antecedent storm responsible for large amounts of precipitation over a large area would be slightly more efficient than it would be for smaller areas. Increasing the antecedent precipitation percentage from 40 to 50 percent, therefore, appears to be in the right direction.

Upstream-Downstream Progression of Rainfall

A study was made of upstream and downstream progression of rainfall in and near the Tennessee River Watershed. Since a storm moving downstream will, in general, give a higher crest, downstream progression of storm rainfall is the more important hydrologically. The data used for the study consisted of 10 years of areal average daily rains computed for the total Tennessee River drainages above and below Chattanooga (supplied by TVA) and daily rainfall maps for the months of November through April for a 10-yr period (1954-63). From the TVA supplied data, all cases of rainfall averaging an inch or more above Chattanooga were categorized as to whether they preceded, coincided with, or followed rainfall below Chattanooga. The drainage area above Chattanooga is 21,400 sq mi and below about 19,000 sq mi. There were 43 cases of daily rainfall above Chattanooga meeting the established criteria of 1-in. average depth over the basin. None of these cases were followed the next day by heavy rains below Chattanooga. Some showed heavy rains on the downstream basin followed by heavy rains on the upstream basin.

Daily rainfall maps for the 10-yr period were also examined carefully. These also supported the conclusion that the heavy rains above Chattanooga

---

*Here, we mean mechanism operates in an optimum manner so that in the PMP storm the available moisture is being utilized to a maximum extent.

followed the heavy rains below Chattanooga. Even when the threshold was lowered and the requirement was that only one station have 1 in. or more of rain in the region above Chattanooga, upstream progression was still strongly favored.

However, when a significant dry interval is permitted, downstream progression becomes possible. For the purposes of this report, therefore, especially when large drainage areas are of concern, as for the Kentucky Dam project, some allowance for downstream progression could be made. This is particularly true for the combined PMP and antecedent rainfall event. This is a maximization step that can appropriately be applied to PMP but not TVA precipitation.

Application of Results

From the conclusions discussed above and evaluation of other antecedent rainfall studies for various TVA basins, the following recommendations are made for the large area involved in the estimate for the large drainage area above Kentucky Dam:

1. Antecedent rainfall for PMP should be 50 percent of 3-day PMP.
2. Antecedent rainfall for TVA precipitation should be 25 percent of 3-day TVA precipitation.
3. A dry interval of at least 3 days should precede both the probable maximum and TVA precipitation.
4. Uniform areal distribution should be used for rainfall antecedent to TVA precipitation.
5. For rainfall antecedent to PMP, in addition to trying uniform areal distribution, the rainfall may be patterned after the PMP and shifted upstream below the major tributary dams. To do this, adjustments are needed for geographical relocation and for isohyetal pattern orientation. These adjustments have been provided in previous chatpers.

This final recommendation (No. 5) on PMP antecedent precipitation derived from the previously discussed study of upstream and downstream progression and from a review of the Cumberland study (U. S. Weather Bureau 1955) hypothetical sequences in which some downstream progression was permitted.

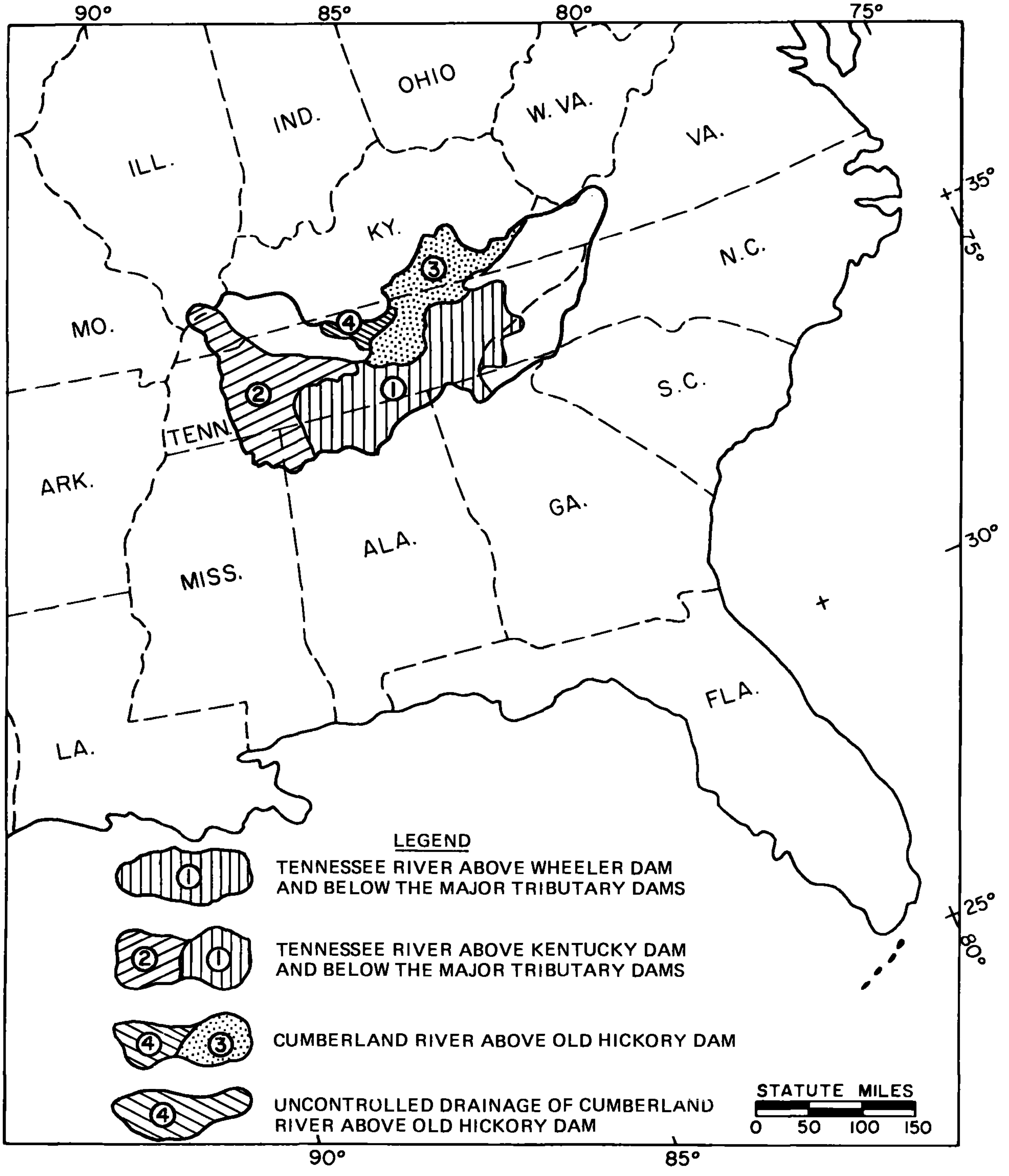


Figure 1-1.--Location of four basins for which PMP and TVA precipitation are provided.

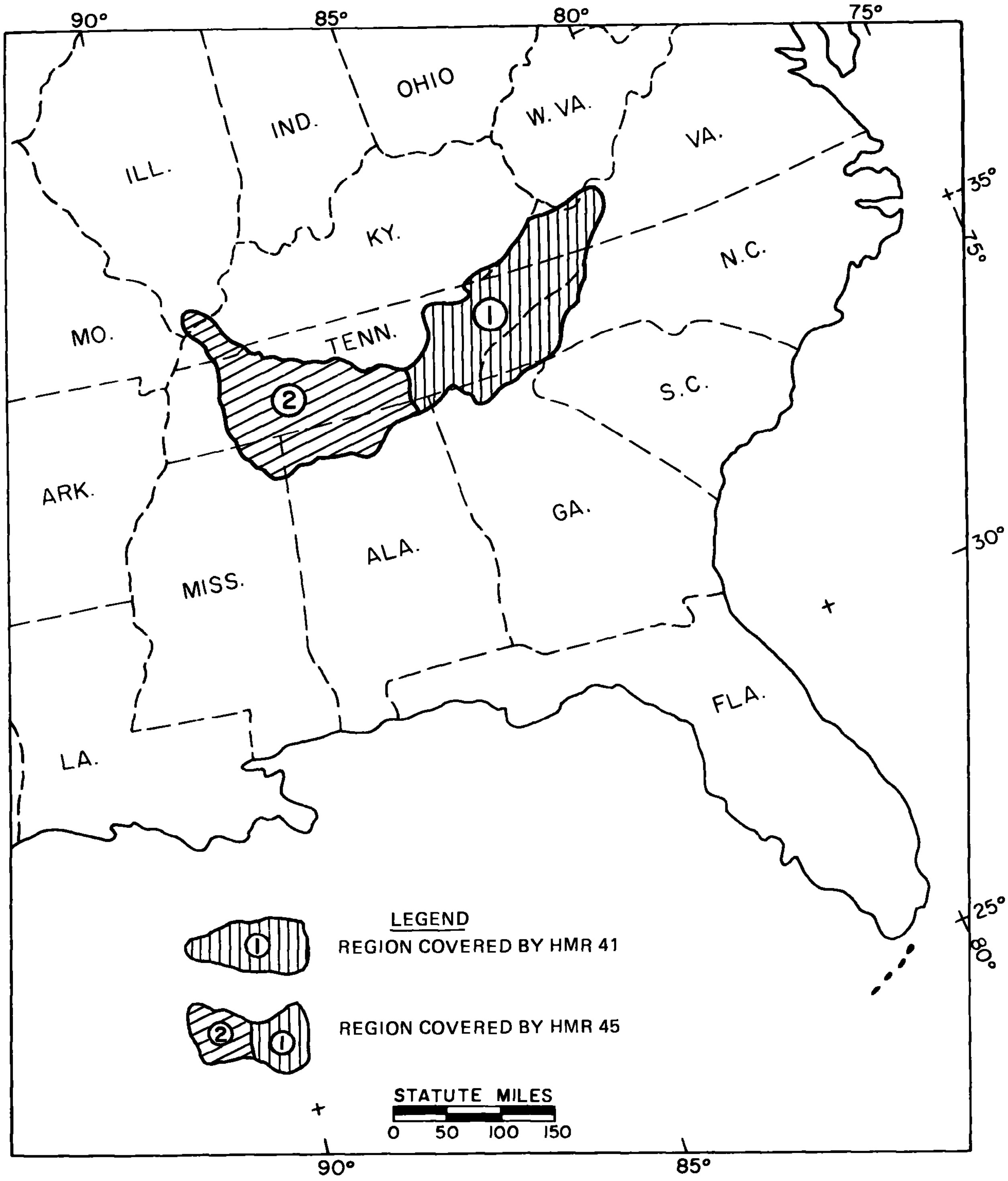


Figure 1-2.--Regions for PMP and TVA precipitation estimates covered by Hydrometeorological Report Nos. 41 and 45.

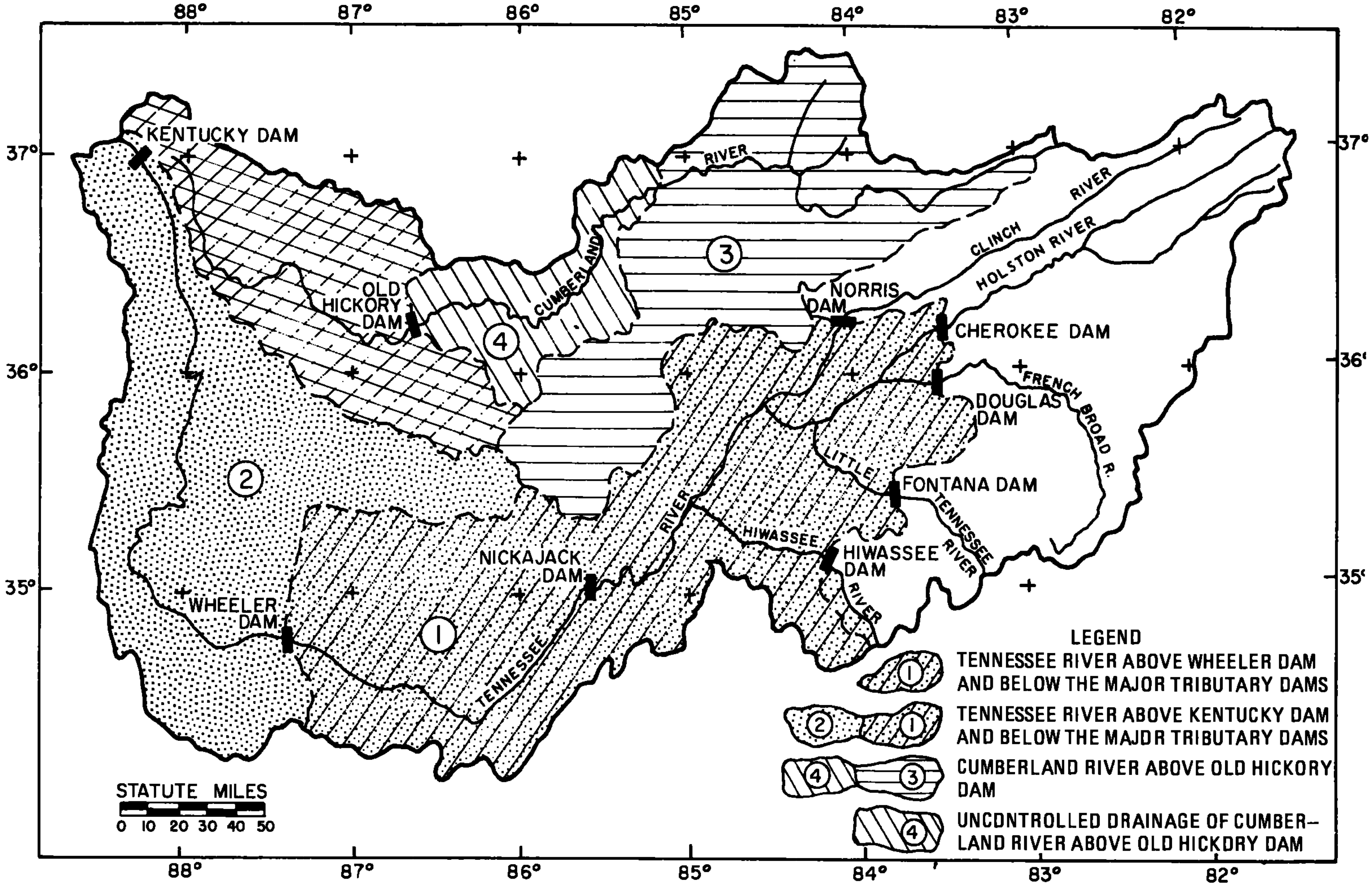


Figure 2-1.--Detailed map of basins for which PMP and TVA precipitation estimates are furnished in this report. The two major watersheds and dam sites important to the report are shown.

