HYDROMETEOROLOGICAL REPORT 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

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(Nos. 6-22 numbered retroactively)

*No. 1 Maximum possible precipitation over the Ompompanoosuc Basin above Union Village, Vermont. 1943.

*No. 2 Maximum possible precipitation over the Ohio River Basin above Pittsburgh, Pennsylvania. 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, Oklahoma. 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 (Unpublished.)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, Missouri. 1938.

*No. 9 A report on the possible occurrence of maximum precipitation over White River Basin above Mud Mountain Dam site, Washington. 1939.

*No. 10 Maximum possible rainfall over the Arkansas River Basin above Caddoa, Colorado. 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, Oregon. 1939.

*No. 12 Maximum possible precipitation over the Red River Basin above Denison, Texas. 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 (Unpublished).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.

U. S. Department of Commerce
Weather Bureau

U. S. Department of Army
Corps of Engineers

Hydrometeorological Report No. 33

SEASONAL VARIATION OF THE PROBABLE MAXIMUM PRECIPITATION EAST OF THE 105th MERIDIAN FOR AREAS FROM 10 TO 1000 SQUARE MILES AND DURATIONS OF 6, 12, 24 AND 48 HOURS

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Chapter I

INTRODUCTION

Assignment

The development of a set of generalized charts indicating the seasonal variation of the probable maximum precipitation was undertaken in accordance with a memorandum from the Corps of Engineers dated March 1953. It was requested that these charts be based on the results of Hydrometeorological Report No. 23, "Generalized Estimates of Maximum Possible Precipitation," subject to such changes as are warranted at this time.

Herewith are presented an all-season envelope and monthly maps of probable maximum precipitation for 200 square miles for a duration of 24 hours. For each of these maps is provided a depth-duration-area relation which gives a method of obtaining the probable maximum precipitation for any area from 10 to 1000 square miles and for durations of 6, 12, 24, and 48 hours.

Definition

The probable maximum precipitation represents the critical depth-duration-area rainfall relations for a particular area during various seasons of the year that would result if conditions during an actual storm in the region were increased to represent the most critical meteorological conditions that are considered probable of occurrence. The critical meteorological conditions are based on an analysis of air-mass properties (effective precipitable water, depth of inflow layer, temperatures, winds, etc.), synoptic situations prevailing during the recorded storms in the region, topographical features, season of occurrence, and location of the respective areas involved. The rainfall values thus derived are designated as the probable maximum precipitation since they are determined within the limitations of current meteorological theory and available data and are based on the most effective combination of factors controlling precipitation intensity. The term "maximum possible precipitation" used in previous reports is synonymous with "probable maximum precipitation", however, it is believed the term "probable maximum precipitation" is a more descriptive one.

Importance of the seasonal variation

The seasonal variation of probable maximum precipitation values becomes an important meteorological consideration in two main problems of engineering design: first, in situations where major floods may occur in conjunction with snowmelt, and second the design and operation of multi-purpose structures. Although much greater precipitation may occur over areas of 10 to 1000 square miles in the summer season, high infiltration rates, evaporation, and storage capacity may greatly reduce the potential threat of flooding. A somewhat lesser storm than the annual probable maximum must be investigated for flood potential when combined with a snow pack of high water equivalent and high melting temperatures. Similarly, in the case of multi-purpose structures, seasonal operation may reduce the reservoir to a safe level during the time of the probable maximum precipitation, whereas storage requirements for future use, at a time of year other than that during which the probable maximum is likely to occur, may present a problem more serious in considering the design and operation of the structure.

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The authors are indebted to the Chief of the Section, Dr. Charles S. Gilman, and to Mr. Dwight E. Nunn of the Corps of Engineers for continuous advice and consultation during the course of this study. Mr. Morton Bailey and Mrs. Lillian Rubin provided editorial assistance. Miss Edna Grooms typed the manuscript.

Chapter II

BASIC THEORY

Theoretical computations

Basic to the theoretical computation of the probable maximum precipitation is the assumption that the probable maximum precipitation can be computed from the optimum combination of moisture charge and convergence of the wind. The moisture charge is the moisture content of a saturated air mass with pseudoadiabatic lapse rate and is a unique function of the dewpoint. The dewpoint used is one which has been reduced pseudoadiabatically to the 1000-mb level in order that dewpoints for stations at differing elevations may be comparable. It is possible, then, to define the moisture charge in terms of precipitable water between the 1000-mb level and various higher levels for given 1000-mb dewpoints.

To estimate the convergence of the wind, it is necessary to consider the speed and direction of both inflow and outflow winds at various levels through the storm area. Considered as a whole, the flow pattern constitutes a storm model through which the moisture is processed, and in computing probable maximum precipitation the most efficient model should be selected. Illustrations of models and the corresponding moisture storage equations may be found in Hydrometeorological Report No. 24 on the San Joaquin. In these models the moisture is expressed as a function of the 1000-mb dewpoint and equals the depth of rainfall deposited by each column of air of unit cross section. The deposited rainfall is termed the effective precipitable water, W_E.

The present study uses an indirect approach to the maximum combination of values which depends on two assumptions: (1) that rainfall can be expressed as the product of inflow moisture charge and the combined effect of storm efficiency and inflow wind; and (2) that the most effective combination of storm efficiency and inflow wind has occurred or has been closely approached in major storms of record. The latter assumption makes storm transposition a necessary tool.

Movement of major storms from one location to another, thereby extrapolating the number of storms that have actually occurred, is considered possible because the location of a major storm involving no significant orographic control is fortuitous within certain geographic limits. These limits define the area of transposition. Determination of the limits of such areas of transposition is largely a problem of synoptic meteorology. The areas are defined as areas of meteorological homogeneity, in which every point therein could experience a storm event with the same storm mechanism and total inflow wind movement, but not necessarily with the same moisture charge or the same frequency. Thus, within the area of transposition of a major storm, the variation of a maximum storm of the same type will be proportional to the variation of the maximum available moisture charge. Furthermore, if one transposable storm has contained the most effective combination of storm mechanism and inflow wind, the result of adjustment to the maximum moisture content will be the probable maximum storm.

Before the storm can be adjusted for changed moisture charge, a storm mechanism or model must be postulated, since the adjustment is a function of the model. Various models of a convective type storm cell have been postulated for use in adjusting to a changed moisture charge. The models vary as to the depth of inflow and outflow layers. A more detailed description of these models is contained in Hydrometeorological Report No. 23. A salient fact in comparing the models is that, although the W_E for a certain dewpoint varies with the cell model, the ratio of W_E values for two certain dewpoints is about the same no matter what the cell model may be. Each ratio is approximately equal to the ratio of the W_p values for the two dewpoints involved, W_p being the precipitable water accumulated from 1000 mb to the cell-top pressure for the particular dewpoint.

Moisture adjustment

Since the W_E ratios are more closely related to the ratios of the W_p than to any other constant parameter of the cell models, the W_p ratio has been employed as the moisture-adjustment factor. These ratios are used with the W_p at 78°F as the base. The validity of the use of this moisture adjustment for extrapolation to upper limits of rainfall depends upon the validity of the assumption that a sufficiently large sampling of major storms is available to provide an optimum or near-optimum combination of inflow wind movement and storm mechanism. Actually, this sampling for a particular location must be increased by storm transposition, as previously explained.

Elevation adjustment

The adjustment to be applied to observed storm rainfall where transposition is to higher elevations requires consideration of the reduction in depth of the moisture charge of the air column and the intensifying effects of orographic lifting upon the amount of rainfall. Models of the type thus far considered have had a common base at 1000 mb, which pressure has been interpreted as sea level. For occurrence at higher elevations - therefore at lower pressures - models based at pressures lower than 1000 mb must be considered. The assumption basic to this further computation is that occurrence at a higher level has a depleting effect. The higher the level at which the storm occurs the less the total W_p that can be processed and therefore the less rainfall. While this is fundamentally true as stated, other significant factors are involved. In regions of upslope topography there are orographic intensifying effects which may overbalance the W_p depletion effect. Moreover, in regions of very abrupt slope, the precipitation produced in a cell based at a low elevation may be transported so as to fall at a higher adjoining elevation. In the development of the present charts, these modifying effects have usually been treated in one of two ways. In some transpositions made in preparation of this report the intensifying effect has been assumed to cancel the depleting effect. In others, the transposition has been restricted to regions of similar topographic characteristics.

Chapter III

BASIC DATA

Four types of basic data are required for application of the moisture adjustment derived theoretically in the previous section. These are: observed storm-rainfall data, observed representative dewpoints in these storms, maximum possible dewpoints throughout the United States east of the 105th meridian, and a surface contour map. The nature and sources of these data will be discussed in this chapter.

Storm rainfall - part II (DDA data)

The seasonal enveloping isohyets on figure 1 are based on more storms than the comparable map in Report No. 23; however, because the seasonal variation requires storm data distributed over 12 months, the number of storms available for consideration in a particular month is considerably less than the number determining the all-season envelope. Although only a comparatively small number of storms furnished the controlling values, all the storm studies available to date were processed to preclude oversight of any significant value. Depth-duration-area values, location of storm center, and isohyetal pattern were taken directly from the approved pertinent data sheet and the isohyetal map pertaining to the individual storm studies. Where there was no approved data, preliminary data were used when considered reliable. The most important storms with part II data, processed in the development of the generalized charts, are listed in appendix A.

Other storm data

Another type of storm data used as an aid in determining the seasonal trends consisted of weekly precipitation values averaged over the climatological divisions of the United States. These averages were compiled under the direction of W. F. McDonald of the U. S. Weather Bureau for the years 1906 to 1935 inclusive. A seasonal chart of the 30-year average weekly precipitation value for a particular climatological division was used as an index to the seasonal trends of the maximum probable precipitation for the larger areas and longer durations within that division. Other values, such as the highest weekly values for the 30 years, were also plotted in like manner.

Use was also made of 24-hour maximum observed precipitation at Weather Bureau stations having over 10 years of record. Trends in these values would be indicative of the trends in maximum probable precipitation for small areas.

The two types of data described above were used primarily as supporting evidence when there was not sufficient part II data to define the seasonal trends. These data also substantiated singularities in the seasonal trends as indicated by the usual part II data.

Representative storm dewpoints

Maximum observed dewpoint data are utilized in adjusting the storms to maximum values. For moisture adjustment, the observed storm-rainfall depths are multiplied by the ratio of maximum to observed moisture charge. On the basis of the theoretical and empirical considerations presented in the previous chapter, the observed moisture charge is determined from the 1000-mb dewpoint representative of the moisture flowing into the rain area of the storm. The chronological sequence of these dewpoints and the corresponding dewpoint-duration relations were determined for each of the storms processed. Ideally, each dewpoint sequence within the storm should be related to a corresponding rainfall period, appropriately lagged. In practice, however, this is rarely found to be feasible, especially in a project of the scope of these charts. Use of the 12-hour adjustment was deemed sufficiently accurate. The 12-hour period of maximum rainfall is closely associated with the 12-hour period of maximum dewpoints, but adjustment for other durations differs only slightly. Furthermore, the major portion of the total-storm rainfall falls within a 12-hour period.

The representative storm dewpoints were determined by going upstream along the air trajectories from the rain area to a region with available observed dewpoints in the warm air. In each storm the rain area was defined as being bounded by the 1- or 2-inch isohyet of the total storm, and the area was then outlined on successive 12-hour synoptic maps for the storm period. When no front separated the rain area from the surface observations representative of the air mass involved in the rain process, the representative dewpoints were selected at stations along this trajectory as close as possible to the edge of the rain area. In the presence of a separating front, dewpoints were selected from the warm sector, as near as possible to the front. Rapid movement of the front in some of the storms made selection of long-duration dewpoints difficult, but the decision to use 12-hour dewpoints in a storm adjustment eliminated most of such difficulties.

A group of stations whose geographical center fell on the inflow trajectory was generally found preferable to a single station for determining the representative storm dewpoints. A station was rarely so located that its dewpoint was uniquely representative of the storm moisture charge. Furthermore, because of occasional lack of representativeness of surface data, it was generally found preferable to make use of a group of stations. The center of the group of stations was the point for which the maximum dewpoint was later determined in order to adjust the rainfall for occurrence at its original location.

The dewpoints used in the study were obtained from the original station records for all observation times within the storm period. The minimum temperatures occurring during the period were also obtained, since the dewpoint persisting for any period cannot exceed the minimum temperature observed during the same period. The dewpoints and minimum temperatures for the group of selected stations were pseudoadiabatically reduced to 1000 mbs (station elevation assumed to be in a pseudoadiabatic, saturated atmosphere with sea level at 1000 mbs) and reduced values of each were then averaged for each observation time. The mean thus obtained was considered to be the representative dewpoint at observation time for the geographical center of the station group. Both in the chronological sequence of these means and in the derived dewpoint-duration array the representative dewpoint for each duration was the lowest observed, i.e., the dewpoint equaled or exceeded throughout the indicated period.

The representative 12-hour dewpoints in major United States storms east of the 105th meridian are listed in Hydrometeorological Report No. 25A. All of the considerations previously mentioned have been utilized in preparation of this report.

Maximum U. S. dewpoints

A discussion of the method by which monthly maps of maximum 12-hour dewpoints (reduced to 1000 mbs) were originally constructed can be found in Report No. 23, pages 20 and 21. Some of the primary features of the method are: dewpoints that were extremely high in comparison with surrounding values were discarded as either being due to observation errors or to being representative of only an extremely shallow layer of surface air; the dewpoints were obtained from the analysis of about 50 first-order Weather Bureau stations with about 30 to 50 years of observations and of 115 airway stations with 5 years of record; in drawing isolines special efforts were made to utilize extreme rather than mean flow patterns

The maximum enveloping 12-hour persisting dewpoints have been revised since the publication of Hydrometeorological Report No. 23 by an intensive study in 1948. Also the values of the dewpoints for the New England-New York area have been subject to a thorough study in the preparation of Hydrometeorological Report No. 28, "Generalized

Estimates of Maximum Possible Precipitation over New England and New York." Dewpoints at additional stations, especially in adjoining Canada, were used. Also the effect of trajectories over the ocean on coastal dewpoints was considered by a technique described in Report No. 28, pages 3 and 4.

Generalized contours

In order to judge the feasibility of transposition of storm values, a **generalized** contour map was developed. It differs from actual contours in that small-scale ruggedness was smoothed, and where large transverse valleys and extremely irregular contours intersected main ridges, the generalized contours were placed upslope from their true position in order to allow greater depth of inflow than indicated by the true contours. As finally drawn, the generalized contours were thus truly effective barriers only when associated with upslope winds directed normal to the contours.

Additional aids

In connection with a study by the Hydrometeorological Section on the Mississippi River at St. Louis, monthly maps were developed which indicate the temperature contrast between cold and warm air masses which can reasonably be expected to interact near any location. One factor in the use of such charts in studies relating to probable maximum precipitation is that in many of the major storms of record minimum or near-minimum temperatures for a particular location and season have been found to the west of the storm center, while above normal temperatures prevailed to the south. It is believed that such contrasting temperatures are related to the energy needed to produce major storms. These monthly maps showing isolines of the temperature contrast factor were used to check the transposition limits of storms for this study.

Another aid in determining the seasonal variation of the probable maximum precipitation is related to the moisture available in the atmosphere. From the maps of 12-hour maximum observed dewpoints the available precipitable water in the column of air from the surface to 30,000 feet was computed for a grid of points over the eastern United States. Isolines of precipitable water were then drawn. Such maps were made for each month. The seasonal variation of these values would logically have a relation to the probable maximum precipitation; however, due to the many other factors involved, these charts were only used as a guide.

When the temperature contrast maps and the available precipitable water maps are combined for each month by multiplying the two indices together, there appears a relatively higher value of the combined index for June and September than for July and August in many locations, which would suggest a dip in the seasonal values of the probable maximum precipitation in July and August. It is believed that the temperature contrast and available precipitable water are two of the factors which are important in what may be termed storm mechanism. How they interact with other parameters is not known at present. The possibility of such a configuration of the seasonal curve of the probable maximum precipitation is also suggested by the 24-hour maximum observed point rainfall for some states in the central part of the country where higher values have been observed in late spring and fall than in the summer months. A similar configuration is shown in McDonald's data of average weekly precipitation over climatological divisions of states--for some divisions higher averages for spring and fall than in the summer. Considering the temperature contrast factor in itself, it would seem that if this dip in the values for July and August is real, it would be augmented for large-area and long-duration storms since the air mass temperatures change gradually and cover large areas. With the above in mind, seasonal curves were drawn so that the final curves for zones 2, 3, 4, 5, 7, 8, and 9 were leveled off in July and August for 1000 square miles, with the amount of flattening increasing with duration. If areas larger than 1000 square miles had been considered in this report the dip mentioned above would have been more pronounced and would have been taken into account.