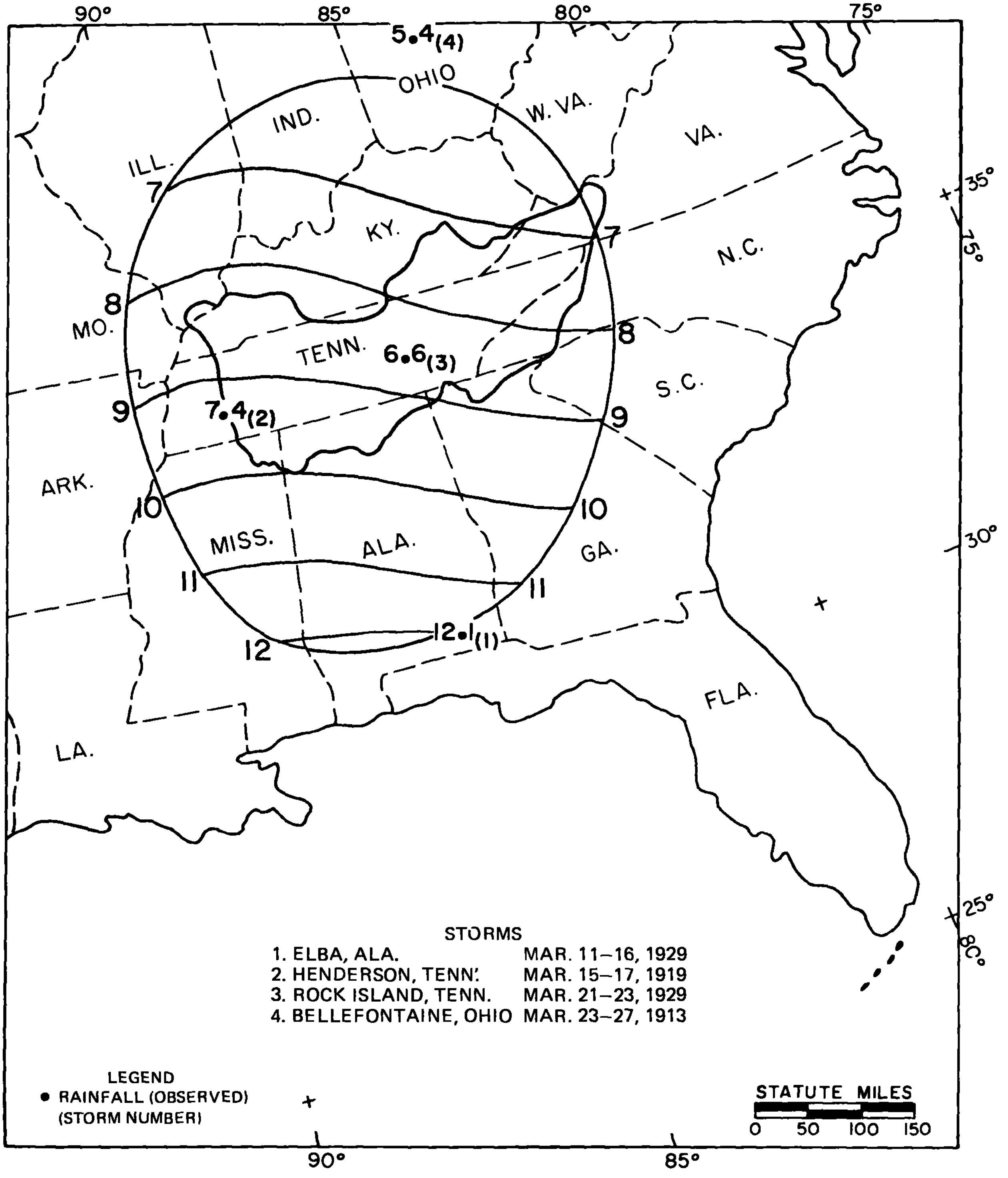


Figure 3-1.—March 24-hr 10,000-sq-mi TVA precipitation (in). This figure was adopted from Hydrometeorological Report No. 41 (fig. 5-2).

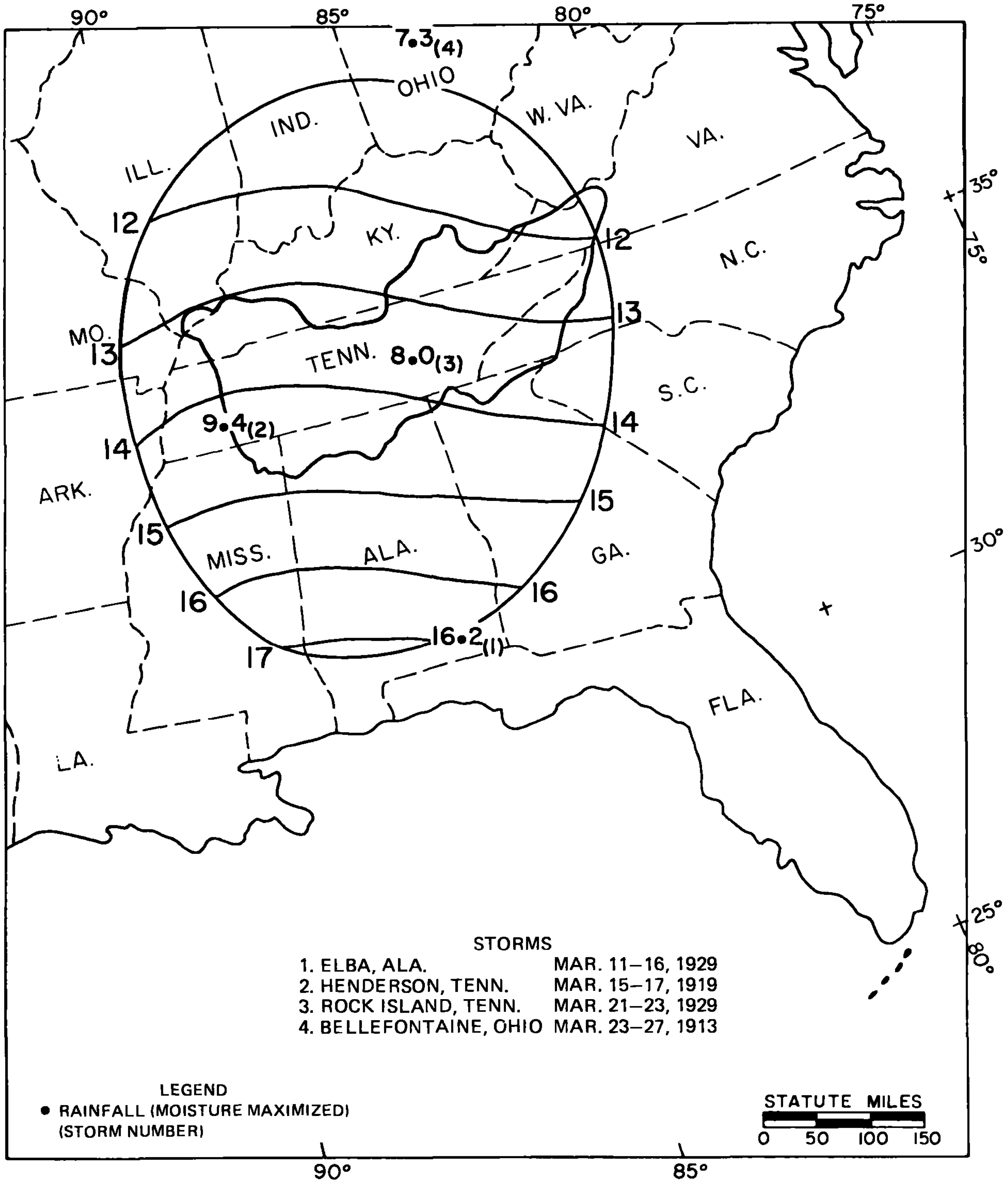


Figure 3-2.--March 24-hr 10,000-sq-mi PMP (in). This figure was adopted from HMR No. 41 (fig. 5-3).

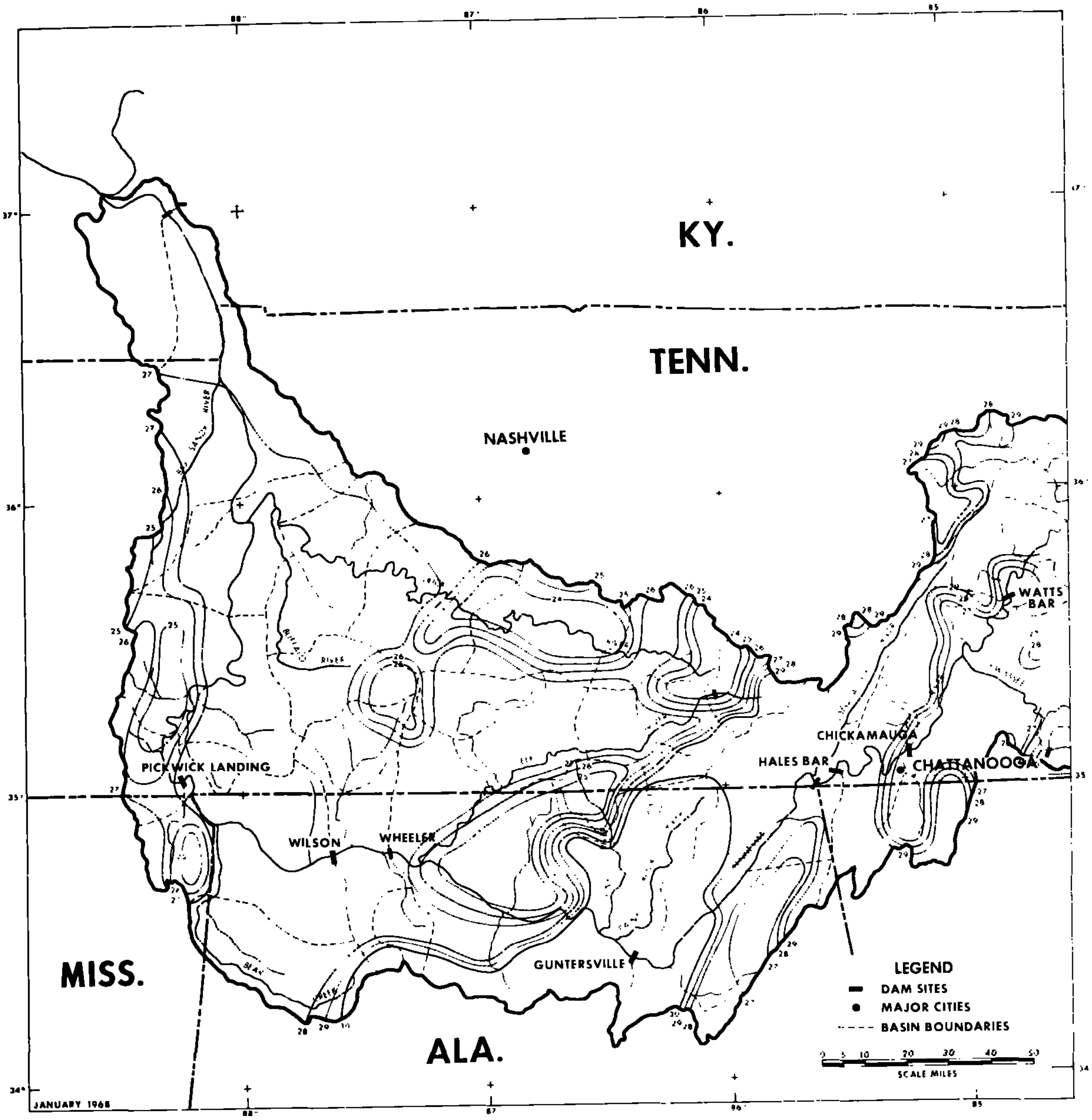


Figure 3-3.--6-hr 5-sq-mi PMP (in) - western half of Tennessee River Watershed (from HMR No. 45, fig. 2-21a).

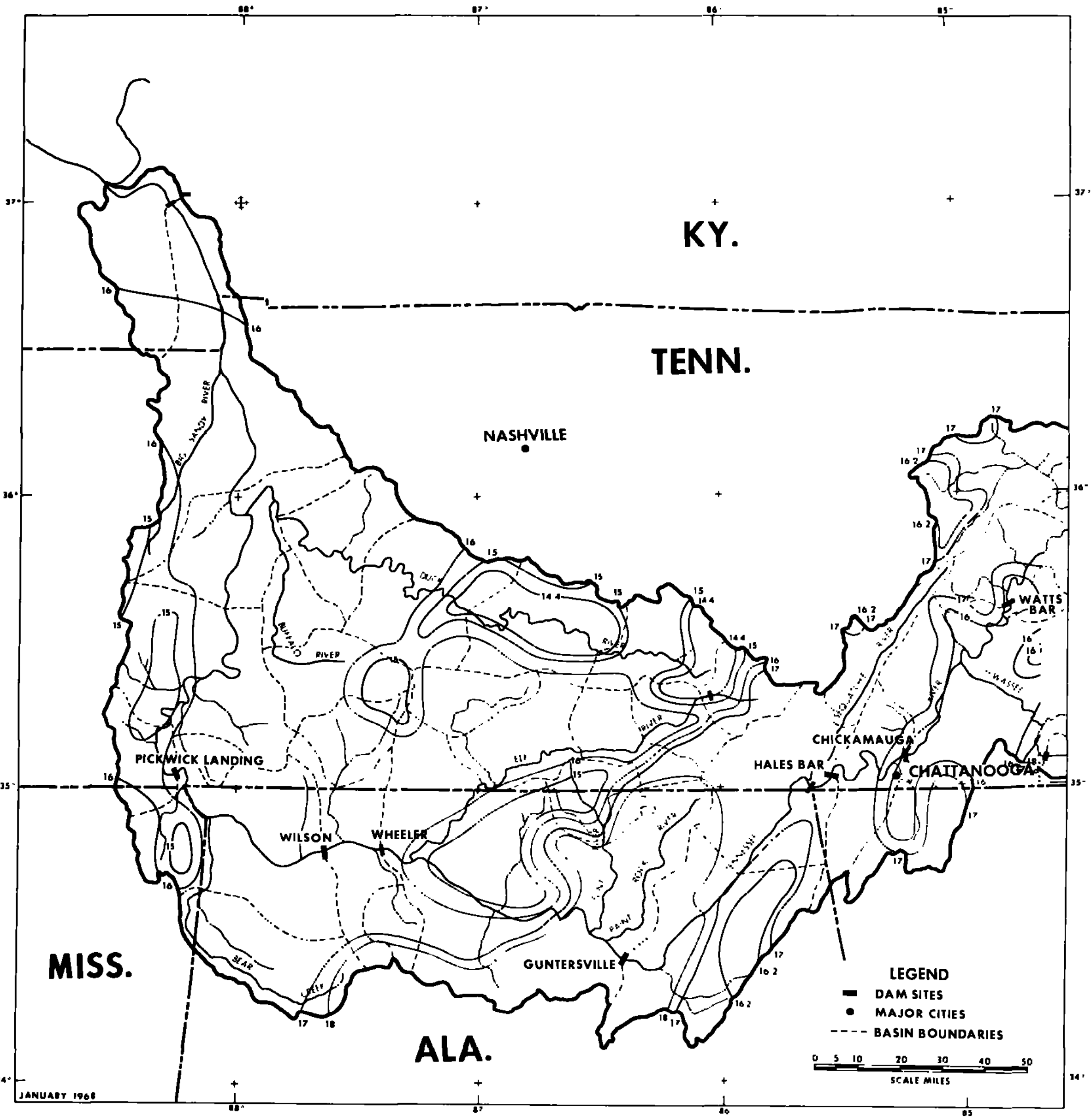


Figure 3-4.—6-hr 5-sq-mi TVA precipitation (in) - western half of Tennessee River Watershed (from HMR No. 45, fig. 2-22a).

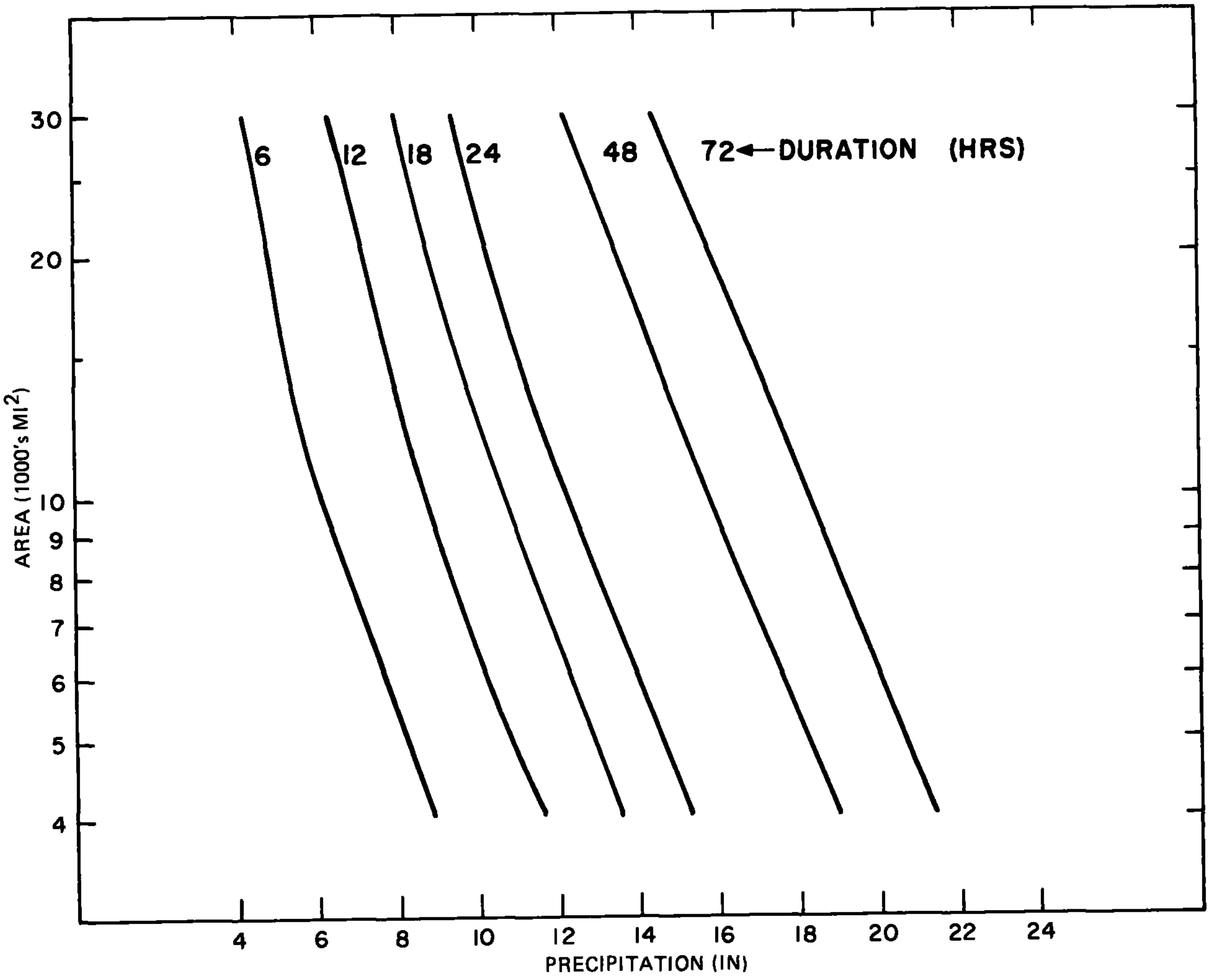


Figure 3-5.--Depth-area-duration curves of PMP for (1) Tennessee River Basin between Wheeler Dam and major tributary dams with rainfall centered at Nickajack Dam and (2) for Tennessee River Basin between Kentucky Dam and major tributary dams with rainfall centered at Fayetteville, Tenn.

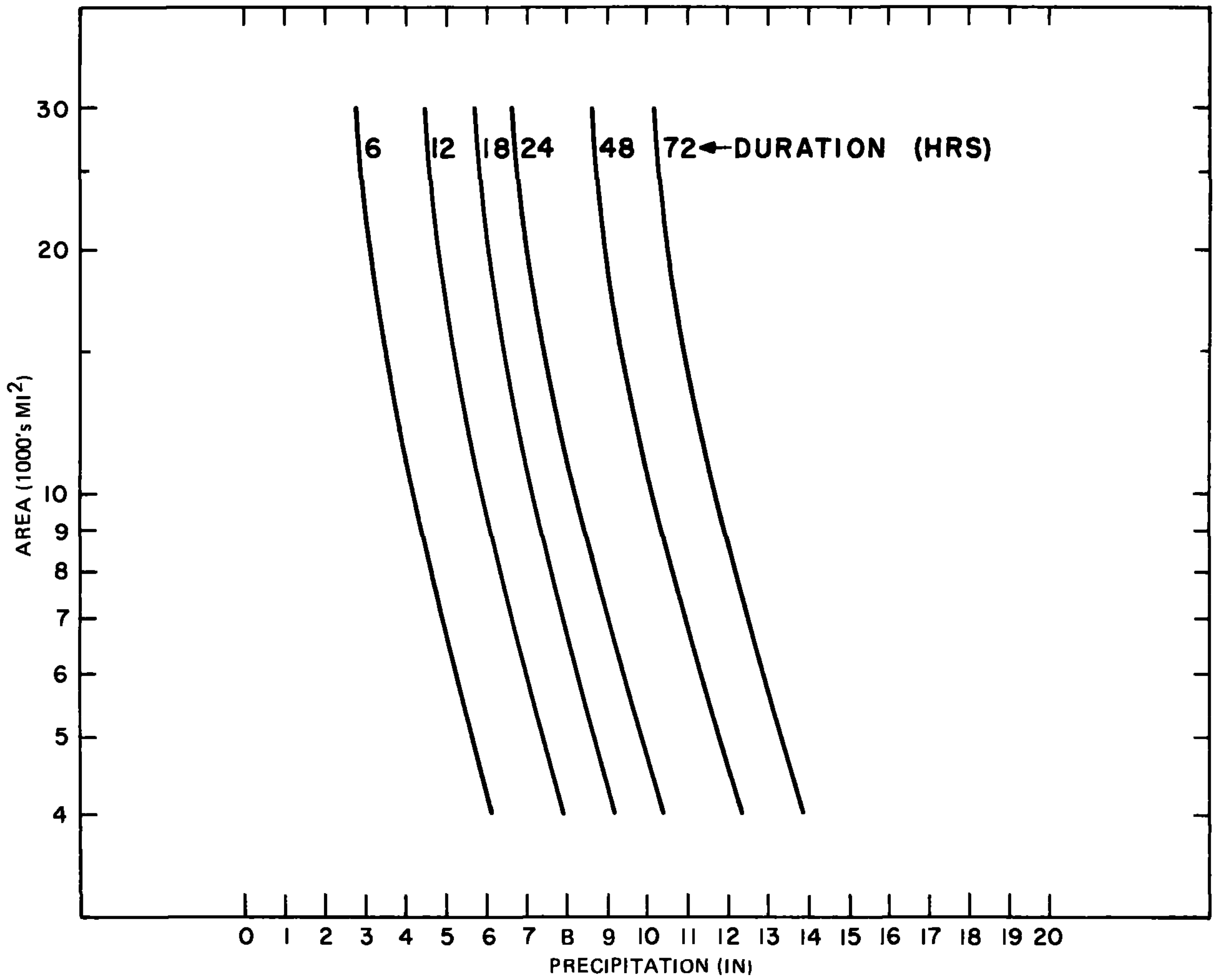
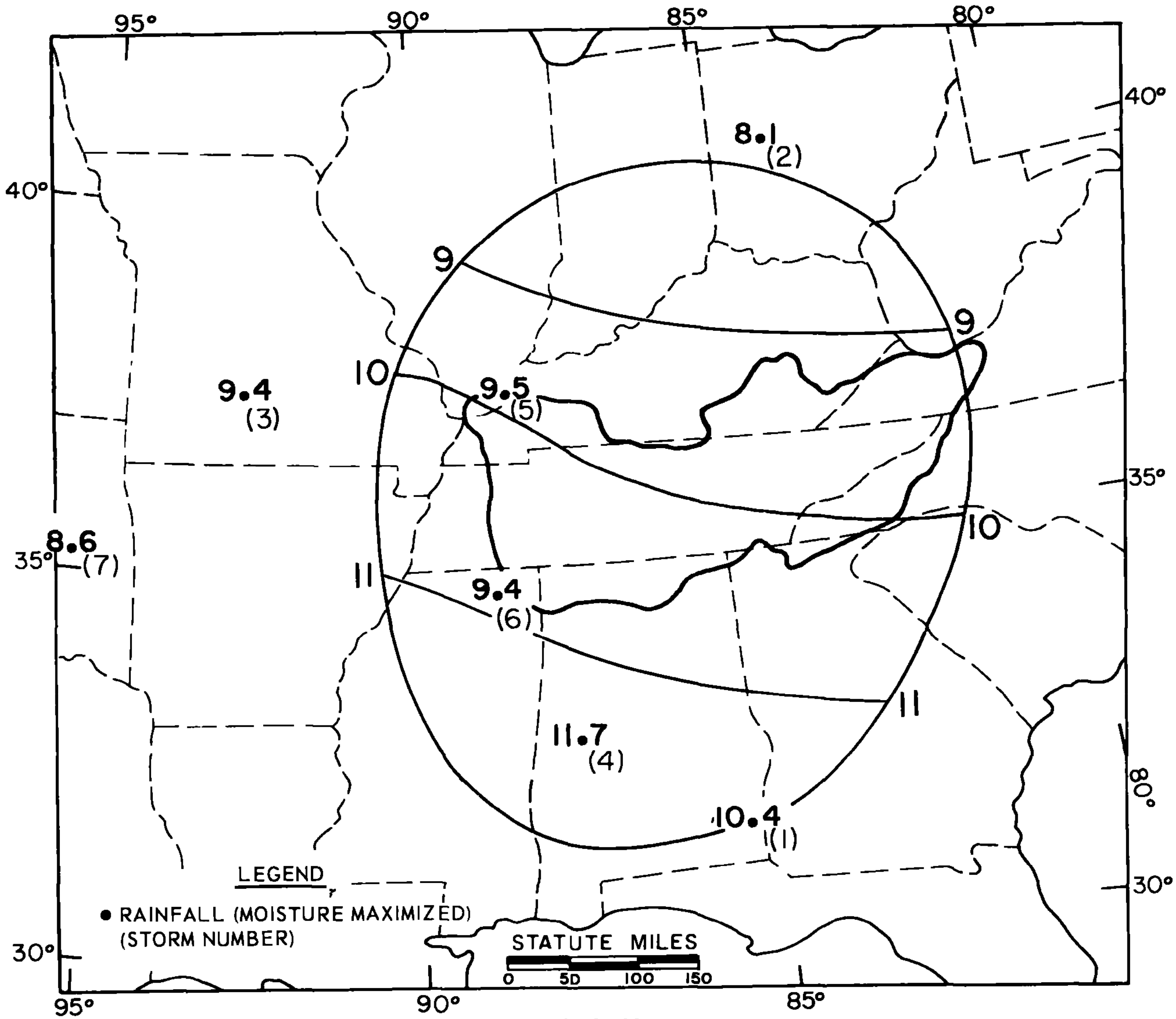