Limitations of data

The storm-rainfall depths obtained from the part II of each storm study, or from a preliminary evaluation of the available rainfall values, are approximations. Study of the reliability of areal rainfall determinations* indicates that the smaller the area for average gage density (distance between gages), the greater the percent standard error of average depths, the error being positive or negative. On its negative side it may be partly neutralized by the part II procedure of finally drawing an enveloping rather than a mean curve through the computed depth-area values. However, no rainfall reliability factors are incorporated in the generalized charts.

The rainfall values of the storms of record should be the greatest that can occur at the representative dewpoints since only a moisture adjustment is imposed on the rainfall values used. The

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*Hydrometeorological Section, Office of Hyd. Dir., U. S. Weather Bureau, Thunderstorm Rainfall, Hydrometeorological Report No. 5, in cooperation with Eng. Dept. Corps of Eng., War Dept., 1947.

method assumes that the storms of record, together with additional values made possible through transposition, provide rainfall values indicative of maximum rain-producing efficiency. No completely analytical demonstration can be made to prove that this is so. However, there is support for the assumption in the following facts. When only the greater depths are considered, without regard to location, the range of the highest values at each dewpoint is of the order of magnitude of the corresponding range in extrapolated moisture content. Such a relation indicates that the highest rainfall values are representative of near-maximum storm efficiency unless the assumption can be accepted that a mechanism approaching the most efficient has never occurred. Some of the greatest rainfall depths, for instance, occurred in the Thrall, Tex., storm (September 8-10, 1921), which is characterized by the highest representative dewpoint, and a liberal storm transposition procedure takes advantage of such a fact. However, it is also rare for one storm to control for all sizes of area and all durations. Comparison of two storms may show that, with increasing area and duration, difference in depth is often decreased and the relative depths even reversed. The procedure of enveloping values from several storms occurring in or transposable to the same region takes advantage of the highest values for all durations considered.

The representative dewpoint determines the denominator of the moisture adjustment-ratio, while the maximum dewpoint determines the numerator. Since the precipitable water is based on a pseudoadiabatic lapse rate extrapolated aloft, a deviation from such a lapse rate could result in a moisture adjustment either too high or too low. When the deviation is in the same direction for both parts of the ratio, however, the effect on the moisture adjustment would be neutralized. In a study of this type the possible error due to an incorrect moisture adjustment in a particular storm would be corrected to a certain extent by the techniques used for smoothing with season, area, and duration.

The absence of observations at the point ideally situated for location of the representative dewpoint usually acts to increase the moisture adjustment used. The ideal location would probably be the region of the highest dewpoints for the latitude, along the axis of the moist tongue involved in the storm. Averaging the observations from a group of stations surrounding the ideal point would thus yield a lower value. An opposite effect arises from the occasional need to go far to the south of the rain area in order to find the representative dewpoint. At lower latitudes, in general, the range of dewpoint is less, the dewpoints in the warm sector or the moist tongue being closer to the maximum. There is an increasing range northward.

Thus, if it were possible to find the dewpoint in the rain area, the spread between representative and maximum dewpoint would usually be greater and the moisture adjustment would be greater. This effect is counteracted slightly by the fact that, for the same spread in dewpoints the adjustment is greater in the higher range of dewpoints.

Chapter IV

PROCEDURE AND DEVELOPMENT

All available storm data were used in developing the charts. For convenience in handling the data, that part of the country east of the 105th meridian was divided into 9 zones, and all storms which would possibly offer controlling values for any duration over any sized area were considered. Some storms were considered for more than one zone, depending upon the transposition limits. The storm value for each of the assigned areas and durations was adjusted for moisture content after comparison of the representative and maximum possible reduced dewpoints. A leeway of 15 days from the storm date was allowed in the choice of the maximum dewpoint.

Transposition

The transposition limits of each storm are the geographical limits within which another storm of essentially the same synoptic characteristics can occur. Because the synoptic storm can be transposed, it is further assumed that its rainfall characteristics, shown by its depth-duration-area curves, can also be transposed.

On a large scale, the main features dividing the United States into separate regions of storm transposition are the Appalachian and the Continental Divides. Few storms cross these barriers without modifications drastic enough to change the synoptic type. Furthermore, transposition from the windward to the leeward slopes of these barriers will generally result in rainfall values much lower than those resulting from transposition confined to the windward slopes. Except for a short distance beyond the crest of the divide, where spillover (carryover) of rain may take place, the leeward transposition requires the complete orographic depletion adjustment without consideration of any counteracting adjustment for orographic intensification. For these reasons, transpositions have been confined to the windward slopes of the main barriers, the wind direction being that of moisture inflow in the storm transposed. On these slopes the effect of the orographic depletion and the effect of intensification act in opposite directions. Since a quantitative expression of only the first effect was available, there was a tendency to confine the transposition to an area of similar topography defined by narrow limits of both elevation and slope (on the basis of the generalized contour map). This resulted in a distribution of adjusted values so untenable climatologically that finally the most important features, such as the main divides or portions of the windward slopes of these divides, were used as limits.

If the effect of topographic slope had made an apparent contribution to the rainfall intensity in a particular storm, no adjustments for transposition to either higher or lower elevations were made. Just as the decreased W_p above higher elevations would be compensated by the effect of steeper slope, so the increased W_p above lower elevations would be compensated by the effect of lesser slope. When there had been no apparent slope effect contributing to the rainfall intensity, transposition to higher elevations was made without elevation adjustment because increased elevation would be compensated by increased slope. Transposition to lower elevations included adjustment for increased W_p since the slope could not decrease further; even at elevations above sea level--plateaus or gradually sloping plains--the effective slope might be zero, and transposition to lower elevations would therefore require adjustment for increased W_p.

No definite over-all latitudinal limitations of transposition were adopted, but possible latitudinal effects were considered separately for each storm or class of storm. Apart from moisture availability, these effects become evident principally in the change in character of tropical storms as they move northward and the decrease of temperature contrast across fronts as they move southward. Synoptic experience, rather than theory, furnished the primary grounds for each decision, with available files of Northern Hemisphere maps and charts of hurricane tracks providing much of the comparative data.

Preparation of charts

Seasonal graphs of the 6-, 12-, 24-, and 48-hour storm rainfall for areas of 200, 500, and 1000 square miles transposed and adjusted in accordance with the considerations previously outlined were plotted for the 9 zones. The abscissa of the graphs is the time of year, while the ordinate is the precipitation average over the area concerned. These storm values were then enveloped. After a minimum of smoothing, mid-month values were plotted on maps and smooth isolines drawn to conform with topographic and meteorological boundaries. From these charts values for each month were taken from the centers of each zone and plotted as depth-duration-area curves to insure consistency. To reduce the tremendous number of charts necessary to show the monthly isohyets for each area and duration, the values for each were expressed as a percentage of the 24-hour 200-square-mile value.

The minimum 200-square-mile 24-hour probable maximum values and the time of occurrence were plotted on maps to verify that undue variations from place to place on the map did not occur and that there was a gradual change of time of minimum from place to place. In order to have smooth seasonal curves for any duration or area, it was necessary that the 200-square-mile 24-hour duration maps be smooth seasonally. For each point on a 4-degree latitude and longitude grid a seasonal curve was drawn through points taken from the 12 maps, and where indicated, adjustments were made in the isohyets until smooth seasonal curves resulted. In like manner, the seasonal curves for areas of 10 and 1000 square miles for durations of 6, 12, 24, and 48 hours were adjusted until they were smooth for the center of each zone. Unless the storm data indicated otherwise, for a certain sized area, for example 1000 square miles, the seasonal curves for the various durations were drawn so as to give a family of curves with the season of maximum rainfall coinciding, etc. The depth-duration-area curves were likewise smoothed as much as possible with area and duration to give a gradual progression from duration to duration and month to month. However, it was not possible to obtain complete smoothness and similar curvature with change in duration for all zones in all months. Further smoothing would result in extreme overenvelopment for some durations and areas. The depth-area relationships show a definite change with season and slight difference in the relationships with size of area. In general the marked change in the relationship with season is due to intense thunderstorm-type rainfall, which occurs in summer.

The maps and charts prepared for this report are: a map of the all-season envelope of 24-hour 200-square-mile probable maximum precipitation (figure 1); monthly maps of 24-hour 200-square-mile probable maximum precipitation (odd-numbered figures 3-25); the depth-duration-area relationships for the all-season envelope of 24-hour 200-square-mile probable maximum precipitation (figure 2); the depth-duration-area relationships to accompany each monthly map of 24-hour 200-square-mile probable maximum precipitation (even-numbered figures 4-26). It will be noticed that there is a separate depth-duration-area relation for each of the zones with the exception of 8 and 9. Sparsity of storm data in zone 9 necessitated combining these two zones.

The curves for 48 hours in the depth-duration-area relationships are dashed for smaller areas to indicate that storm data for this duration and range of areas is not as suitable as for the other durations and areas. The decreased reliability, however, is not as critical as one would suspect, since for small-area basins peak flows resulting from precipitation would, in practically all cases, be the result of thunderstorm rainfall which would be concentrated in a much shorter period of time.

Controlling storm

Approved part II data for several of the controlling storms used in Report No. 23 have become available and necessitated revision of the calculations based on preliminary data. In addition, maximum observed dewpoint data for a considerable number of first-order Weather Bureau stations have produced substantial changes in the distribution of maximum possible 12-hour dewpoints. As a consequence, the moisture adjustments possible for many controlling storms have been changed--usually upward, but occasionally downward.

Whereas for the all-seasonal chart in this report and the charts in Report No. 23 all storm data were available for preparation of each chart, seasonal distribution requires that the same data be spread out over the 12-month period--considerably reducing the number of storms available for consideration in a particular month. However, other storms that were outstanding for a region in seasons other than those in which the probable maximum occurs increase the number of storms controlling the seasonal values.

Some of the controlling storms for this study are listed in appendix B by center, date, and assignment number. This list does not include all the storms that provided controlling values, but is a fair sample of the largest storms in each month. The adjustment factor for each of these for transposition to the zone center and for the zones concerned is given in parenthesis after the zone and is the adjustment for the actual date of each storm.

Chapter V

LIMITATIONS AND USE OF THE CHARTS

Estimates of the probable maximum precipitation for all areas and durations designated can be taken from the present charts and figures. No special advice on the manner of interpolation is required, since variation due to type of coordinate paper and curve used to fit the plotted data are well within the accuracy of the basic data values.

Limitations of the charts

An array of values taken from the charts to represent the probable maximum precipitation for various sizes of areas and various durations is not necessarily identical with a corresponding array of values from a probable maximum storm. The depth-area values are the results of all types of storms. These short-duration values may be controlled by an intense short-duration type storm in which no rain fell after 12 or 48 hours. Longer-duration values may be controlled by a longer-duration storm in which the 6- and 12-hour values do not approach the corresponding values in the short-duration storm. For areas up to 1000 square miles, however, the controlling values for durations as long as 48 hours usually are from the same storm.

The isohyets shown on the charts do not necessarily have the same degree of reliability in all regions. Transposition, particularly for small basins in rugged regions, as in the Appalachian and Ozark mountains, is hazardous, and accurate estimates of the probable maximum precipitation would require calculation of a spillover effect, the importance of which varies inversely with the size of the basin. Upwind rainfall and the funneling of air by gorges and steep valleys would have to be evaluated.

In the detailed study of the New York-New England area (Report No. 28) a division into two zones was made. The division being a line through the Catskills and Adirondacks. Each zone has its own set of ratios for obtaining precipitation values for various durations and areas. For the present more general report, the above mentioned division was not made. Because of this difference in the procedure the Report No. 28 values are not reproduced exactly. However, they are generally within half an inch.

Use of charts

To obtain preliminary depth-area values over a particular basin for all durations in a particular month, the steps outlined below should be followed:

(1) the 200-square-mile 24-hour value is taken from the chart for the appropriate month at the location of the basin; (2) the percentages to be applied to this value for each duration are then obtained from the depth-duration-area relations for the particular zone in which the basin lies, and for the size of the drainage area under consideration. The degree of accuracy does not warrant the refinement logically called for by using pattern storms over basins larger than those under consideration here. Near the boundaries of the zones straight line interpolation between the ratios of the two can be made. The six-hour rainfall values in the 24-hour period (0-24 hours), shown on the charts, may be arranged in critical order of occurrence as desired within this maximum 24-hour period. The rainfall of the second period (24-48 hours) may be distributed in proportion to the six-hour increments indicated in the maximum 24-hour rainfall. This procedure in the distribution of the lesser 24-hour rainfall period is permissible due to the fact that two separate bursts of rainfall could have occurred within each 24-hour period. The two 24-hour rainfall periods are interchangeable and, if desired, may be arranged with the lesser 24-hour rainfall occurring before the maximum 24-hour rainfall.

FIGURES

and

APPENDICES

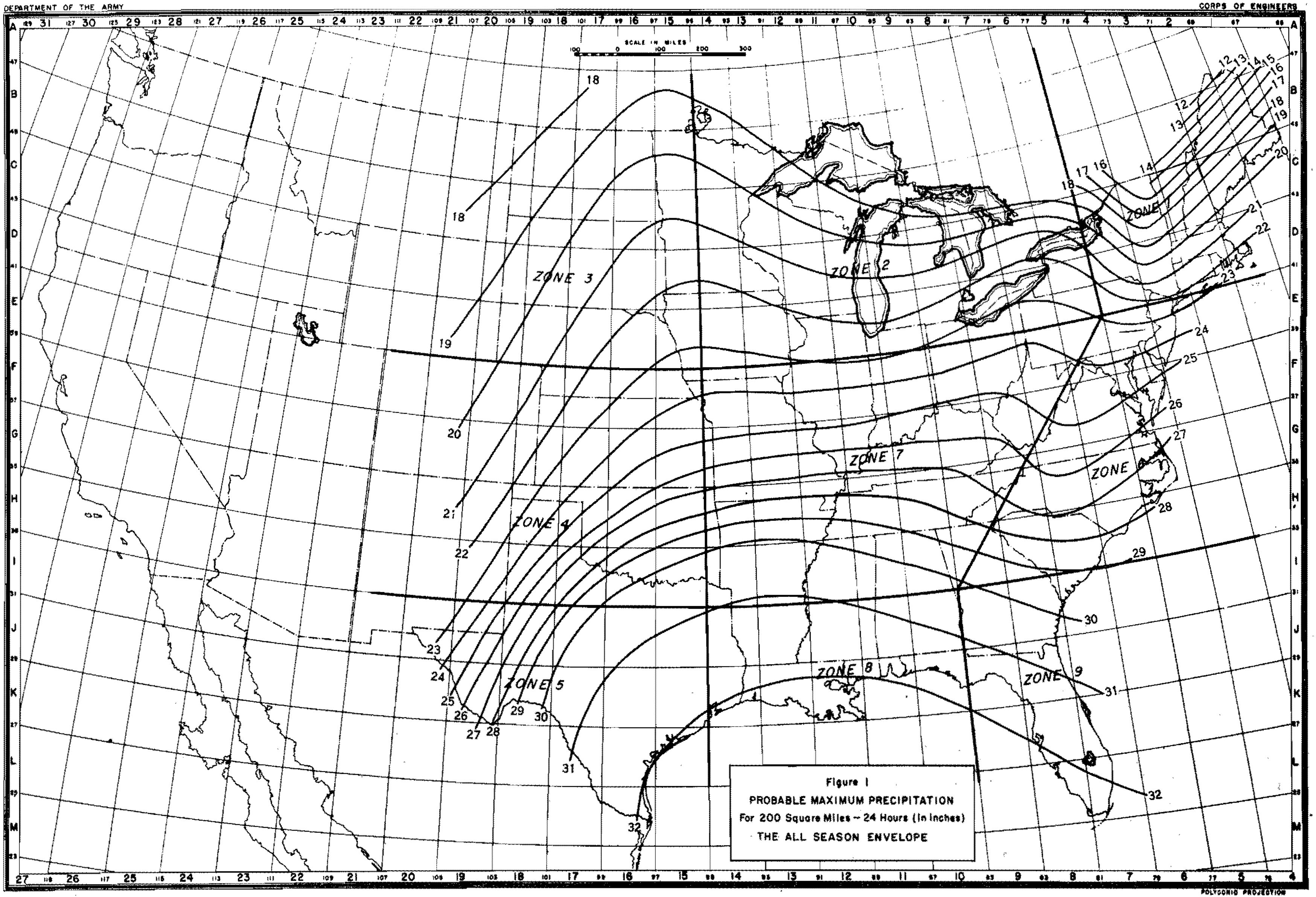


Figure 1
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (In Inches)
THE ALL SEASON ENVELOPE