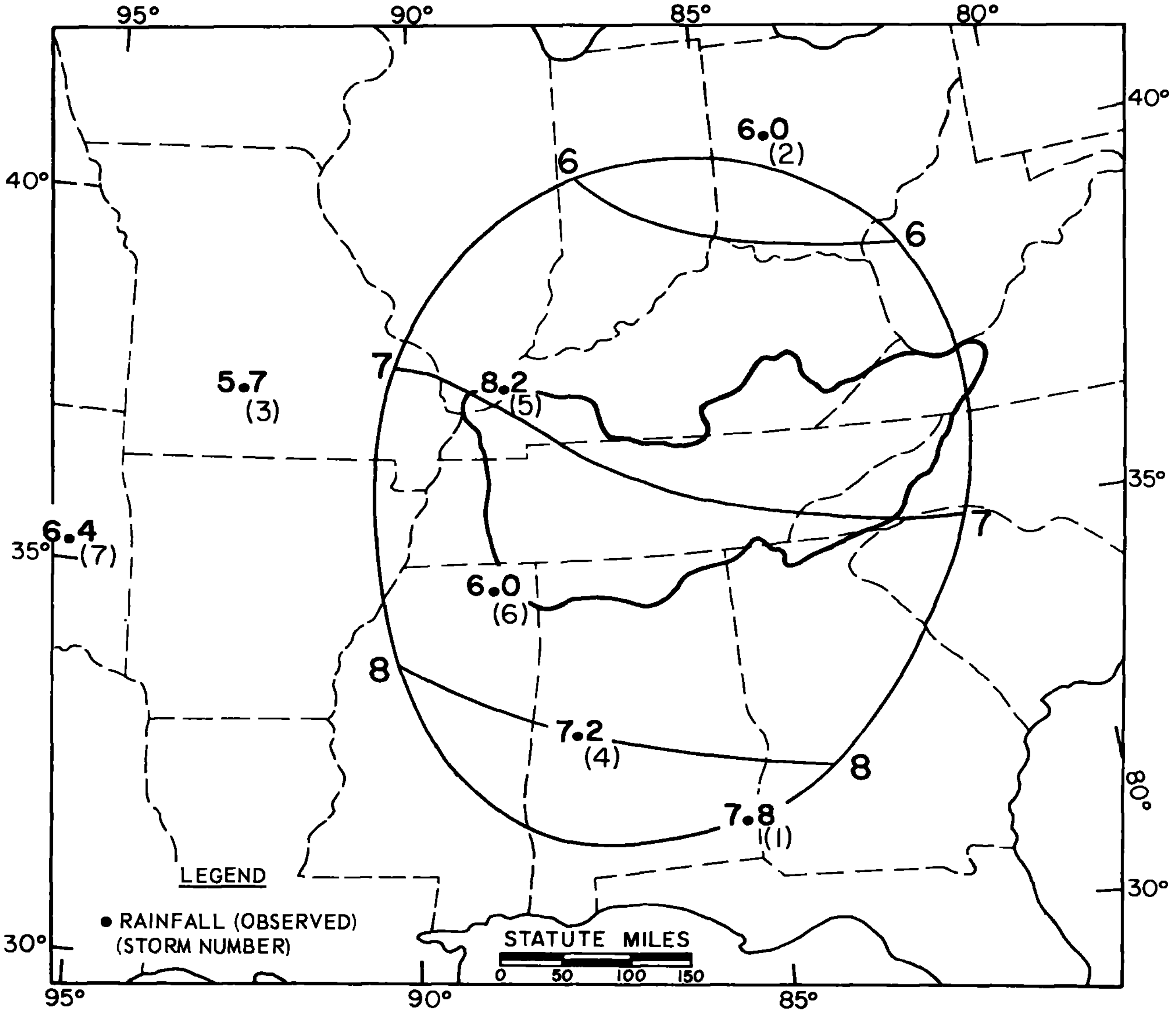
Figure 3-6.--Depth-area-duration curves of TVA precipitation for (1) Tennessee River Basin between Wheeler Dam and major tributary dams with rainfall centered at Nickajack Dam and (2) Tennessee River Basin between Kentucky Dam and major tributary dams with rainfall centered at Fayetteville, Tenn.



STORMS

1. ELBA, ALA.	MAR. 11–16, 1929
2. BELLEFONTAINE, OHIO	MAR. 23–27, 1913
3. PHILLIPSBURG, MO.	DEC. 16–20, 1895
4. EUTAW, ALA.	APR. 15–18, 1900
5. GOLCONDA, ILL.	OCT. 3–6 , 1910
6. RIPLEY, MISS.	MAR. 25–29, 1902
7. WARNER, OKLA.	MAY 6–12, 1943

Figure 3-7.—March 72-hr 100,000-sq-mi PMP (in.). Lines of generalized PMP come from moisture-maximized rainfall in major large-area storms in and surrounding the Tennessee and Cumberland River Watersheds.



STORMS

1. ELBA, ALA.	MAR. 11–16, 1929
2. BELLEFONTAINE, OHIO	MAR. 23–27, 1913
3. PHILLIPSBURG, MO.	DEC. 16–20, 1895
4. EUTAW, ALA.	APR. 15–18, 1900
5. GOLCONDA, ILL.	OCT. 3–6 , 1910
6. RIPLEY, MISS.	MAR. 25–29, 1902
7. WARNER, OKLA.	MAY 6–12, 1943

Figure 3-8.--March 72-hr 100,000-sq-mi TVA precipitation (in.). Lines of generalized TVA precipitation come from rainfall in major large-area storms in and around the Tennessee and Cumberland River Watersheds.

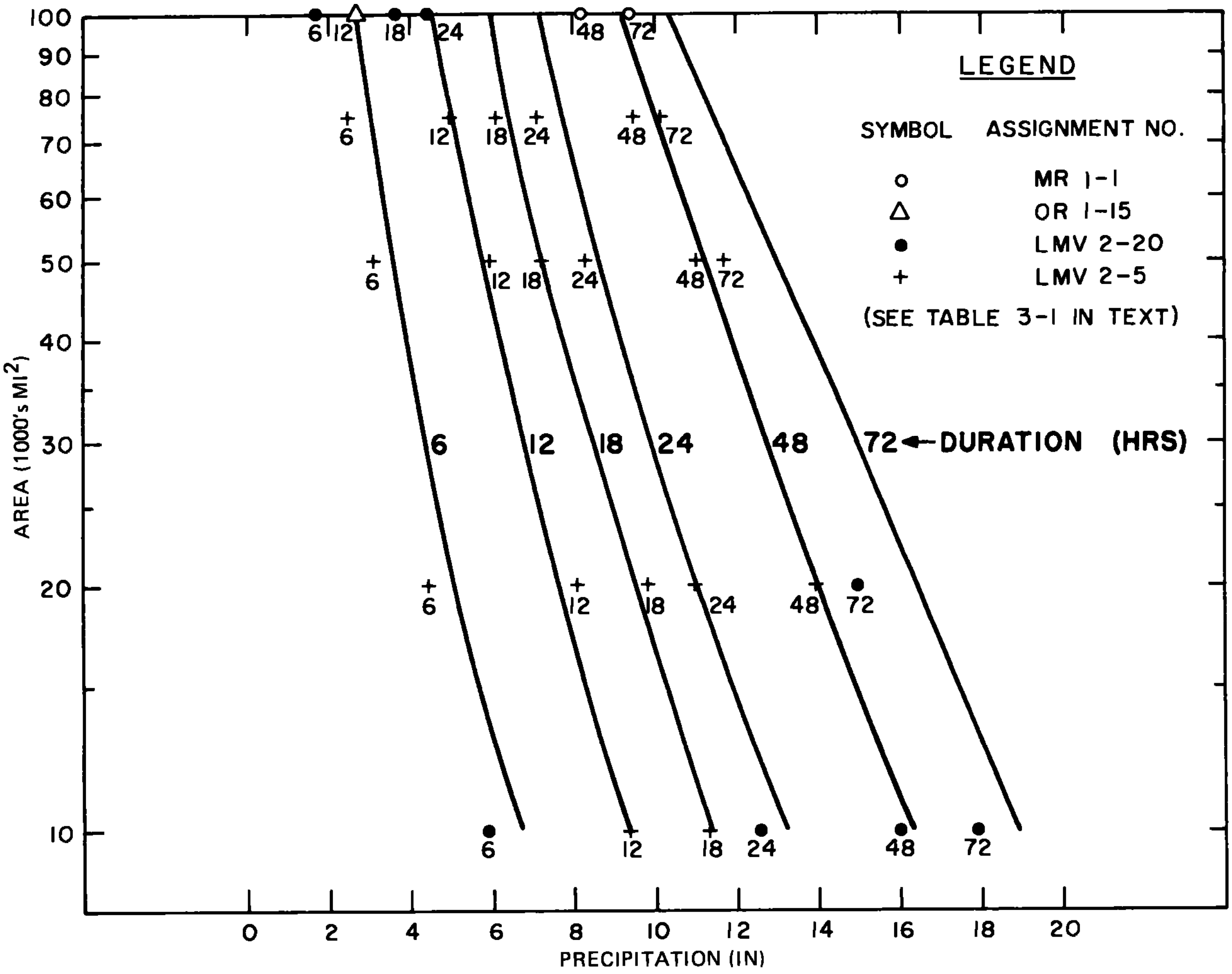


Figure 3-9.--PMP depth-area-duration curves applicable to rainfall centered at Fayetteville, Tenn. (35°10'N, 86°33'W). The curves are an extension to 100,000 sq mi of those shown in figure 3-5. Moisture-maximized storm rainfall values (adjusted to Fayetteville) are plotted on the figure.

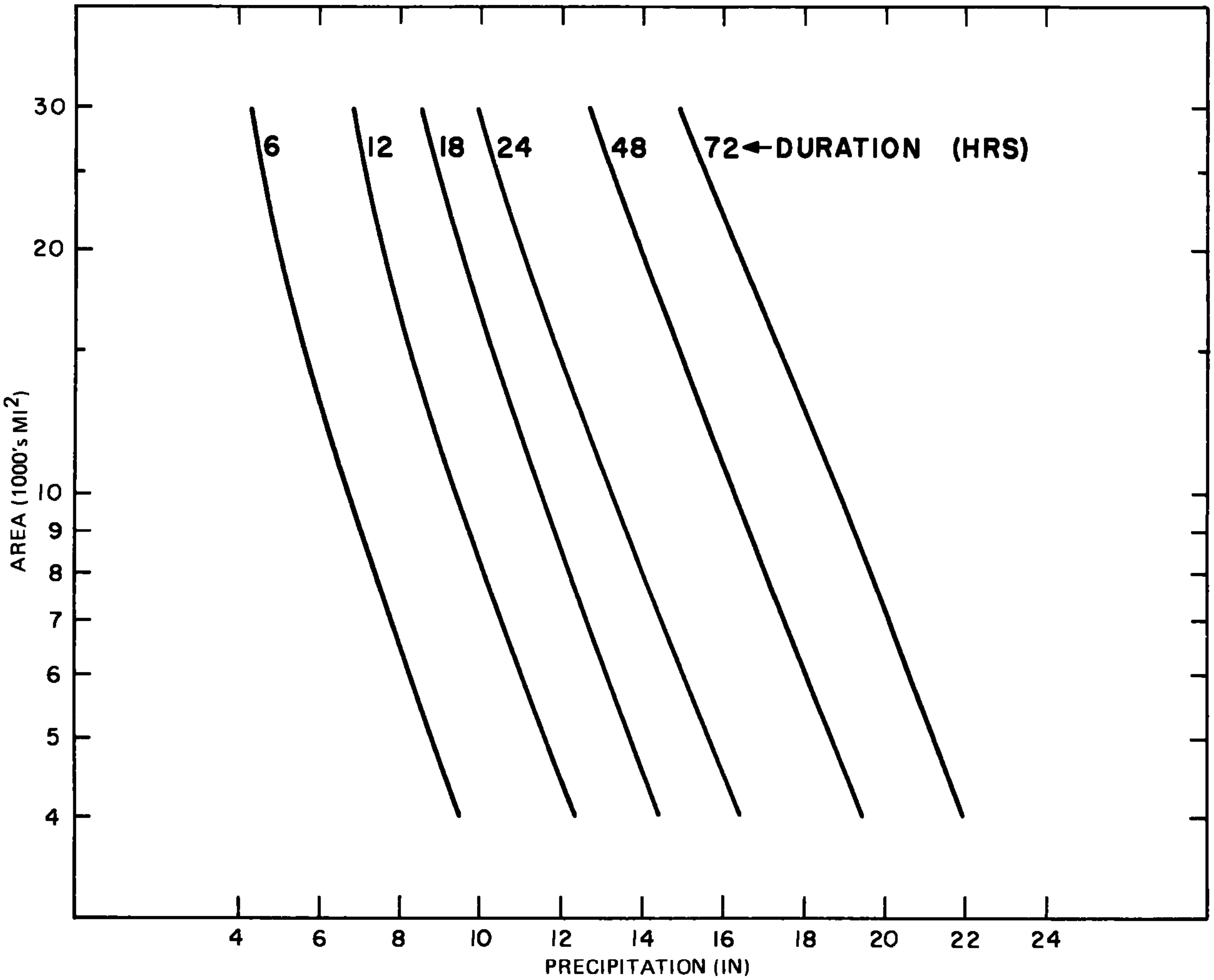


Figure 3-10.--PMP depth-area-duration curves applicable to rainfall centered at 36°38'N and 85°00'W. These are for the 11,674-sq-mi drainage above Old Hickory Dam.