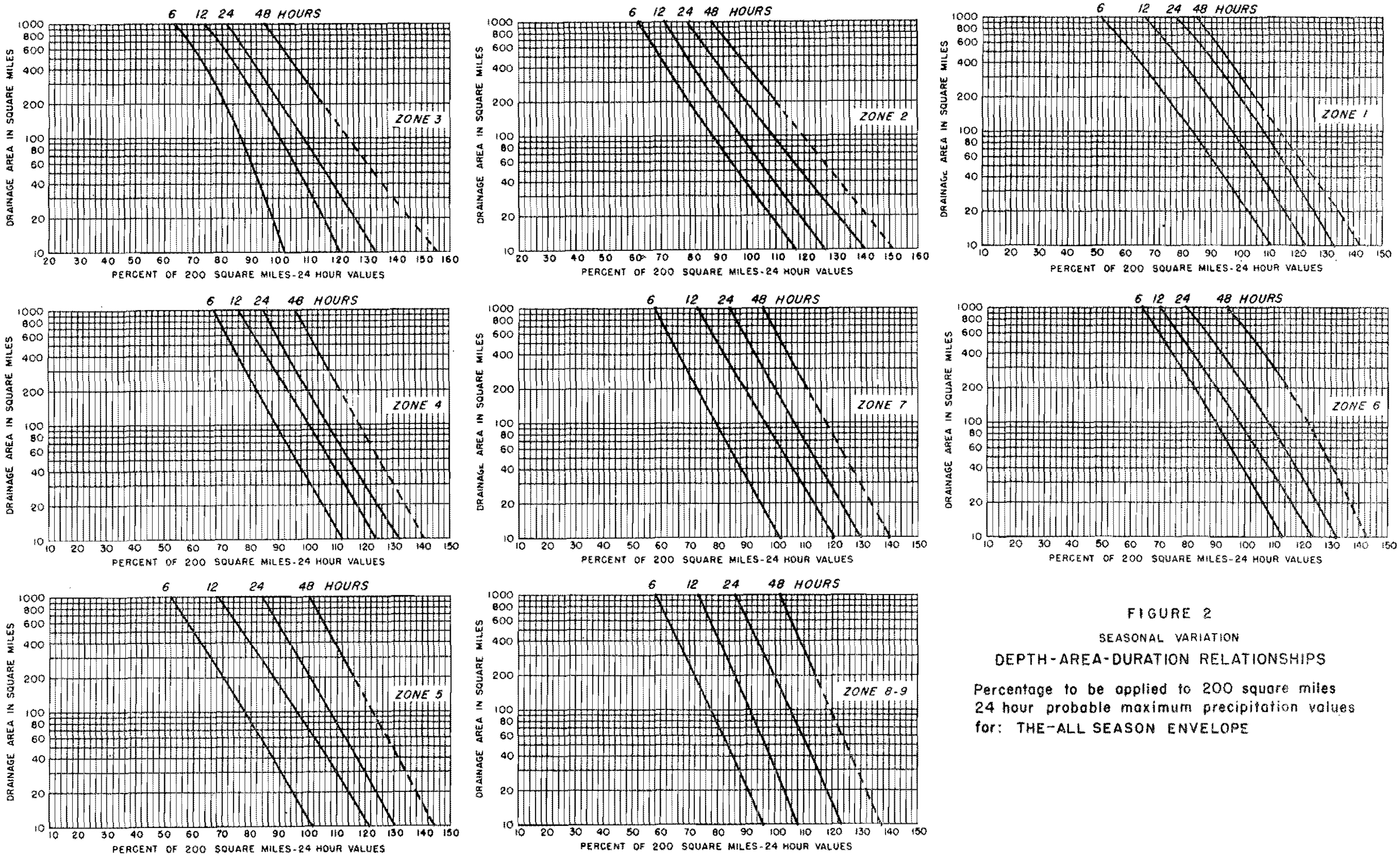


FIGURE 2

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: THE-ALL SEASON ENVELOPE

DEPARTMENT OF THE ARMY

CORPS OF ENGINEERS

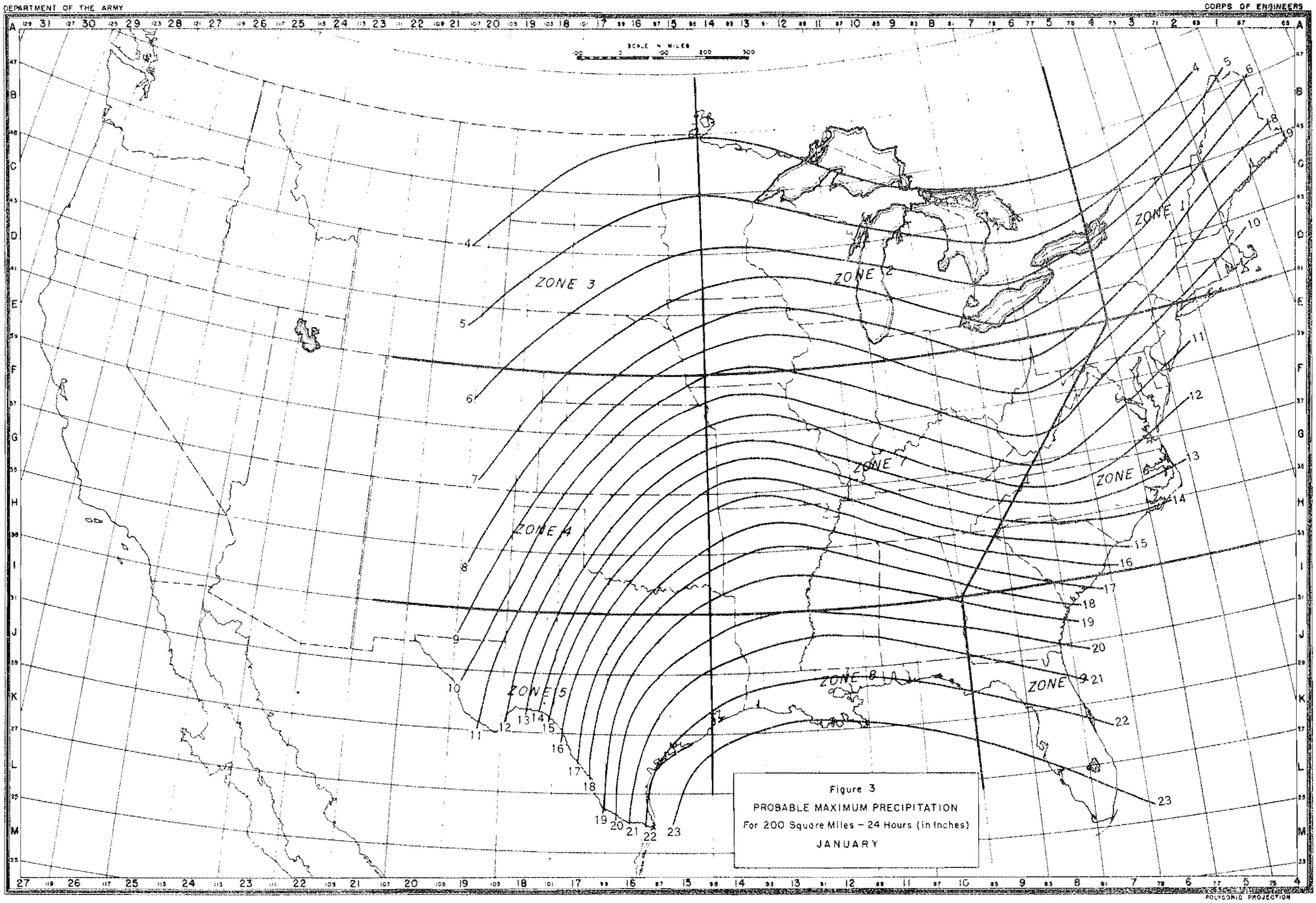


Figure 3
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (in Inches)
JANUARY

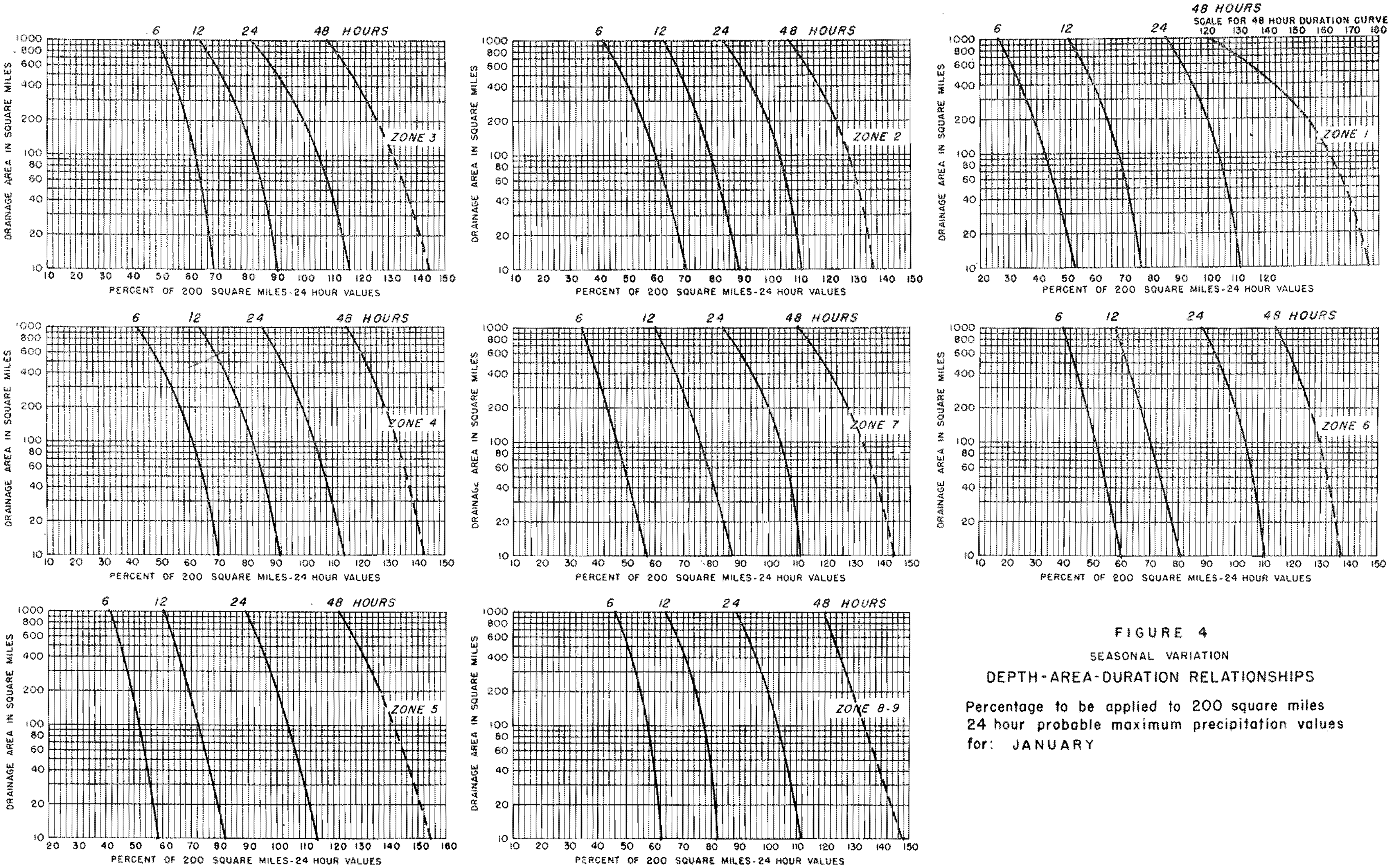


FIGURE 4

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: JANUARY

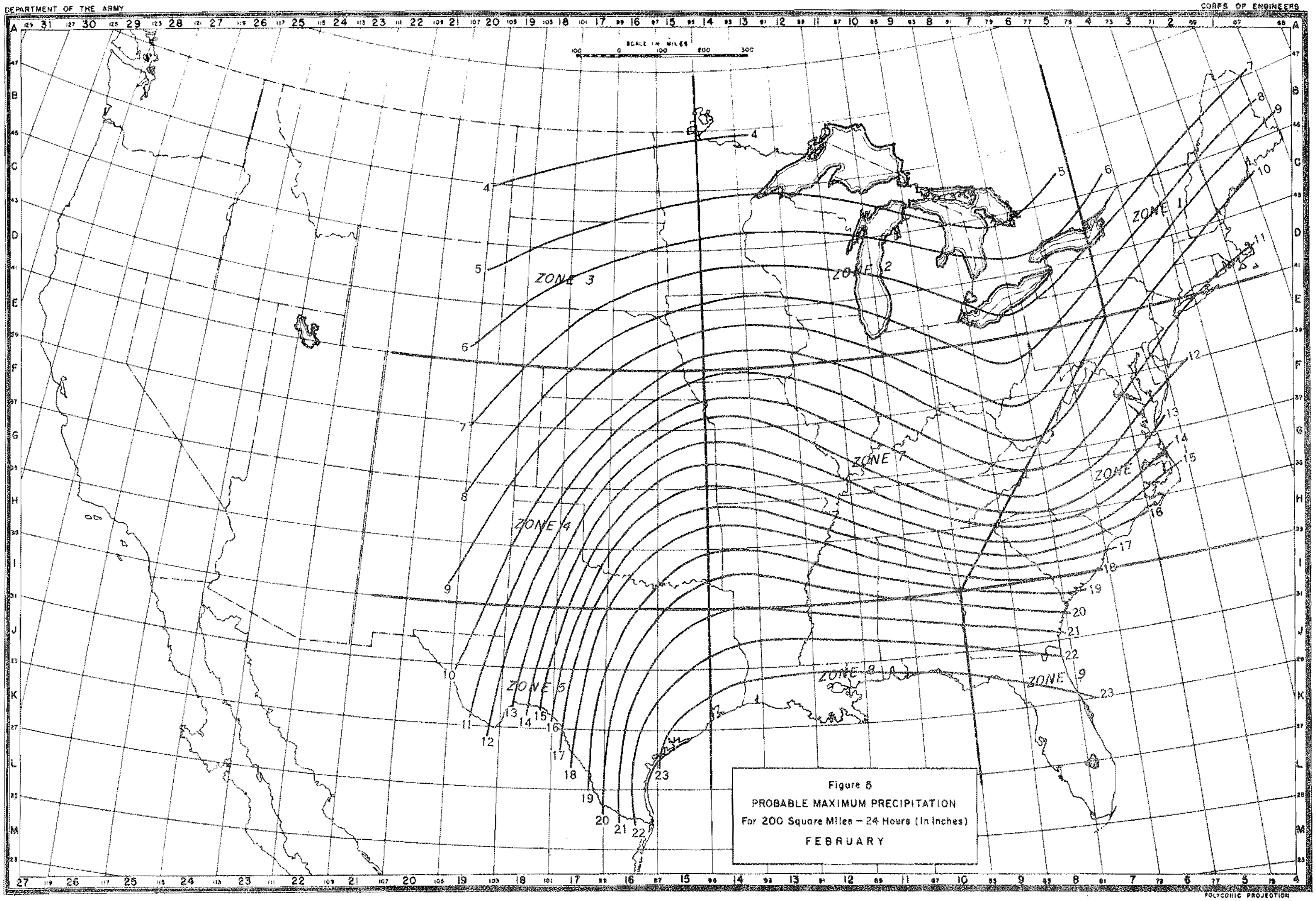


Figure 5
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (In inches)
FEBRUARY