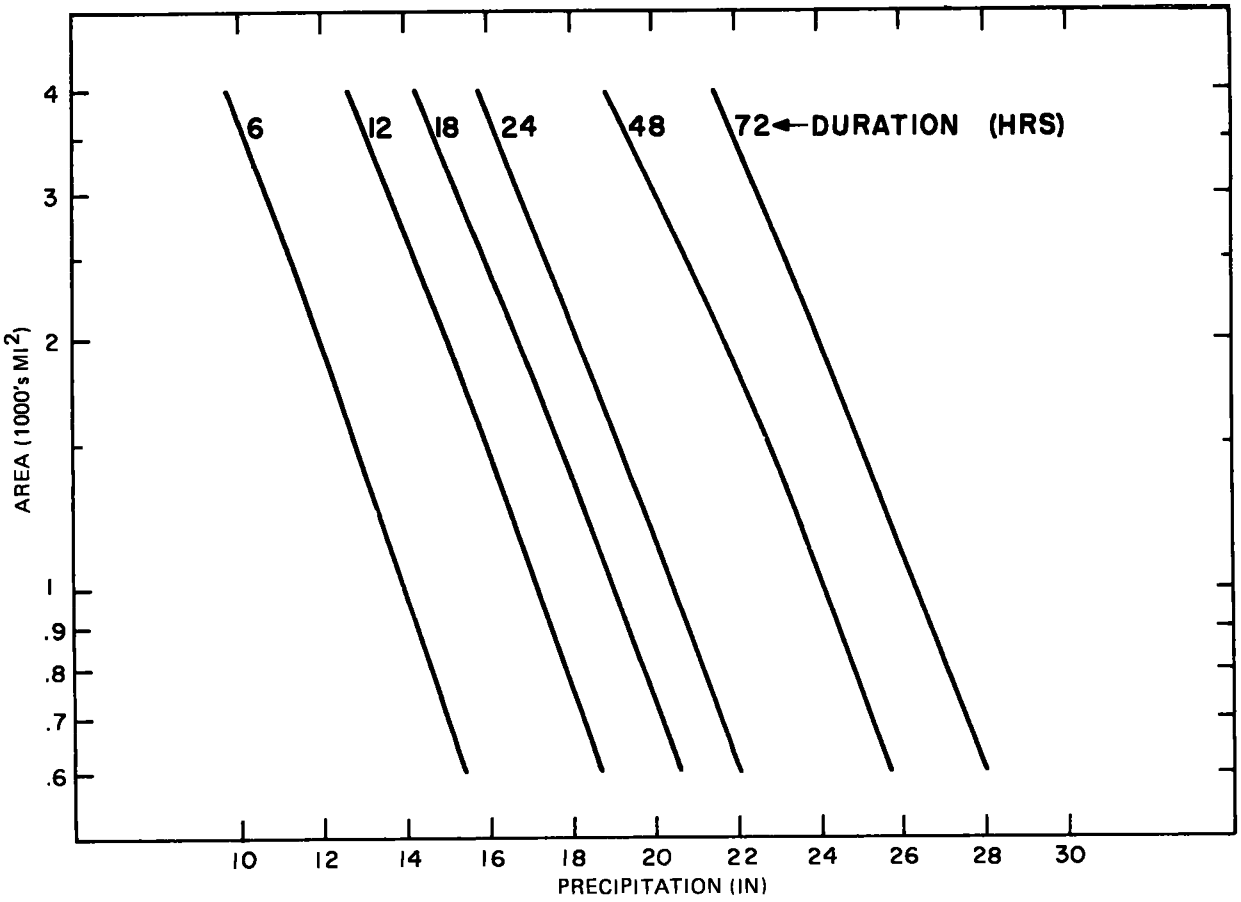


Figure 3-11.--PMP depth-area-duration curves applicable to rainfall centered at 36°18'N, 85°46'W. These are for the 2734-sq-mi uncontrolled drainage above Old Hickory Dam. They are derived from warm-season storms.

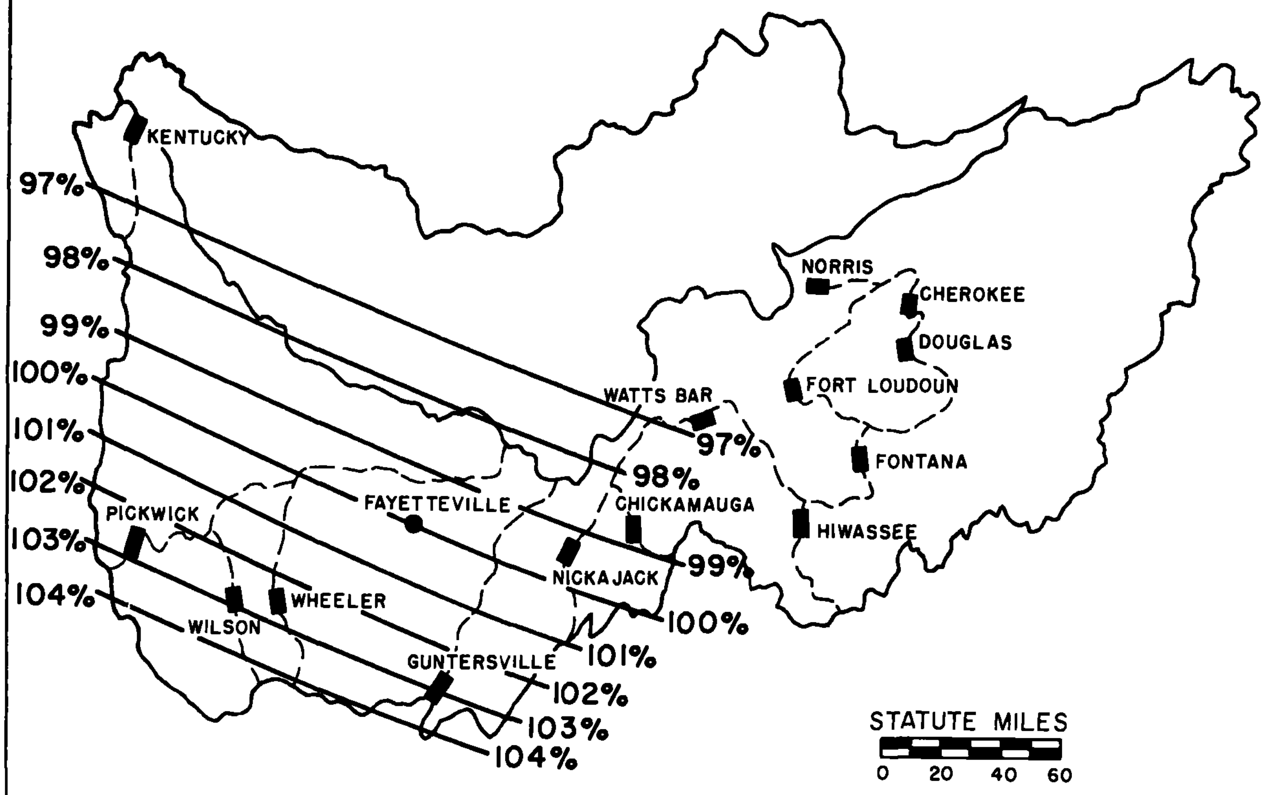


Figure 3-12.--Geographical adjustments for transposing rainfall from Fayetteville to the 26,780-sq-mi drainage above Kentucky Dam.

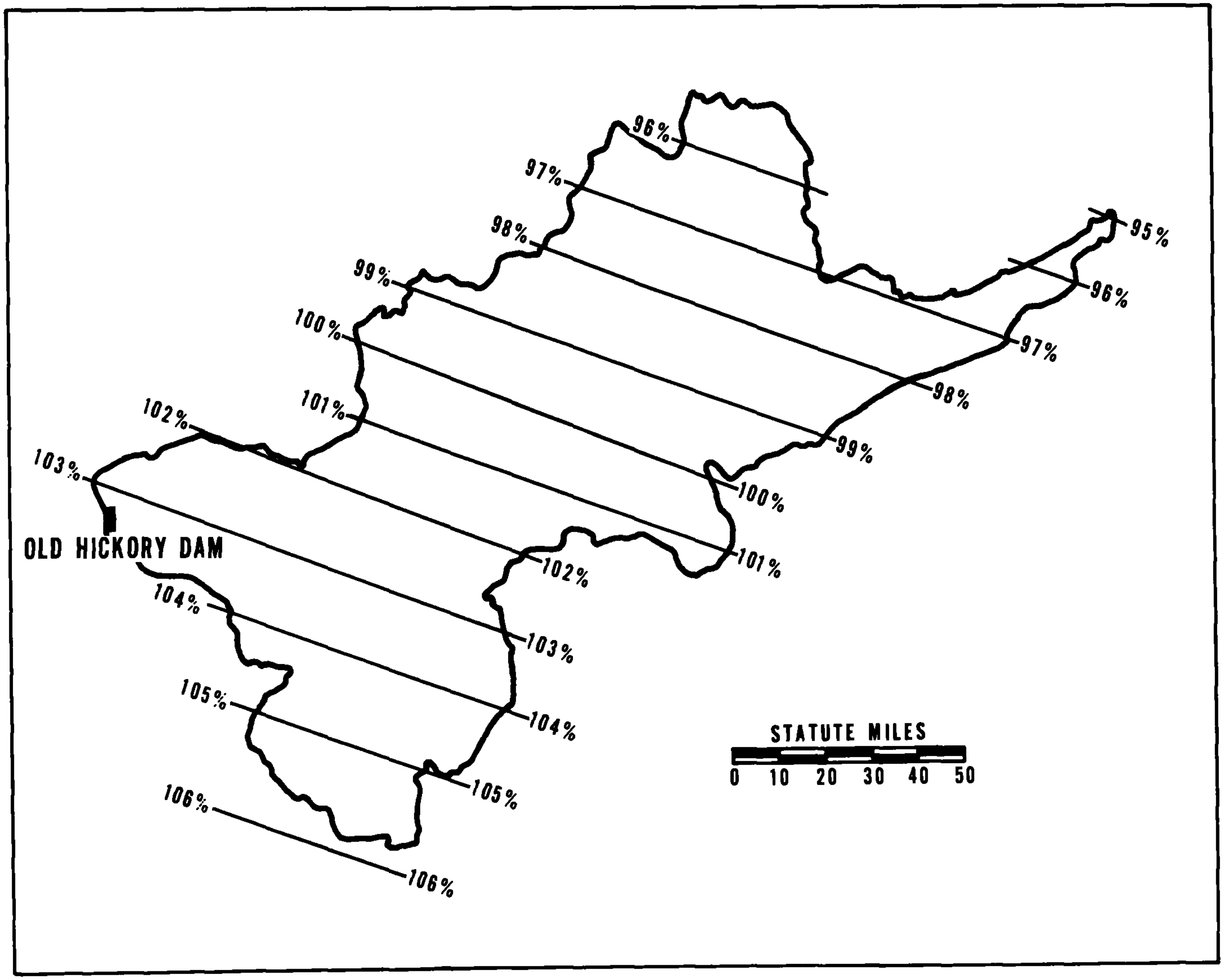


Figure 3-13.--Geographical adjustments for transposing PMP from 36°38'N, 85°00'W to points within the 11,674-sq-mi drainage above Old Hickory Dam.

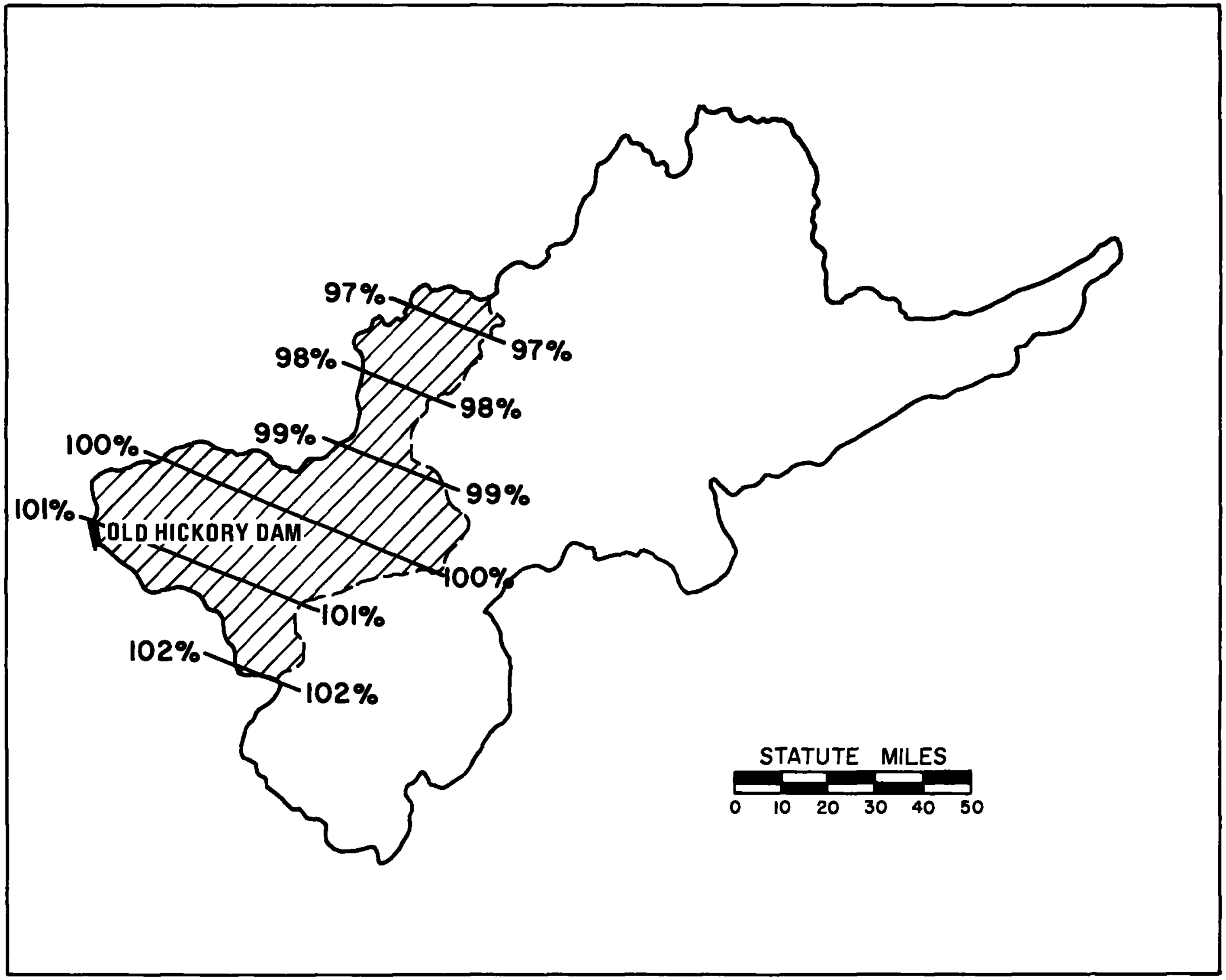


Figure 3-14.--Geographical adjustments for transposing PMP from 36°18'N, 85°46'W to points within the 2734-sq-mi uncontrolled drainage above Old Hickory Dam.

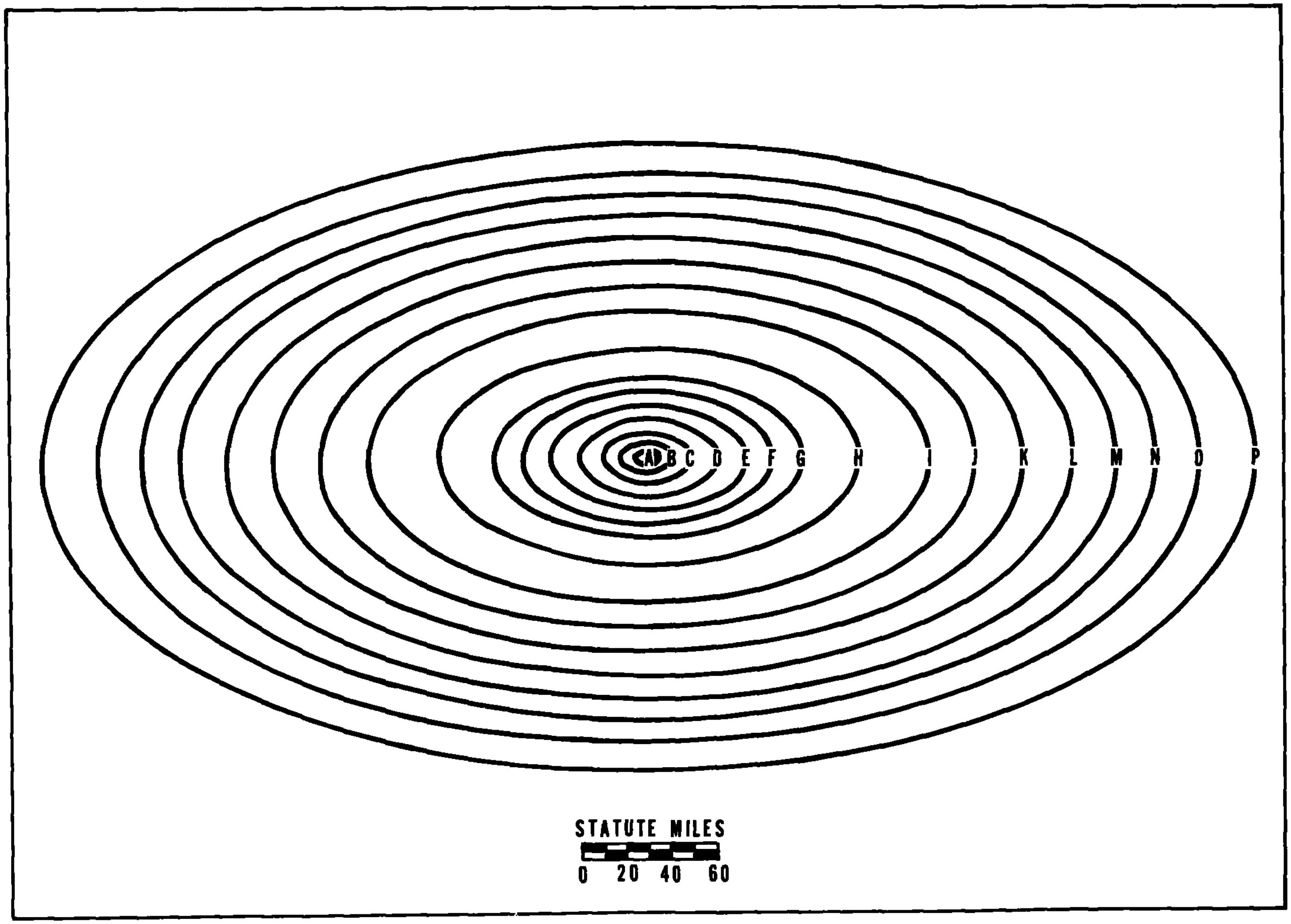


Figure 5-1.--Generalized storm pattern with a major-to-minor axis ratio of 2:1. The total pattern (118,960-sq-mi) is used for the applicable drainage above Kentucky Dam (tables 5-3 and 5-4). The pattern out to isohyet "I" is used for the other basin estimates and is the basis for patterns in figures 5-2 to 5-4 (enlarged scale).

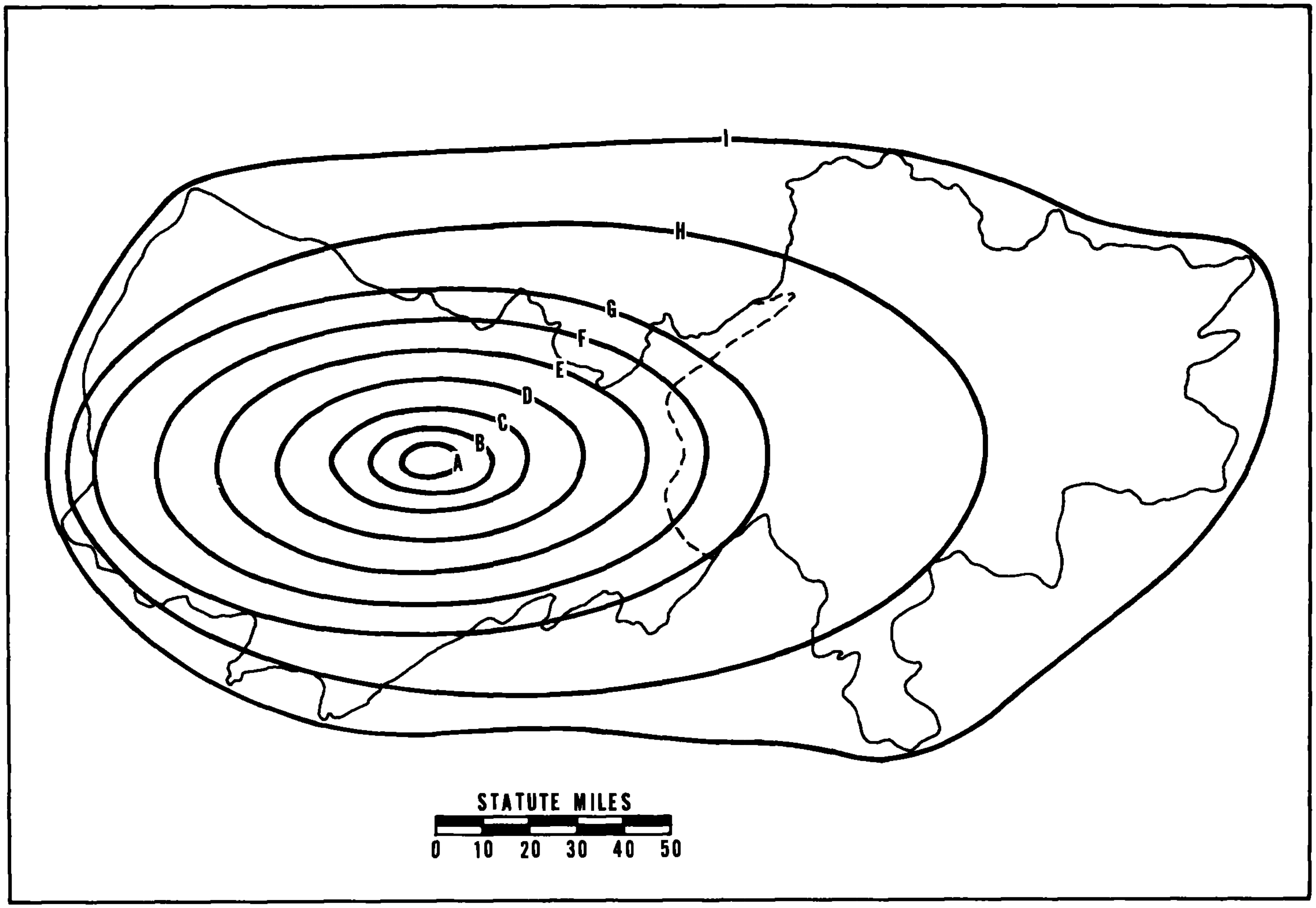


Figure 5-2.--Modified storm pattern for the 16,170-sq-mi drainage above Wheeler Dam centered near Nickajack Dam. Outer isohyets have been warped to reduce the "basin-shape" factor.

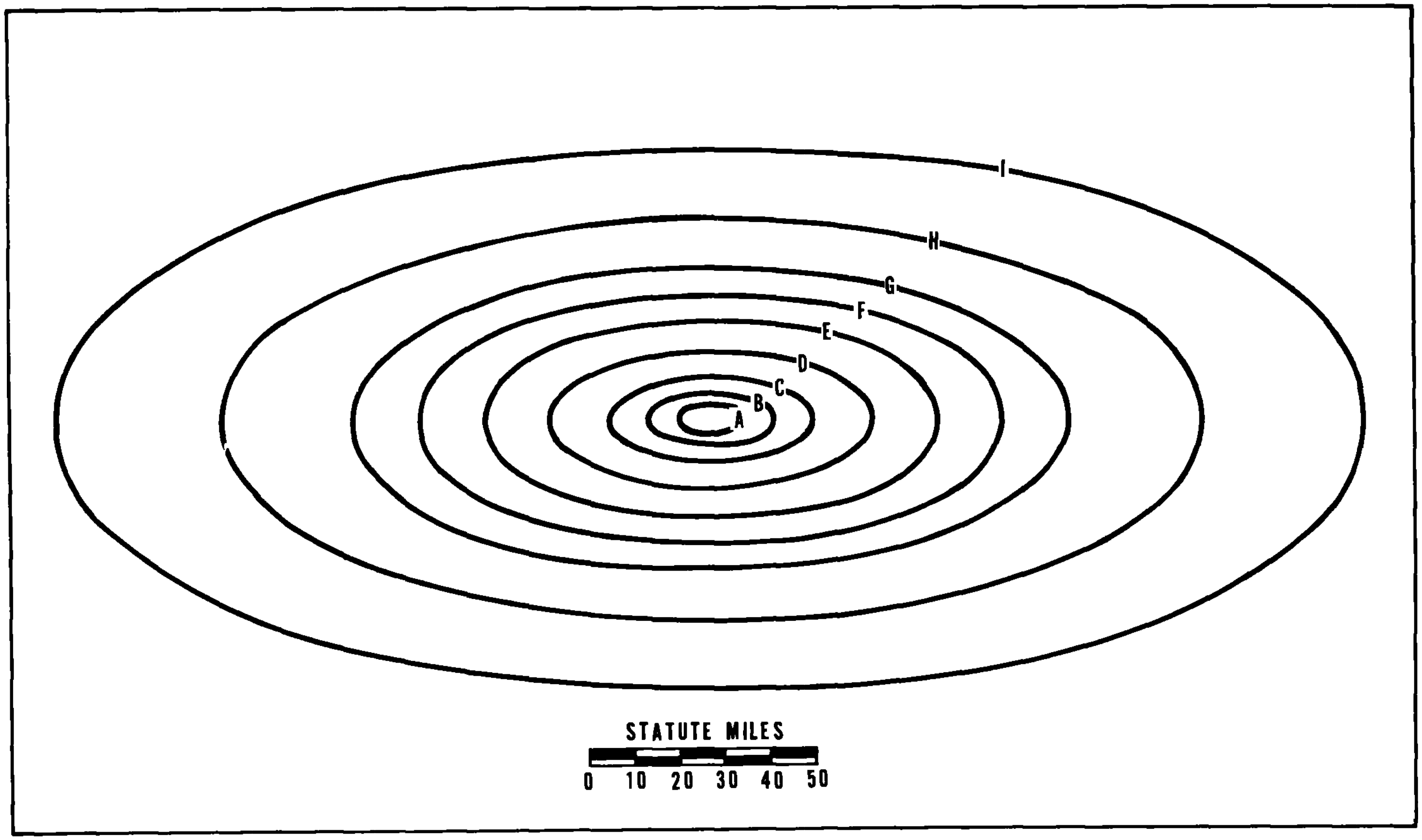


Figure 5-3.--Generalized storm pattern with a major-to-minor axis ratio of 5:2. This is an alternate pattern used only for the 16,170-sq-mi drainage above Wheeler Dam.