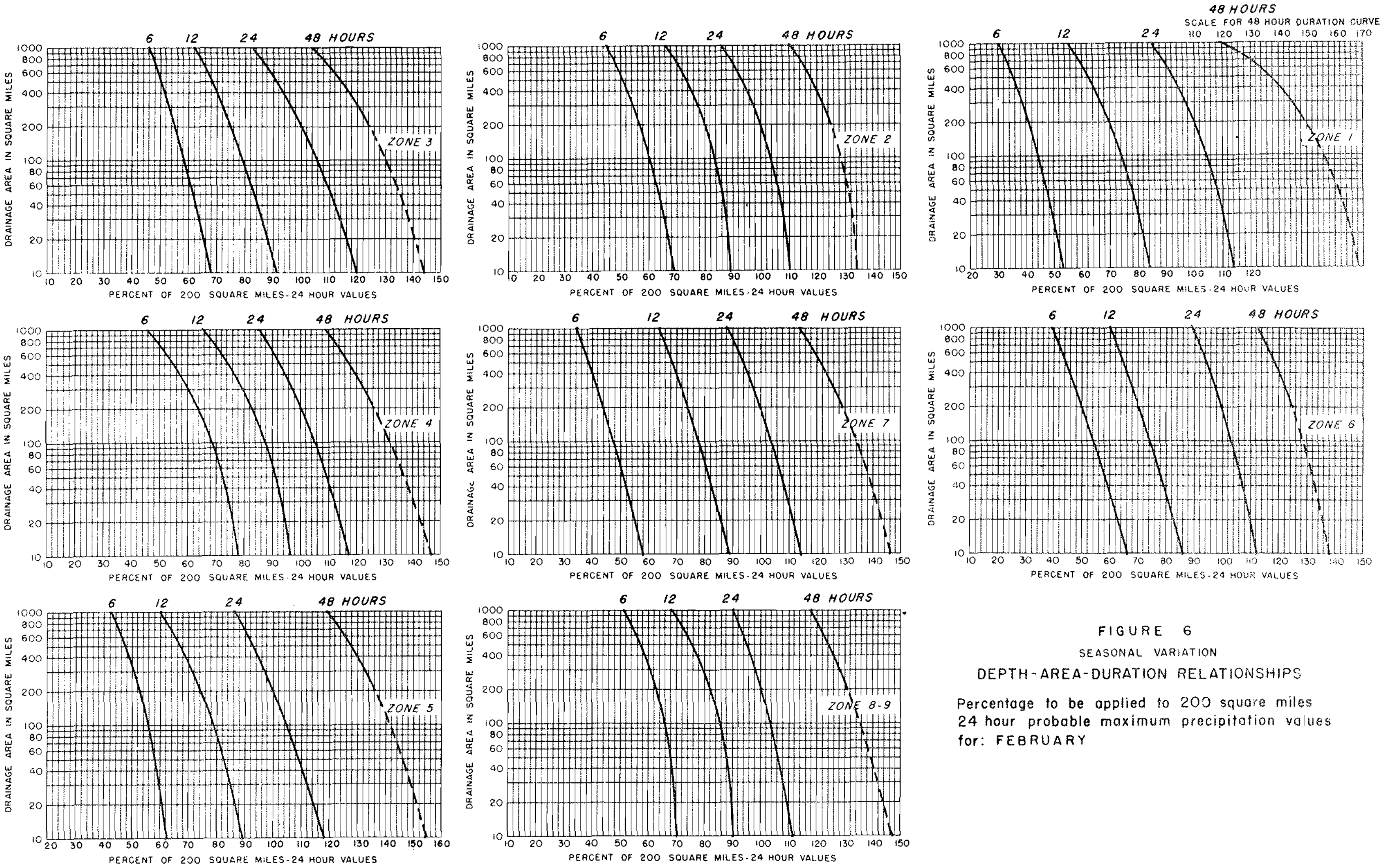


FIGURE 6

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: FEBRUARY

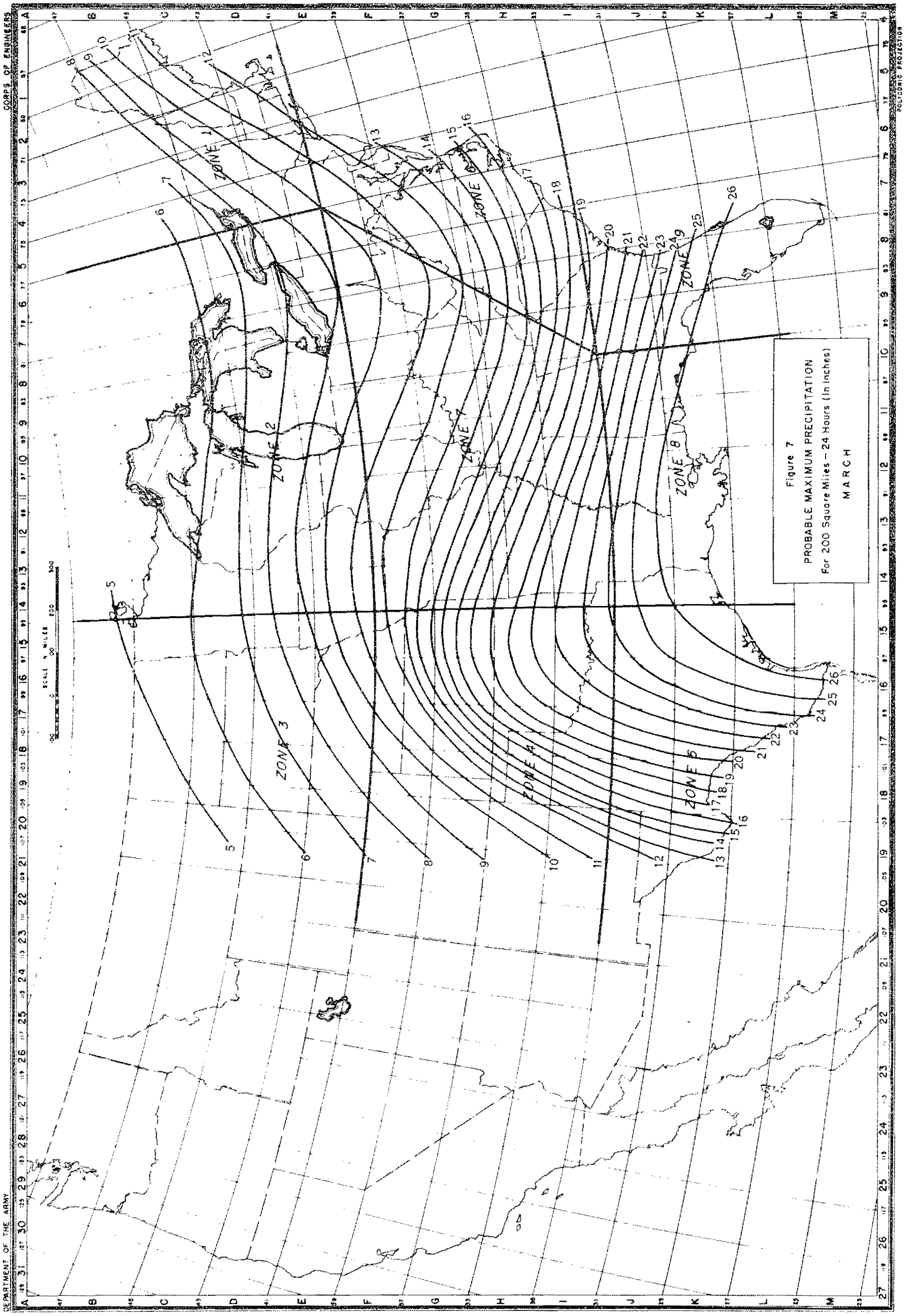


Figure 7
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (In Inches)
MARCH

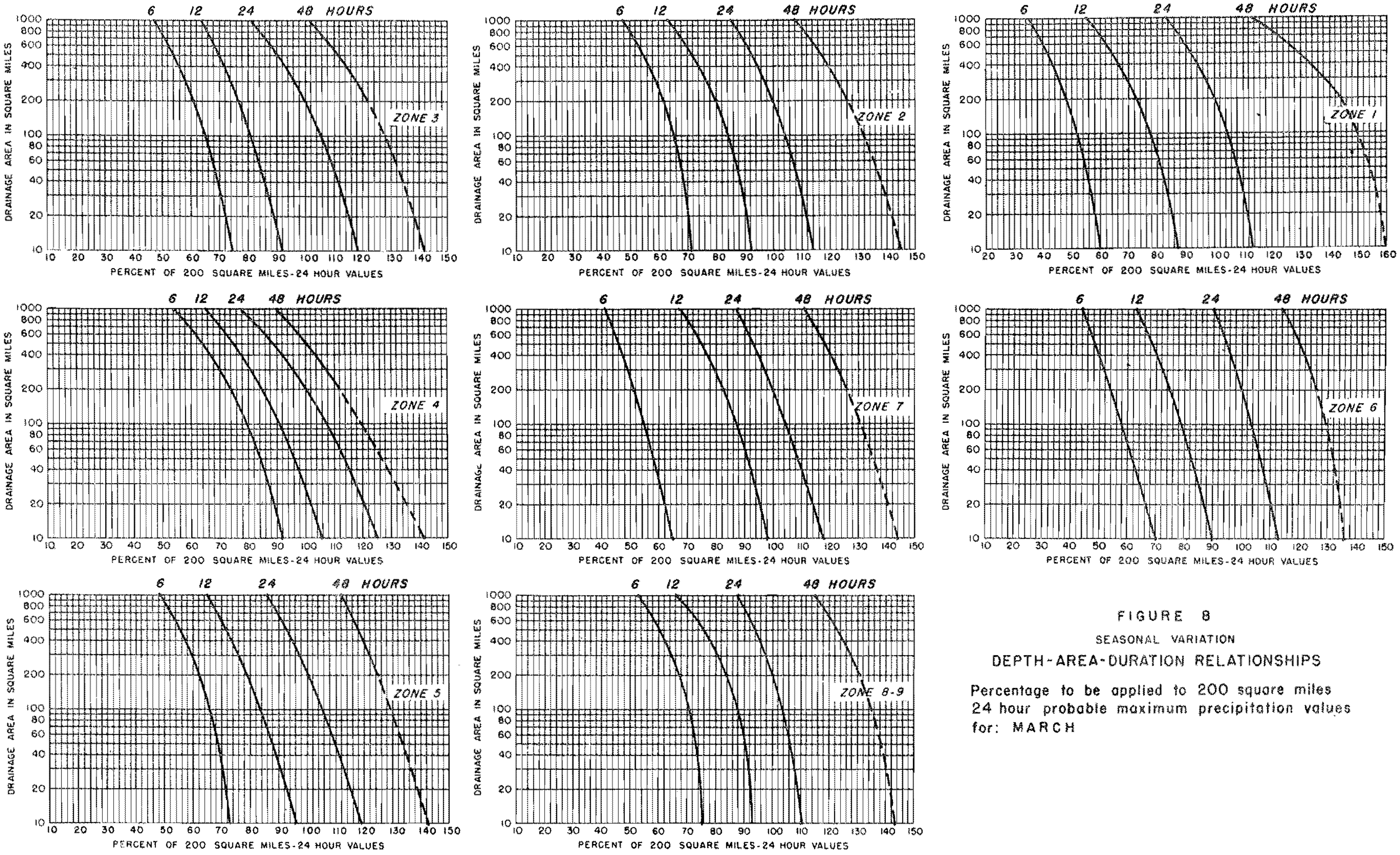


FIGURE 8

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles 24 hour probable maximum precipitation values for: MARCH