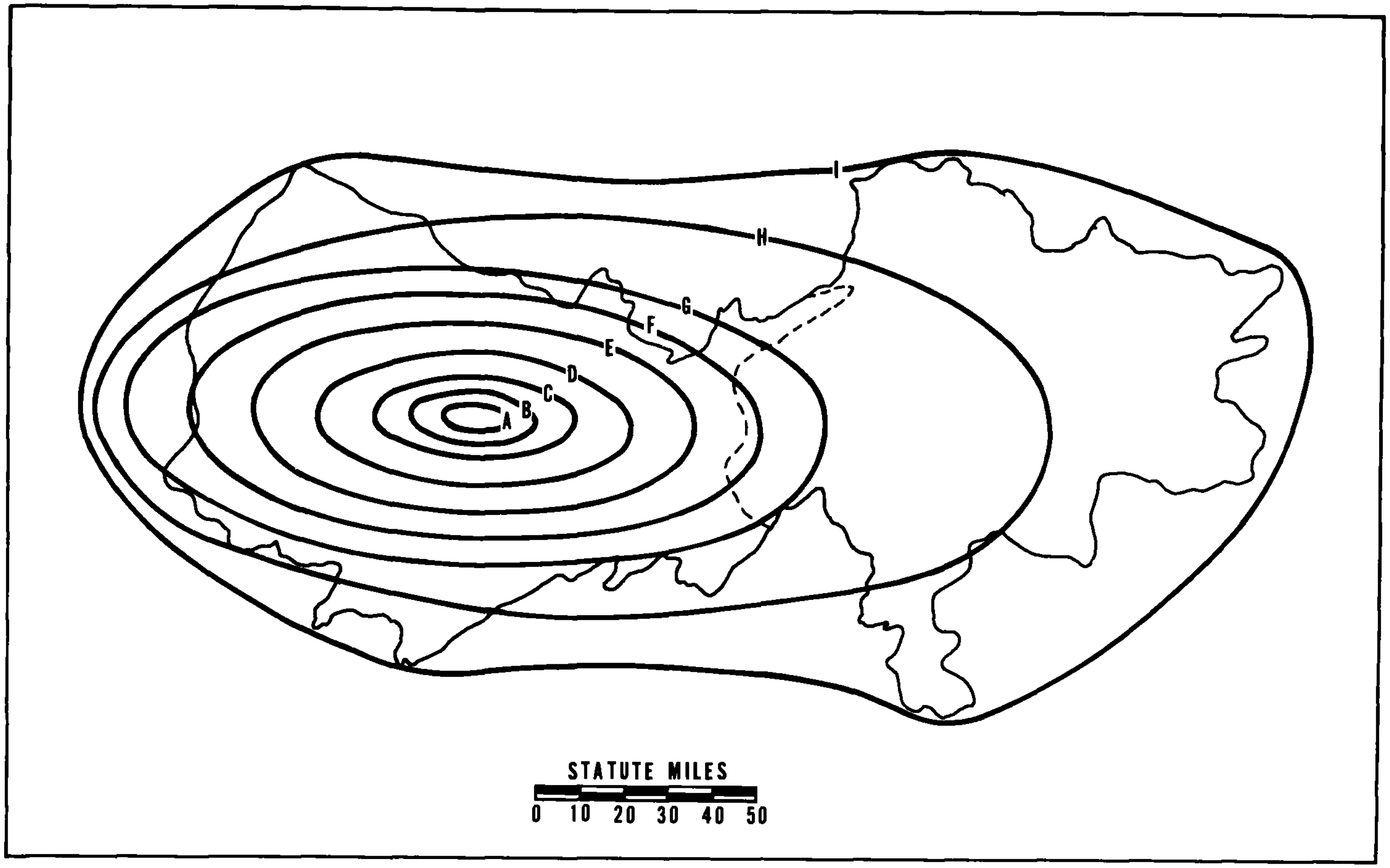


Figure 5-4.--Modified storm pattern based on figure 5-3 and used only for the 16,170-sq-mi drainage above Wheeler Dam.

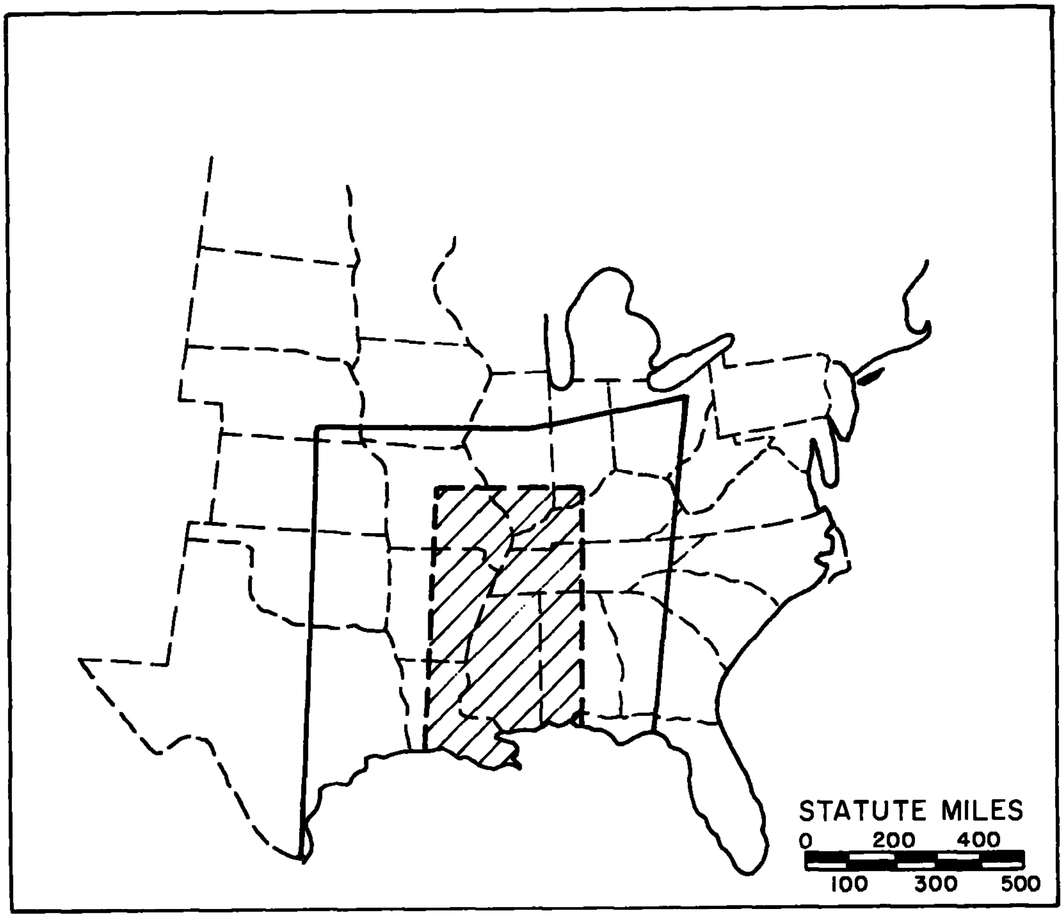


Figure 5-5.—Regions used for storm selection in isohyetal orientation study. The center of the rainfall had to be within the borders of the larger area in the figure. Furthermore, a significant portion of the isohyetal pattern had to fall within the hatched area.

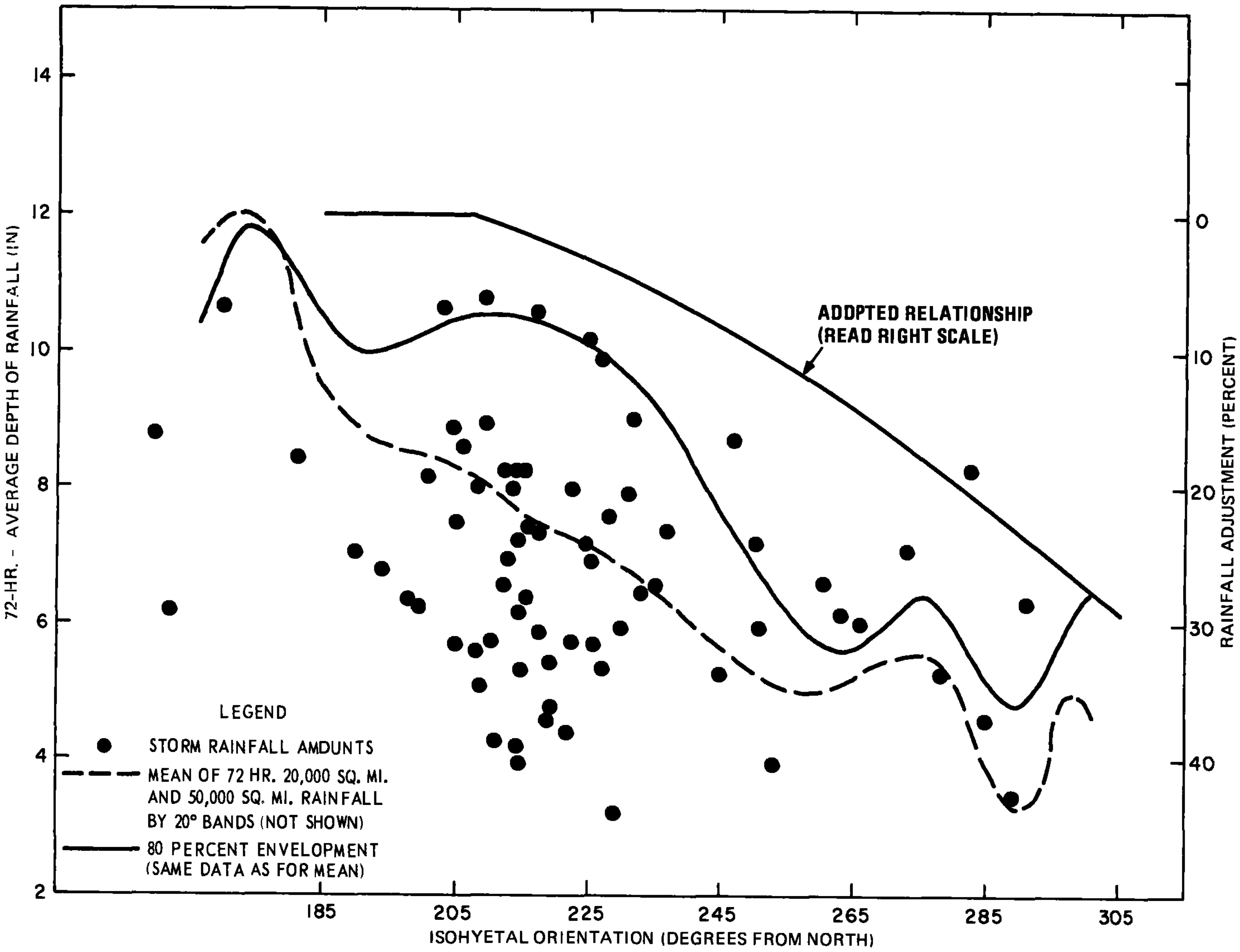


Figure 5-6.—72-hr rainfall versus orientation of major axis of isohyetal pattern. Adopted curve shown. Although only the 20,000-sq-mi 72-hr rain data are shown on this figure, means (of mean and 80% envelopment data) are for both 50,000 and 20,000-sq-mi data.

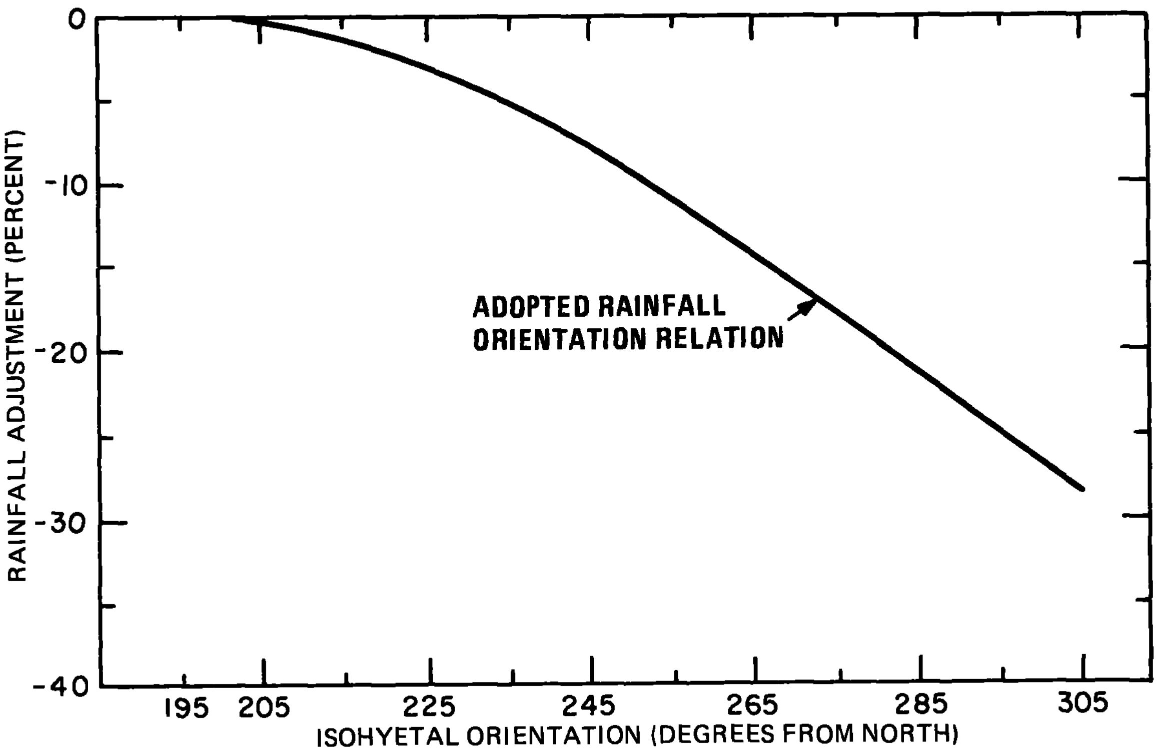


Figure 5-7.--Smoothed adopted isohyetal orientation rainfall adjustment.