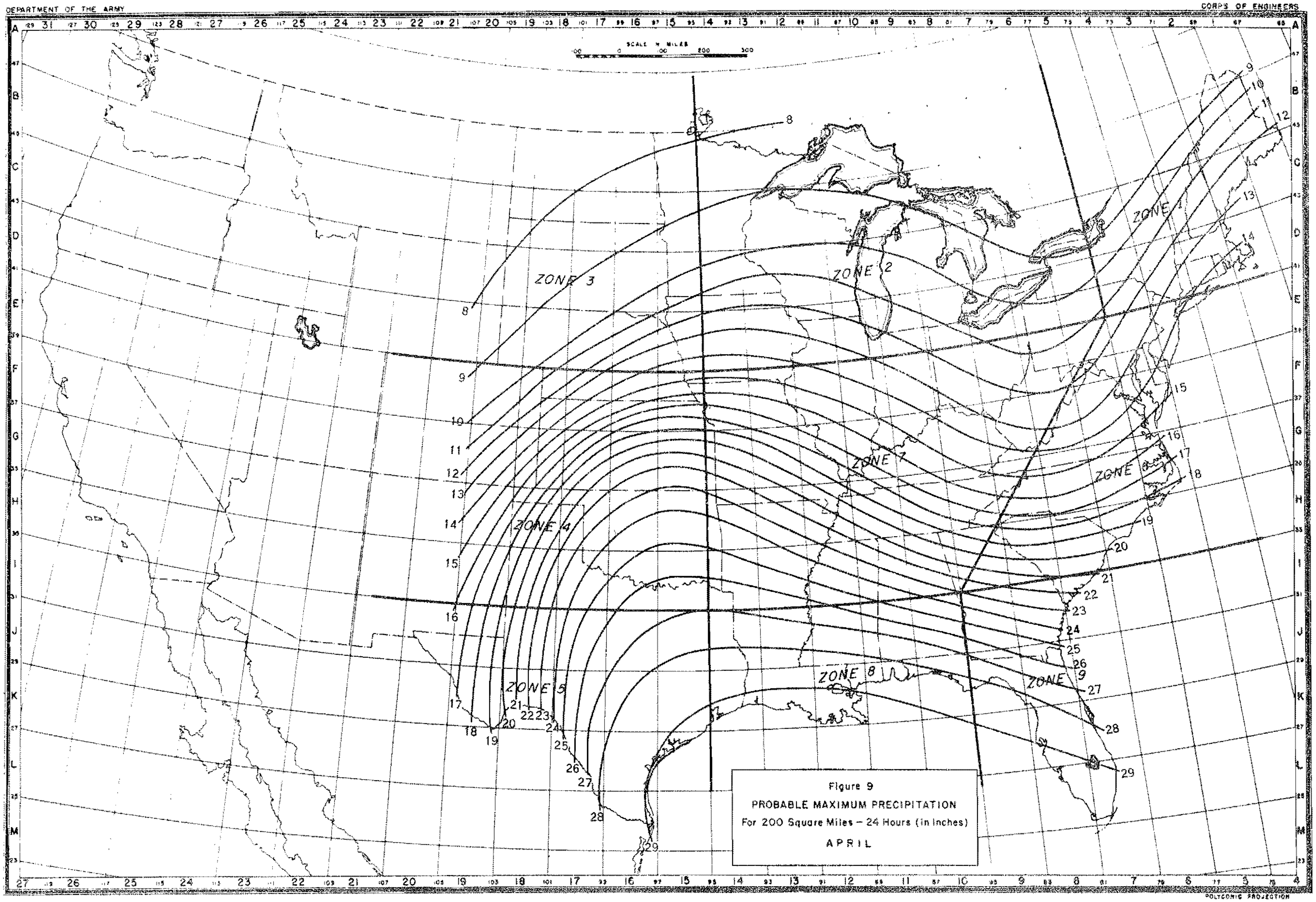


Figure 9
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (in Inches)
APRIL

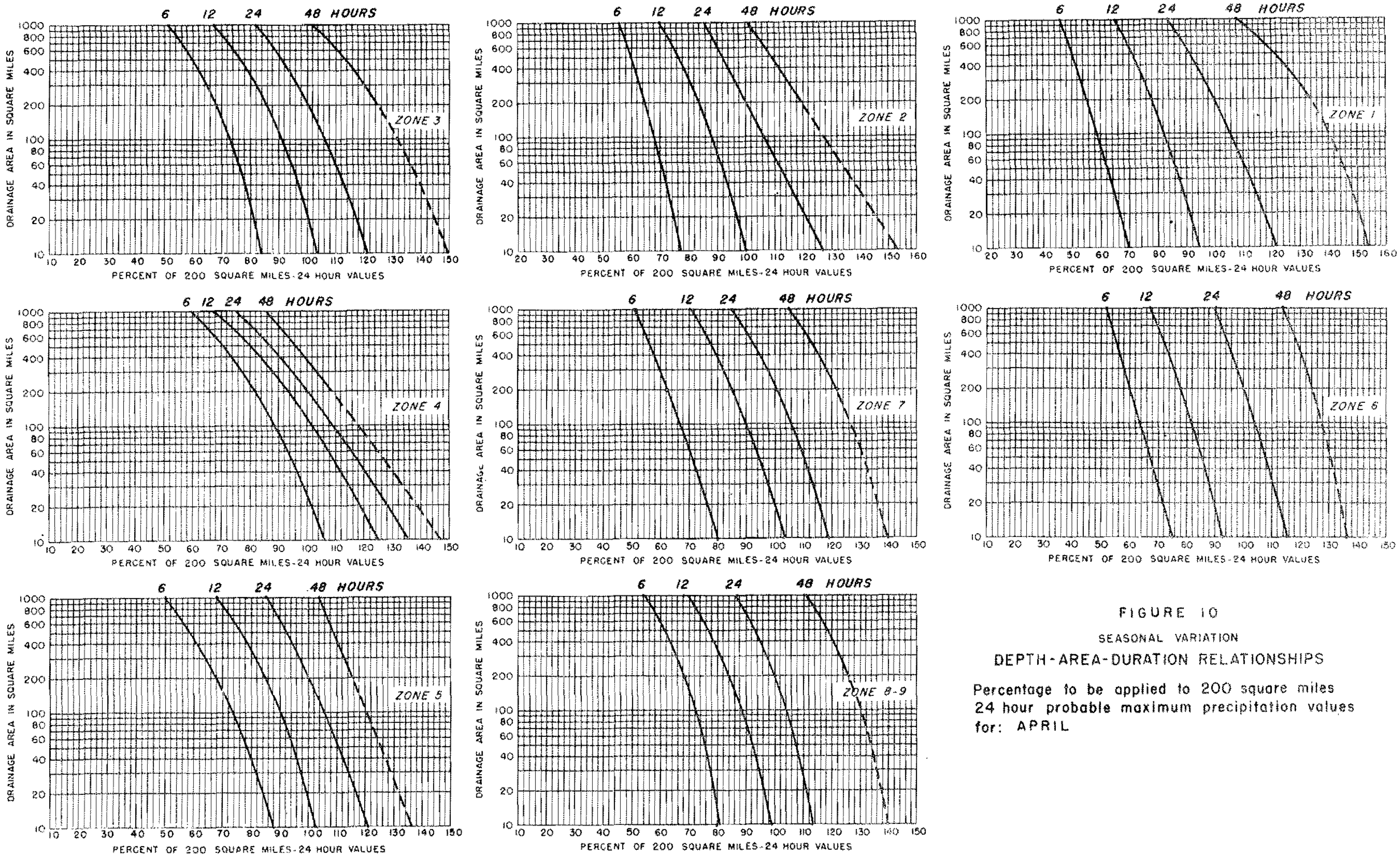


FIGURE 10

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: APRIL

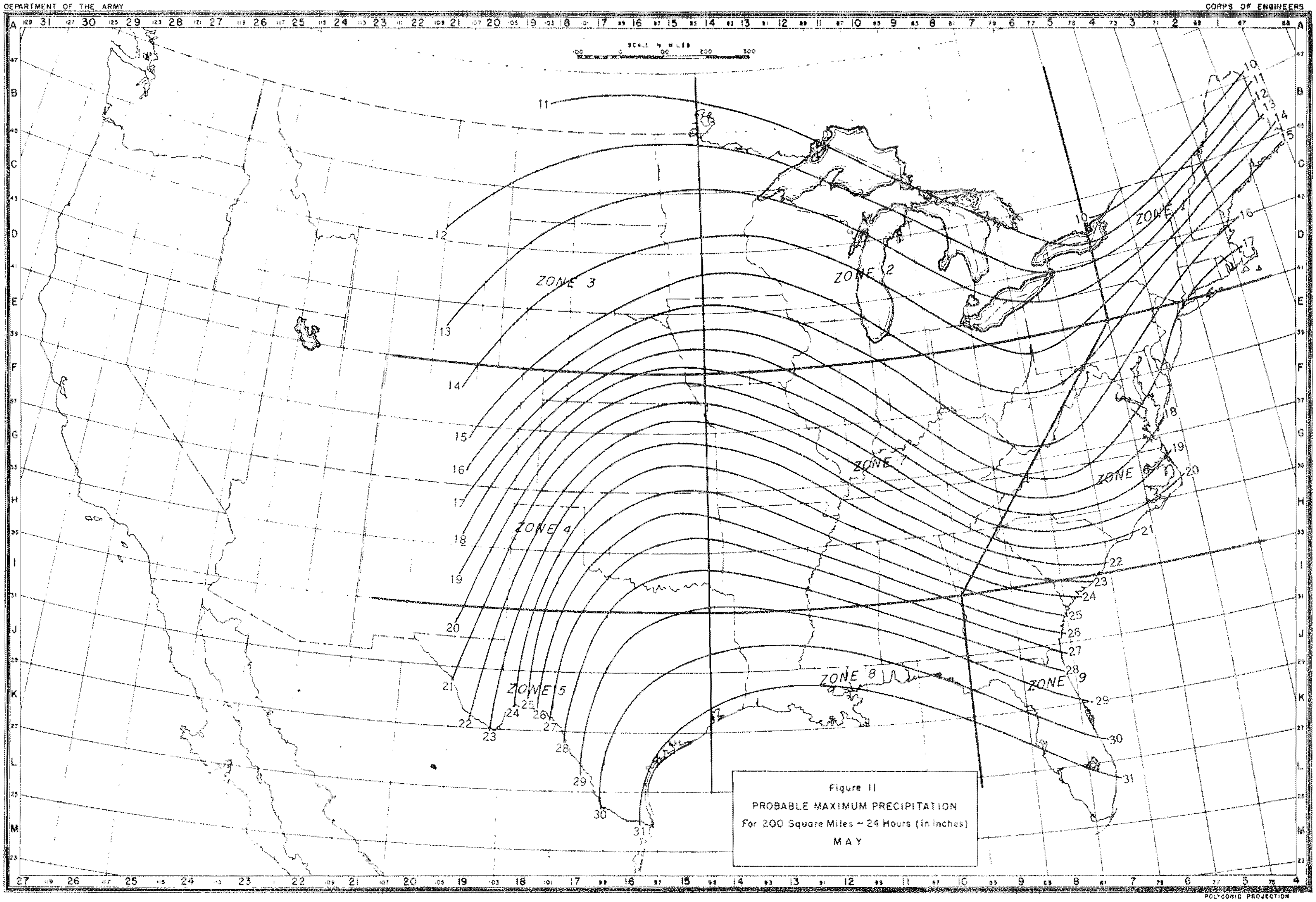
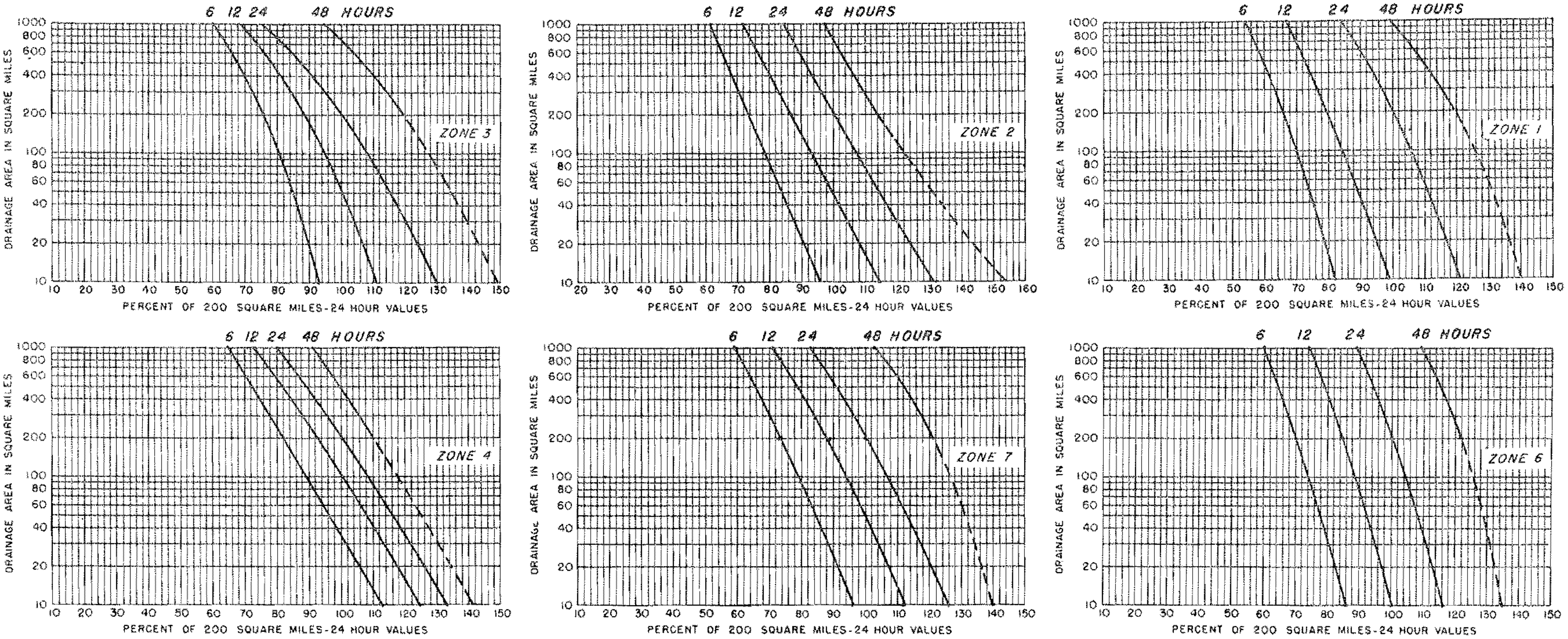


Figure 11
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (in inches)
MAY



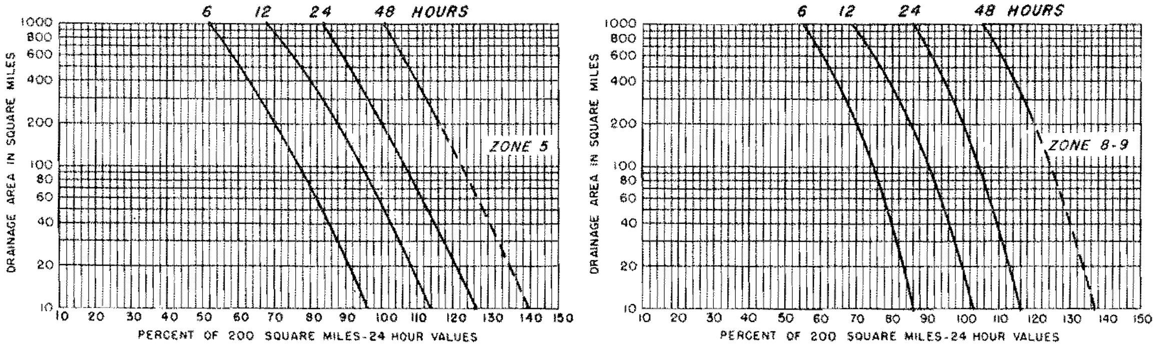


FIGURE 12

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: MAY

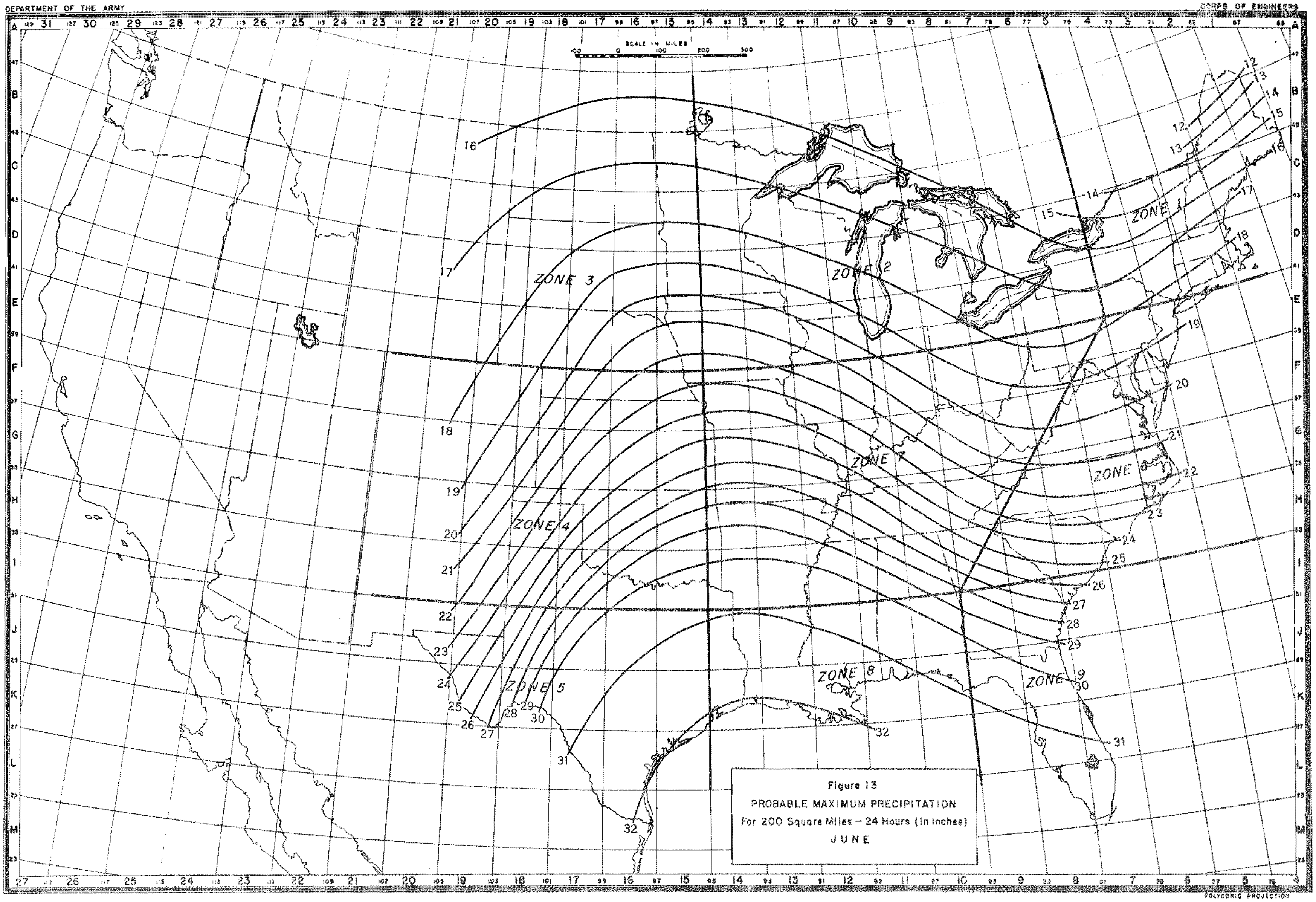


Figure 13
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles — 24 Hours (In Inches)
JUNE

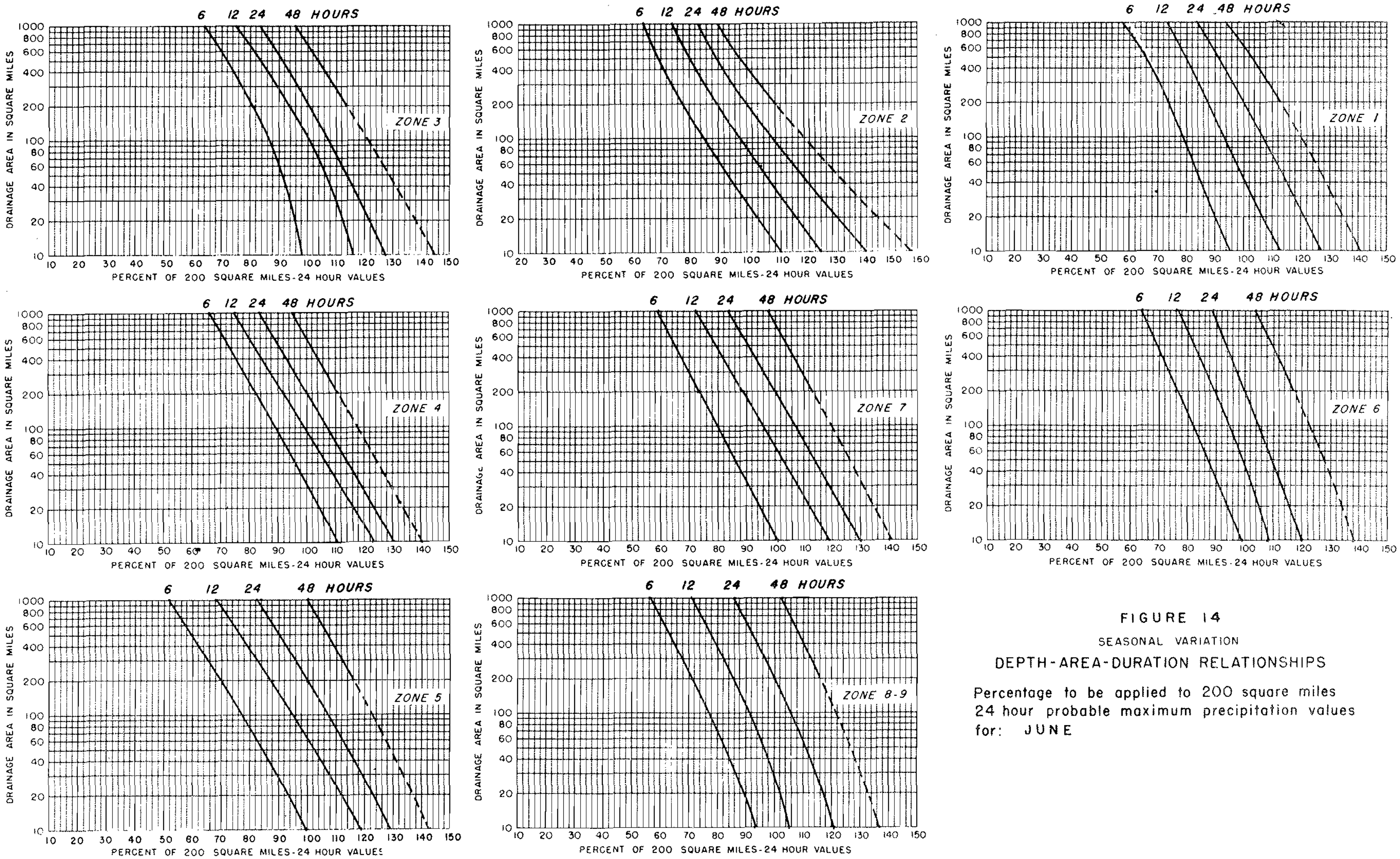


FIGURE 14

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles 24 hour probable maximum precipitation values for: JUNE

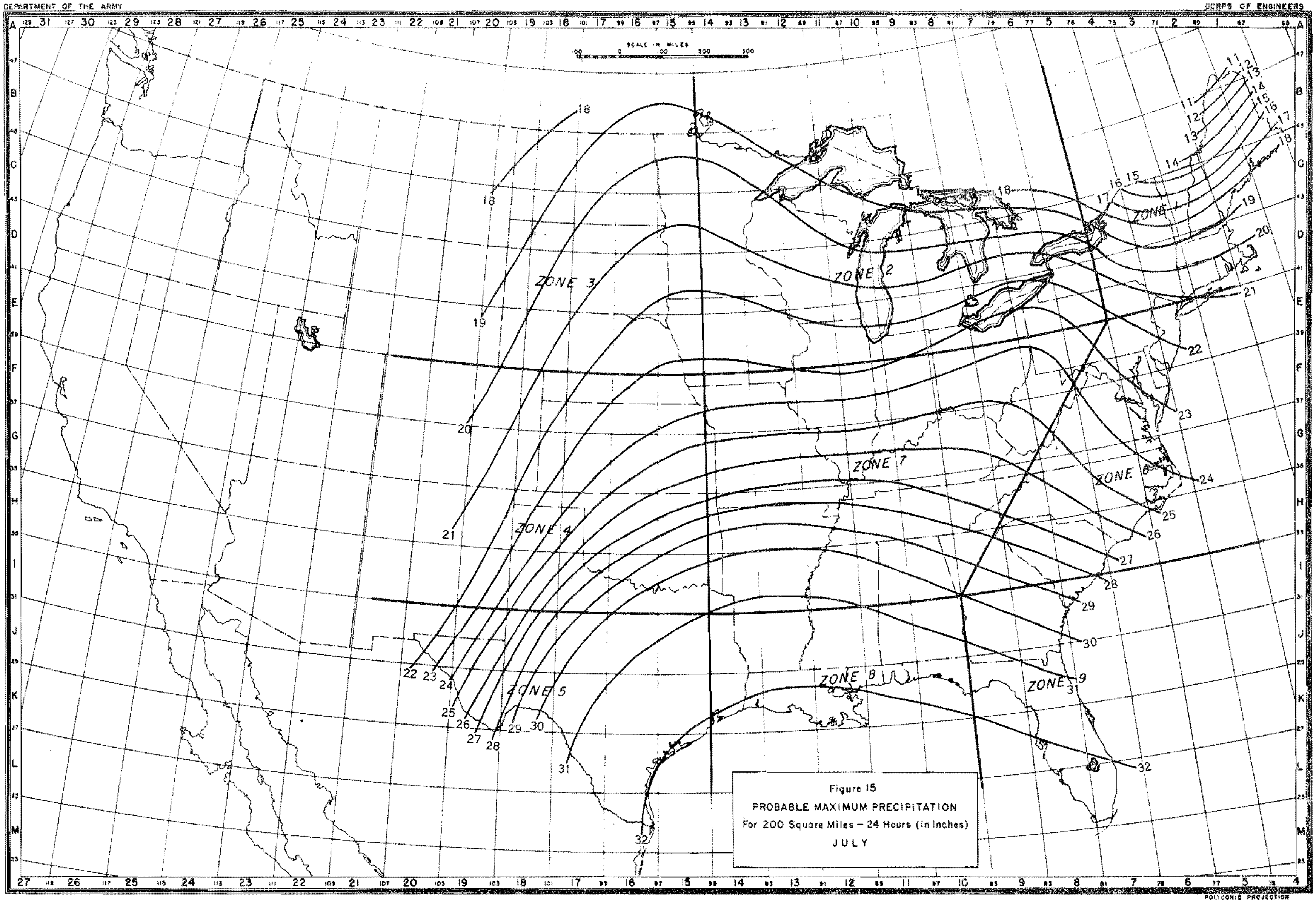


Figure 15
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (in Inches)
JULY

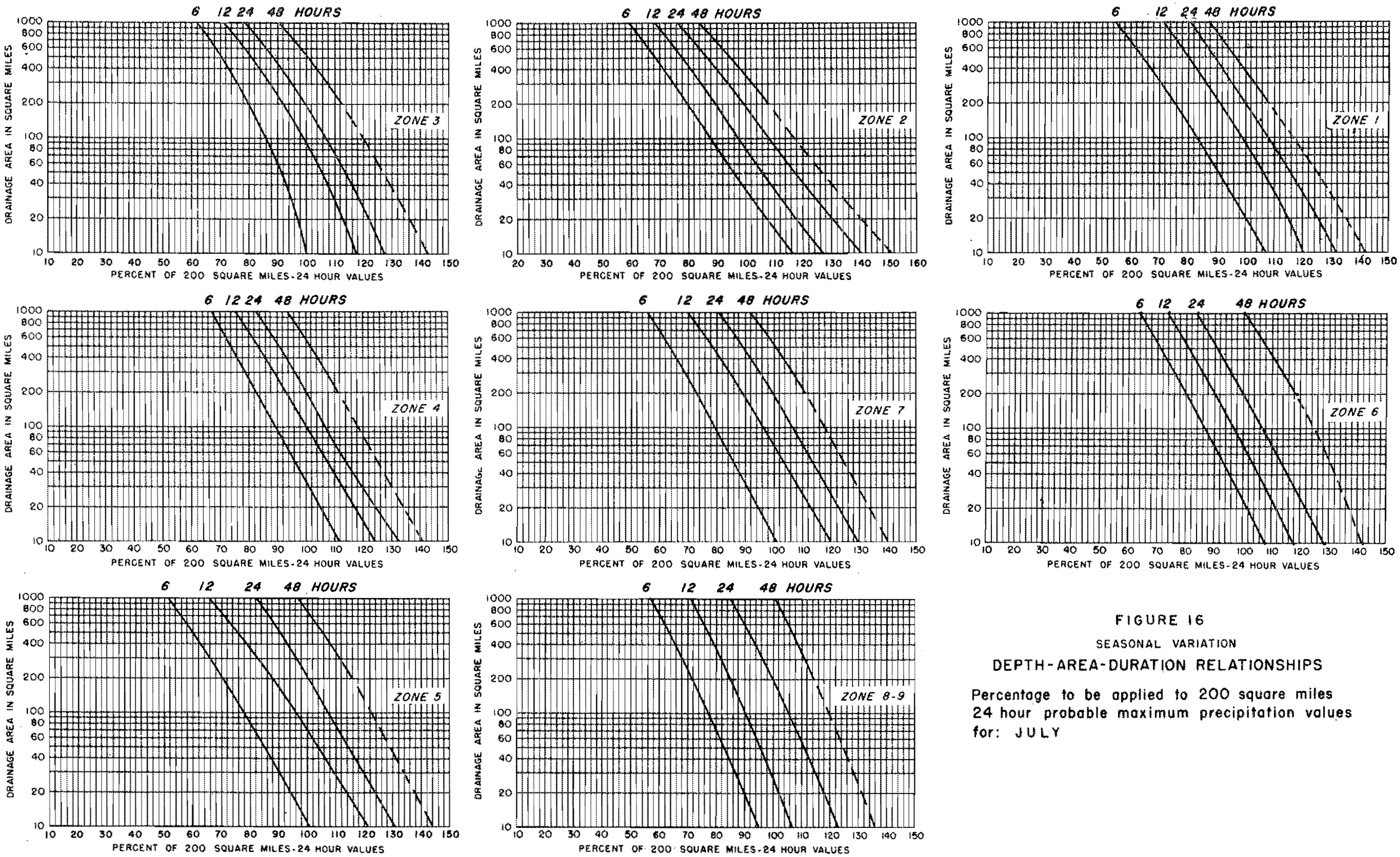


FIGURE 16

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles 24 hour probable maximum precipitation values for: JULY

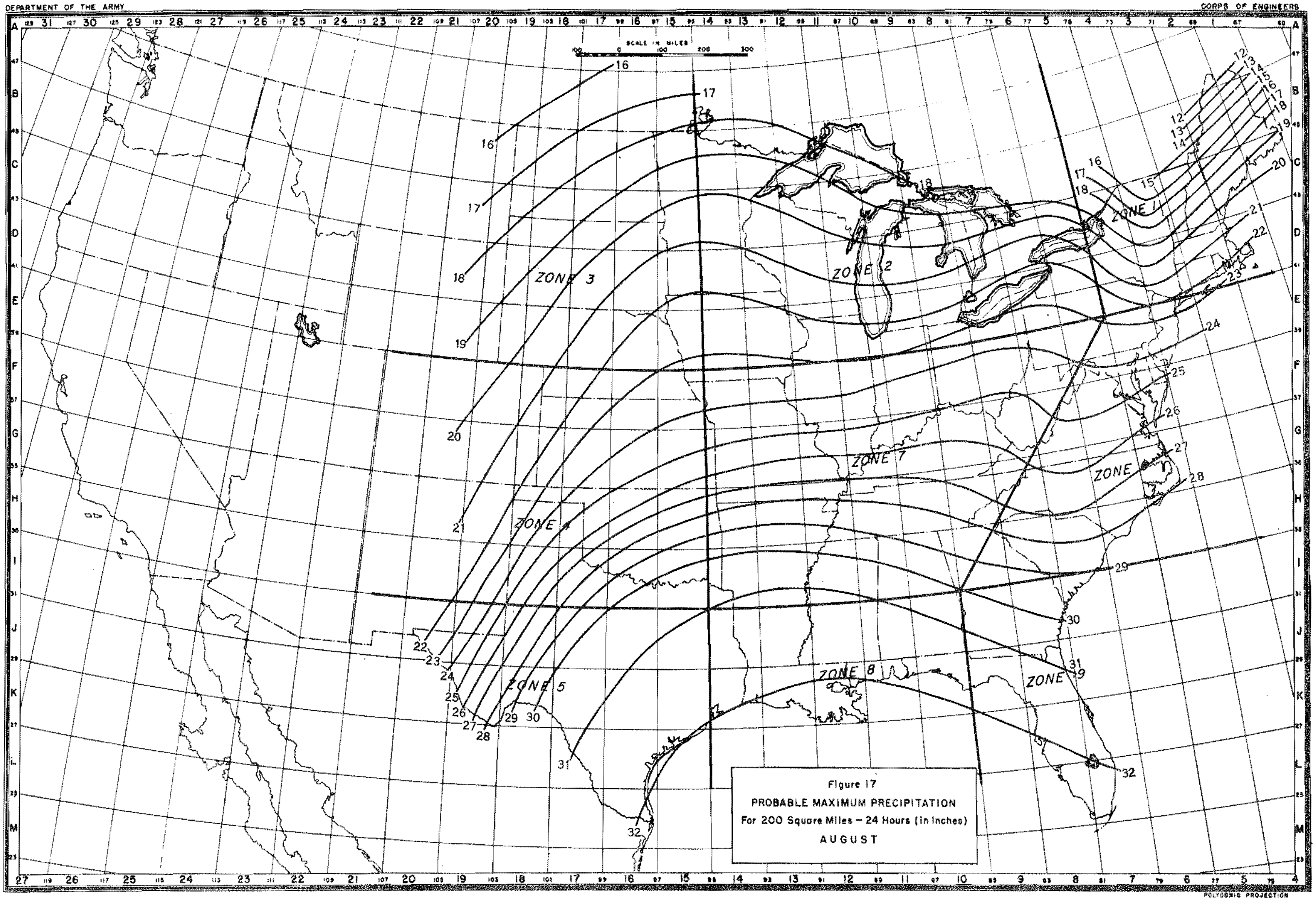


Figure 17
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (in Inches)
AUGUST

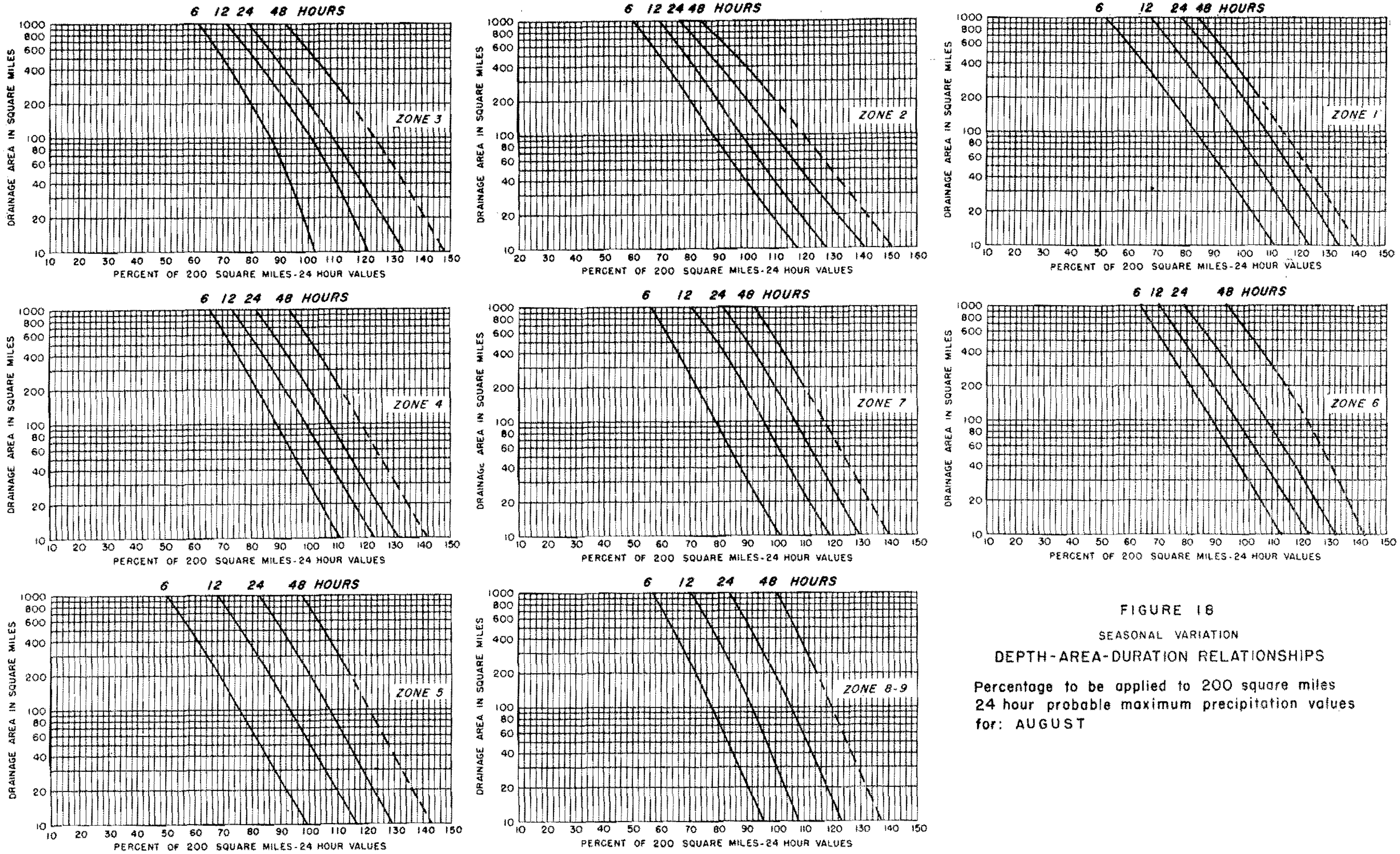


FIGURE 18

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles 24 hour probable maximum precipitation values for: AUGUST