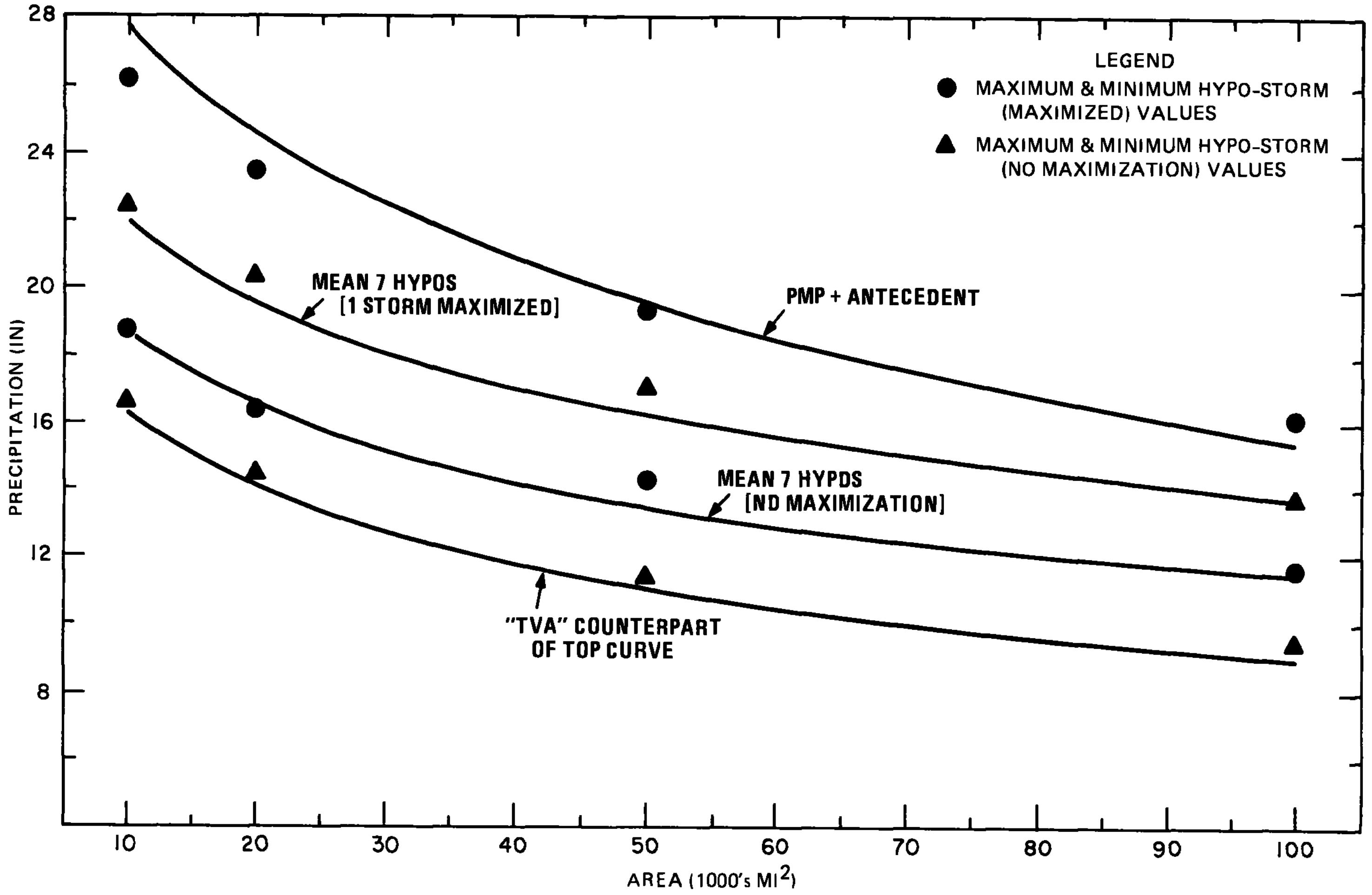


Figure 6-1.--Depth-area relations for 9-day hypothetical sequences and comparisons with adopted PMP and TVA precipitation plus dry internal and antecedent rainfall. The upper mean of 7 hypothetical sequences are from sequences in which one storm, in each case, was maximized for moisture.

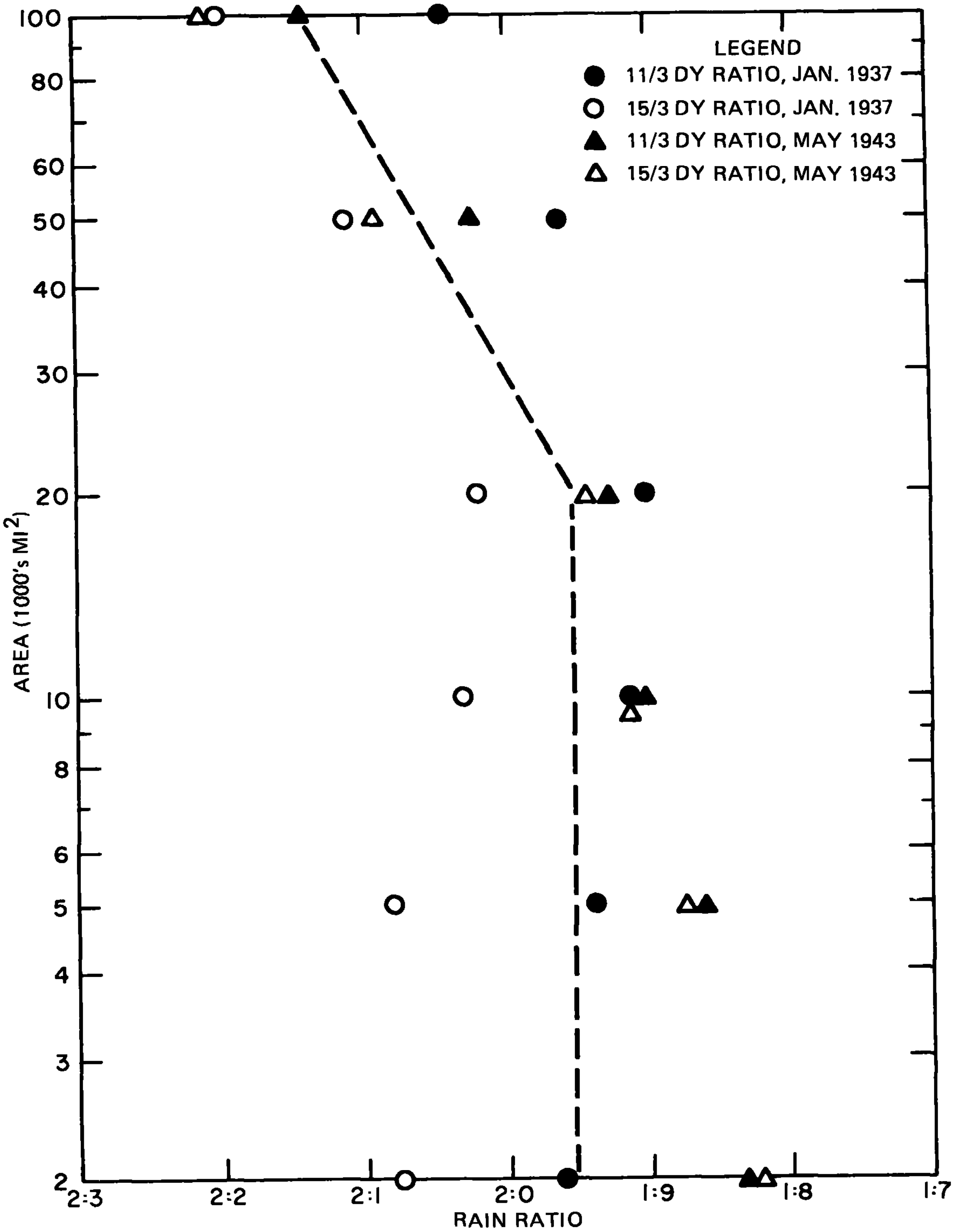


Figure 6-2.—Ratios of long-duration rain to 3-day rain in observed storms. The January 1937 rains centered over the Ohio River Watershed while the May 1943 sequence of storms were in Oklahoma.

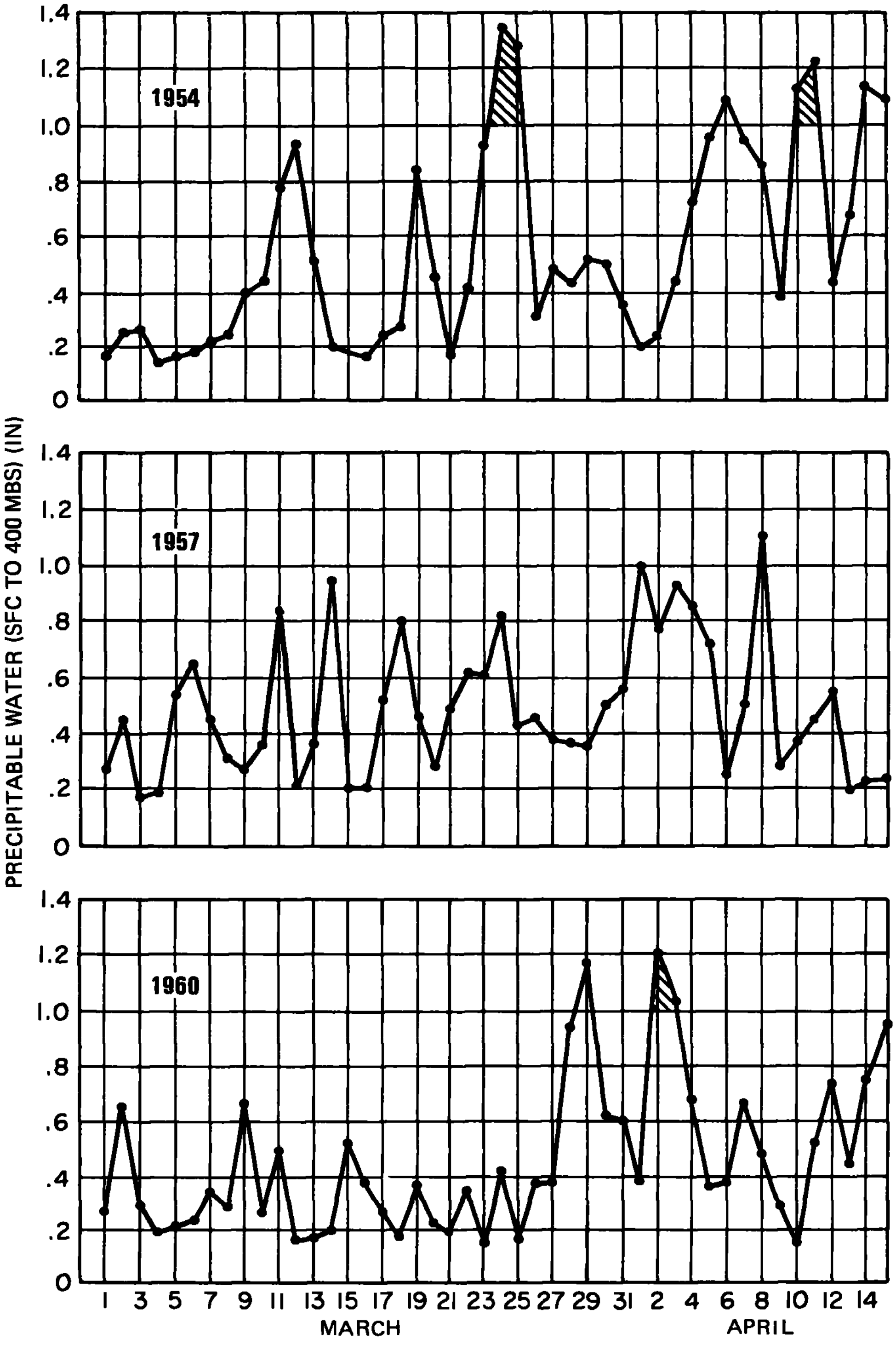


Figure 6-3.--Nashville once-a-day precipitable water values for March and the first half of April in 1954, 1957 and 1960. Runs of high precipitable water cases are hatched. Linear interpolation was used when data were missing.

ACKNOWLEDGMENTS

The studies discussed in this report were supported by funds provided by the Tennessee Valley Authority under Contract TV-23942A, dated January 22, 1963. The funds for publication were provided under Contract TV-36522A. The nature and scope of the studies were agreed upon in discussions between Messrs. Bob Buehler and Donald W. Newton of TVA and Messrs. Vance A. Myers, John T. Riedel and Francis K. Schwarz of the National Weather Service.

The author appreciates the guidance provided by Mr. John Riedel, Chief of the Hydrometeorological Branch, and Mr. John Miller, Chief of the Water Management Information Division. Coordination of the report through the efforts of Mr. Bob Buehler and Mr. Donald Newton of the Tennessee Valley Authority, is appreciated. In addition, Mr. Louis Schreiner of the Hydrometeorological Branch is recognized for performing most of the work involving the development of rainfall adjustments for orientations of isohyetal patterns. Mr. Norbert Helfert, formerly of the Hydrometeorological Branch, assisted in these studies. The Meteorological Technicians of the Hydrometeorological Branch, under the direction of Miriam McCarty, provided valuable research support.

REFERENCES

Corps of Engineers, U. S. Army, "Storm Rainfall in the United States," Washington, 1945-.

U. S. Weather Bureau, Hydrometeorological Section, Lower Cumberland Reservoir Project. Memorandum to Office of Chief of Engineers, Corps of Engineers, dated November 9, 1955, 17 pp.

U. S. Weather Bureau, "Meteorology of Flood-Producing Storms in the Mississippi River Basin," *Hydrometeorological Report* No. 34, 1956, 226 pp.

U. S. Weather Bureau, "Meteorology of Flood-Producing Storms in the Ohio River Basin" *Hydrometeorological Report* No. 38, 1961, 67 pp.

U. S. Weather Bureau, "Probable Maximum Precipitation, Susquehanna River Drainage above Harrisburg, Pa.," *Hydrometeorological Report* No. 40, 1965, 70 pp.

U. S. Weather Bureau, "Probable Maximum and TVA Precipitation over the Tennessee River Basin above Chattanooga," *Hydrometeorological Report* No. 41, 1965, 148 pp.

U. S. Weather Bureau, "Probable Maximum and TVA Precipitation for Tennessee River Basins up to 3,000 Square Miles in Area and Durations to 72 Hours," *Hydrometeorological Report* No. 45, ESSA, U. S. Department of Commerce, 1969, 166 pp.

World Meteorological Organization, "Estimation of Maximum Floods," *Technical Note* No. 98, 1969, 288 pp.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1973—511-327/292