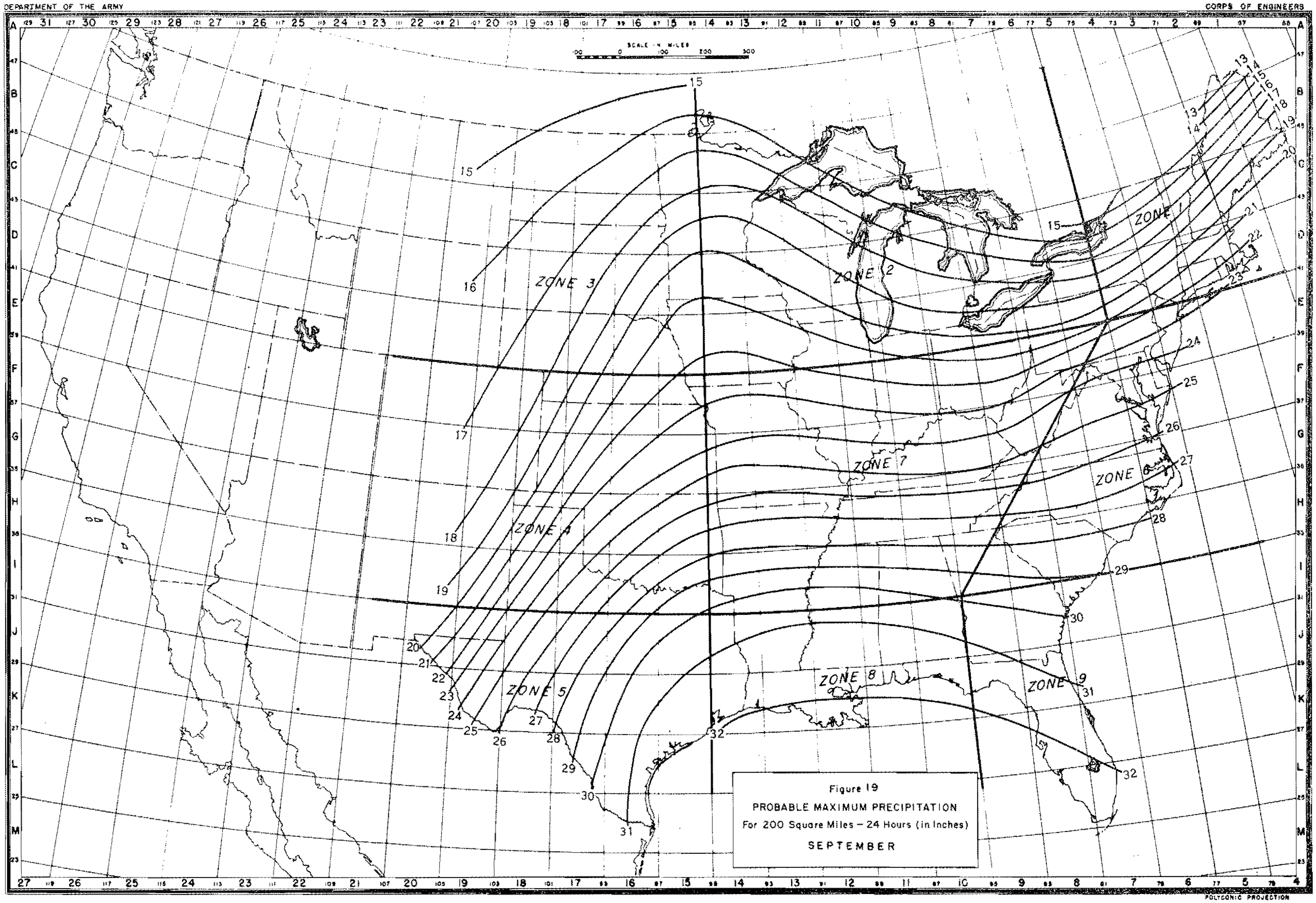


Figure 19
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (in Inches)
SEPTEMBER

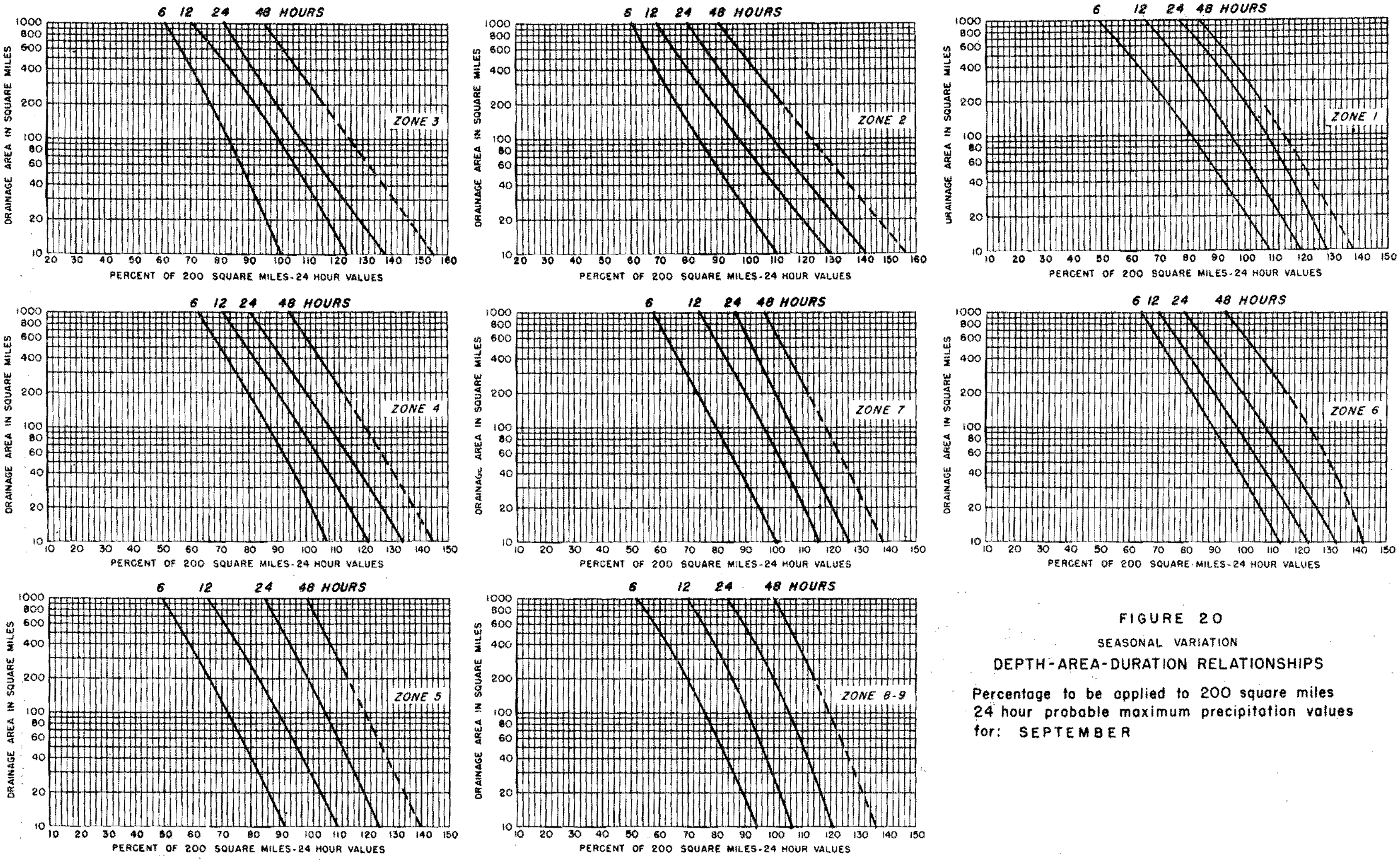


FIGURE 20

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: SEPTEMBER

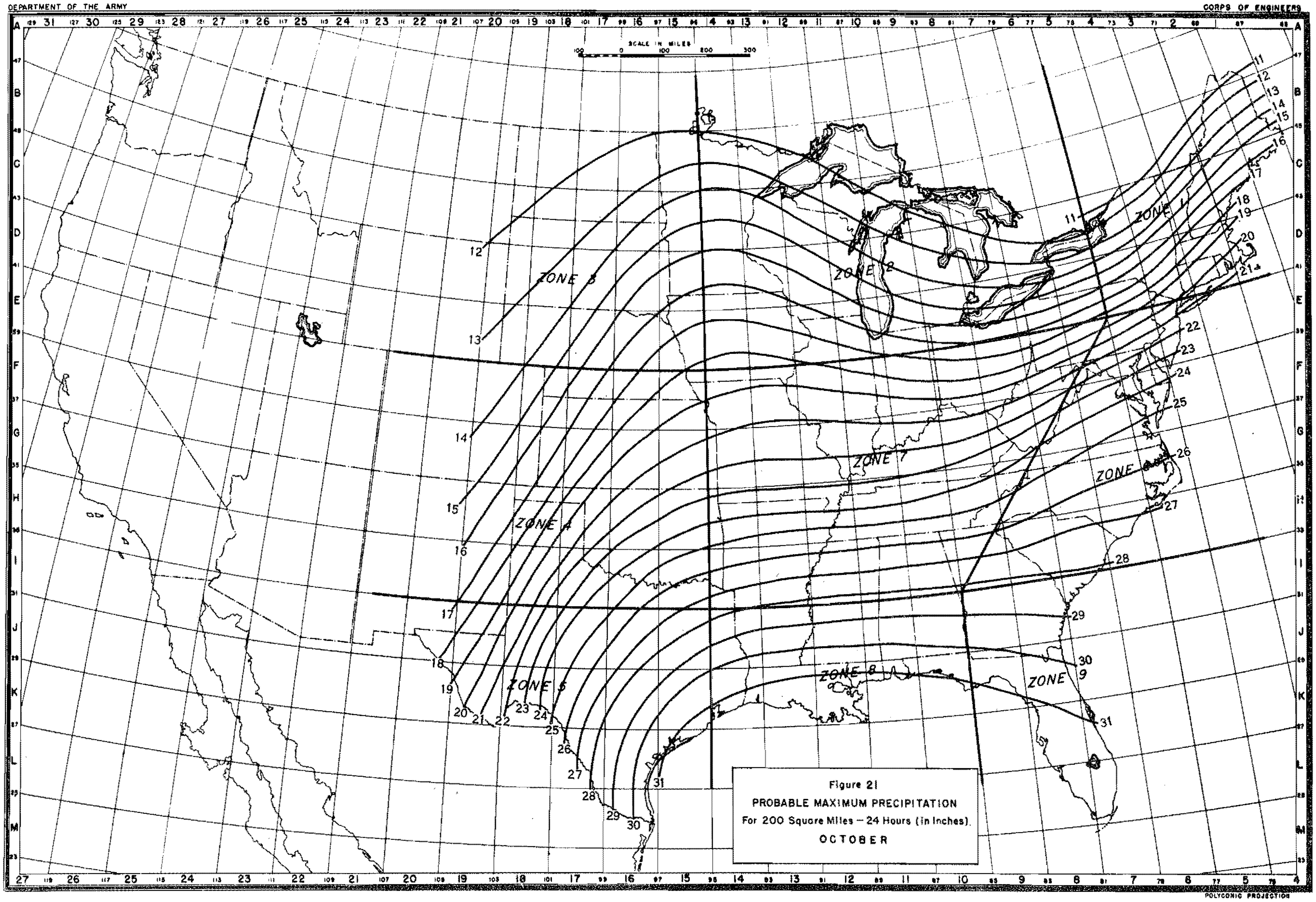
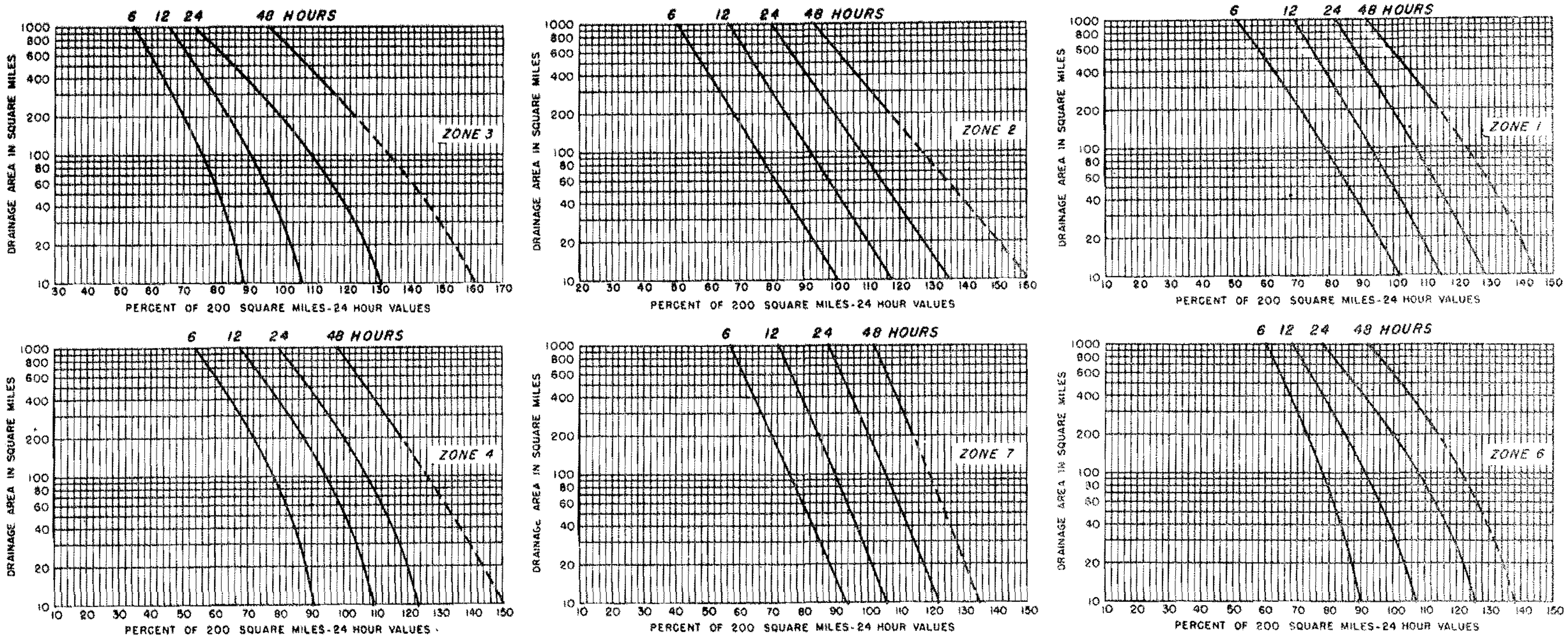


Figure 21
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (in Inches).
OCTOBER



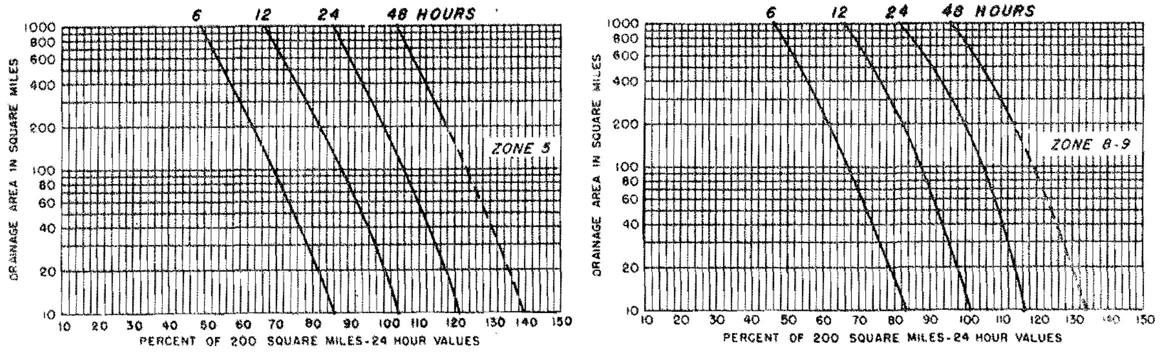


FIGURE 22

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: OCTOBER

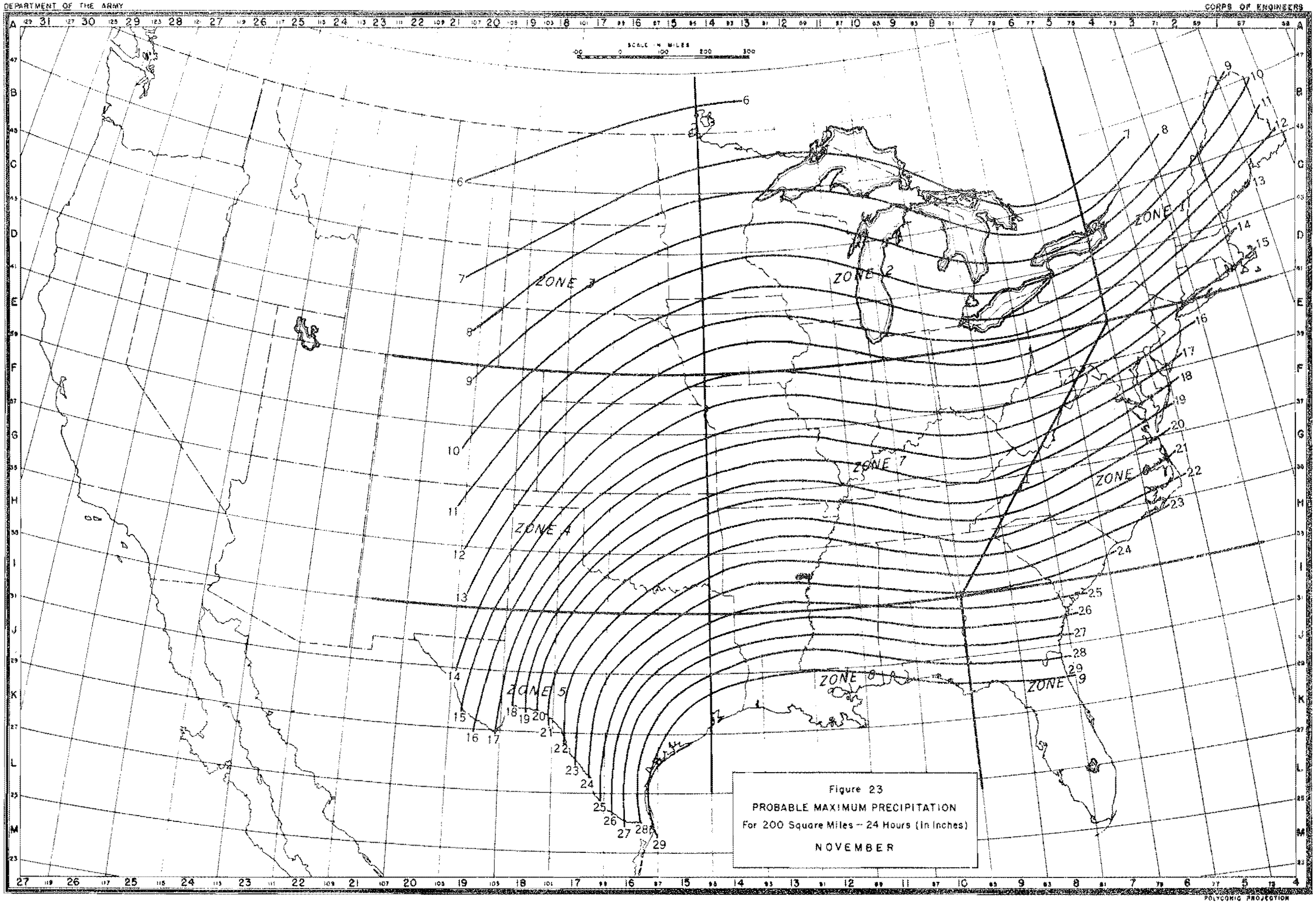


Figure 23
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles — 24 Hours (In Inches)
NOVEMBER

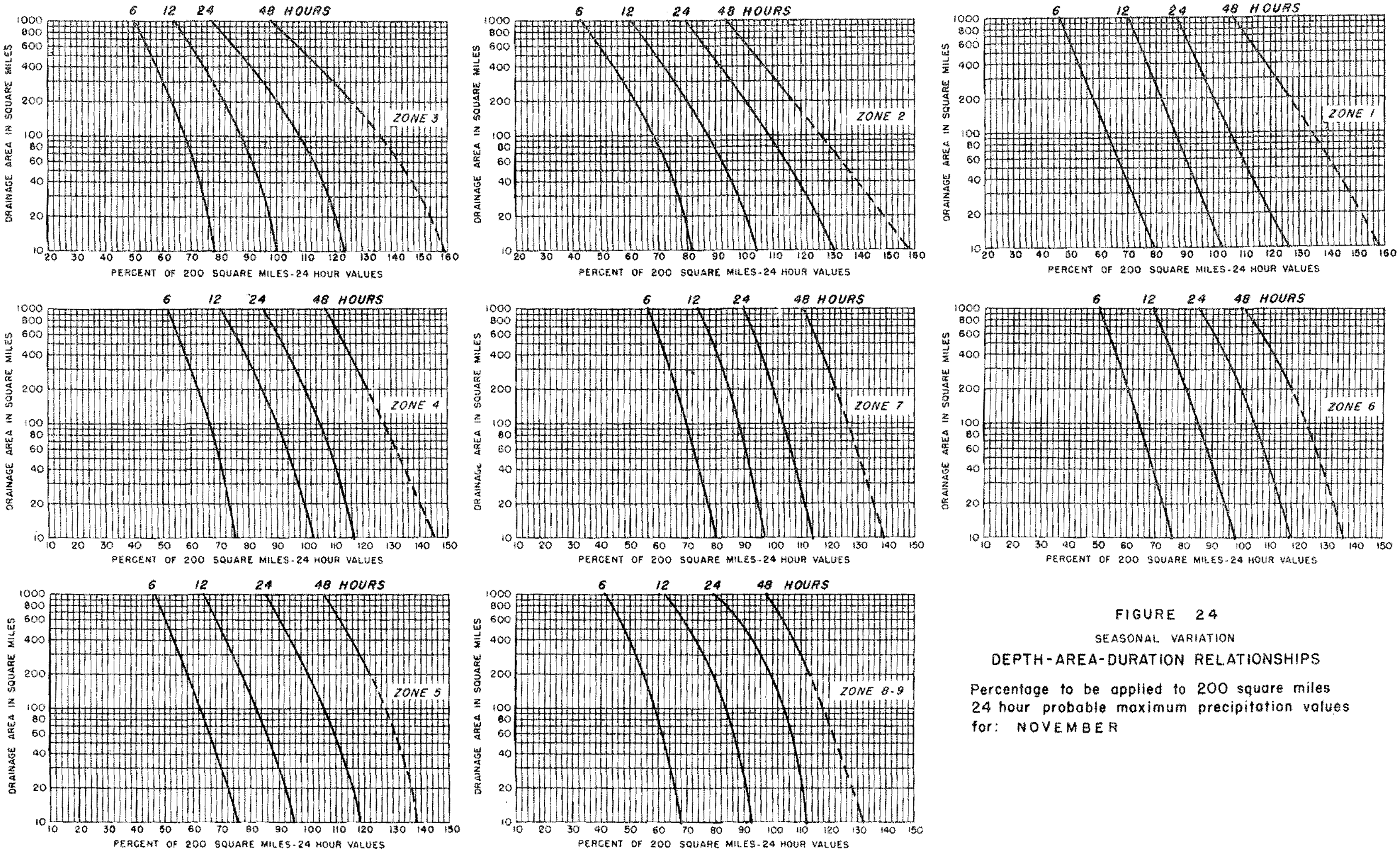


FIGURE 24

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: NOVEMBER

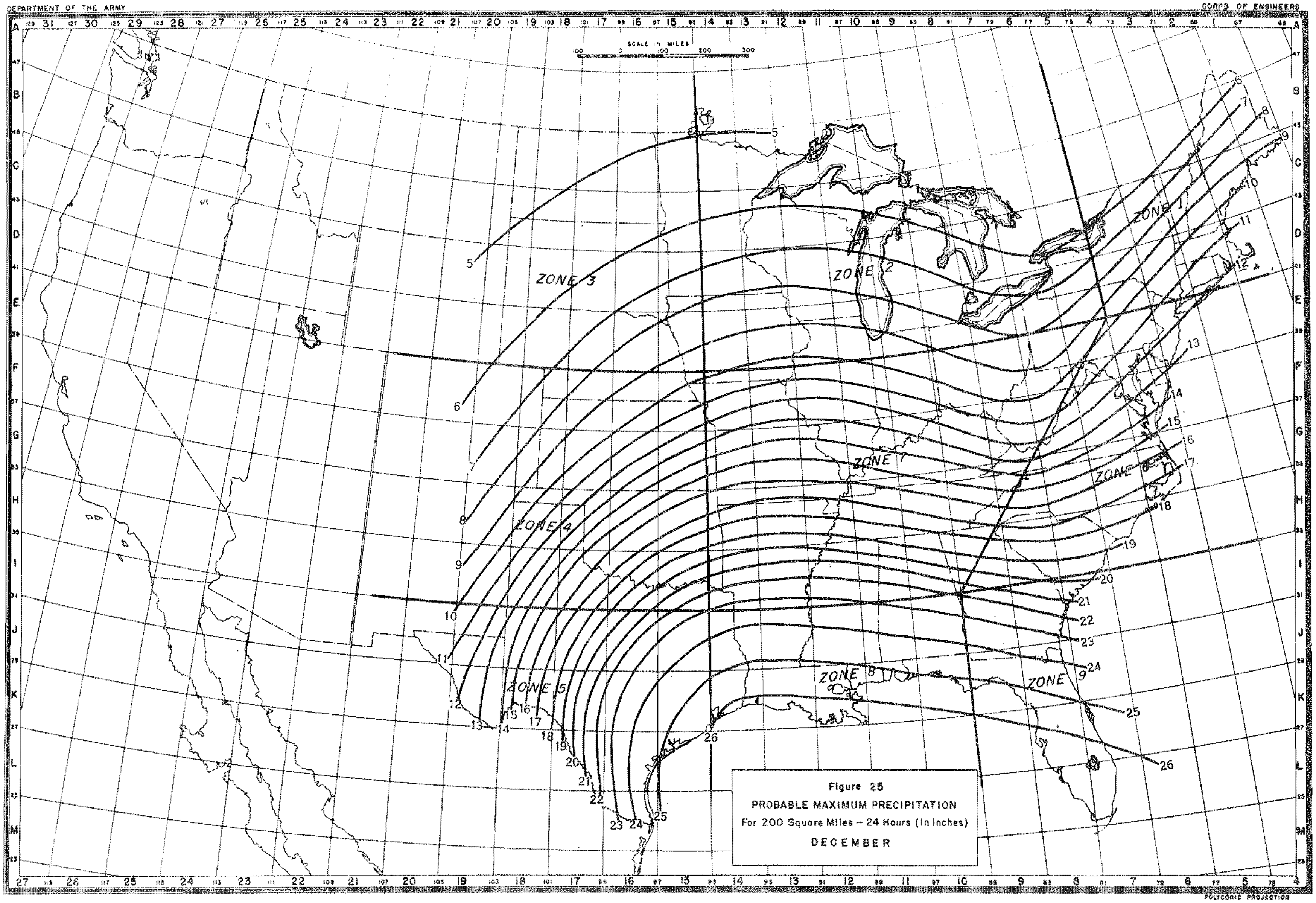


Figure 25
PROBABLE MAXIMUM PRECIPITATION
For 200 Square Miles – 24 Hours (In Inches)
DECEMBER

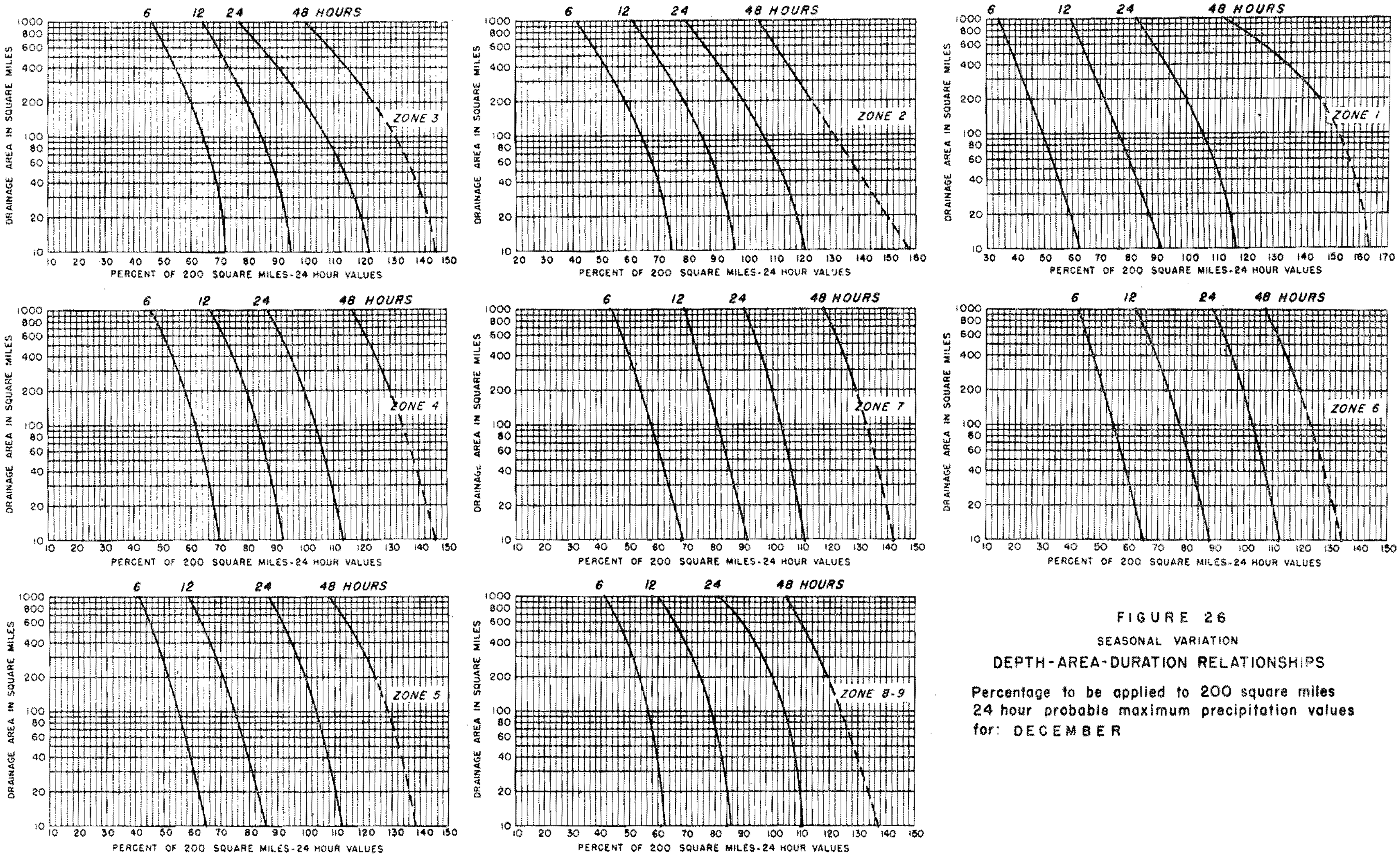


FIGURE 26

SEASONAL VARIATION

DEPTH-AREA-DURATION RELATIONSHIPS

Percentage to be applied to 200 square miles
24 hour probable maximum precipitation values
for: DECEMBER

APPENDIX A

Storms Processed

Year	Date	Assignment No.* (or center)	Type of+ data
1869	October 3-5	NA 1-2	a
1875	February 23-25	Clingman's Dome, N. C.	p
1875	July 25-August 3	OR 4-1	a
1878	September 10-13	OR 9-19	a
1883	February 2-18	OR 5-11	a
1886	March 26-April 1	Pink Beds, N. C.	p
1886	June 13-18	LMV 4-27	a
1887	July 27-31	SA 3-1	a
1889	May 30-June 1	SA 1-1	a
1891	June 23-26	MR 4-2	a
1892	July 24-28	UMV 1-1	a
1892	August 24-27	GL 1-3	p
1894	May 17-22	NA 1-4	a
1894	May 29-June 1	MR 6-14	a
1894	September 18-20	SA 1-13	a
1895	December 16-20	MR 1-1	a
1895	December 16-21	GL 2-8	a
1896	June 4-7	MR 4-3	a
1896	September 27-30	SA 1-19	a
1897	July 18-22	UMV 1-2	a
1897	July 25-27	GL 4-5	a
1897	July 26-29	NA 1-7	a
1898	May 2-6	SW 1-2	a
1898	June 2-6	UMV 1-3	a
1898	August 3-5	SA 1-4	a
1898	August 16	Des Moines, Io.	p
1898	September 21-23	SA 2-3	a
1898	Septmeber 28-October 1	LMV 1-3	a
1898	September 28-October 1	LMV 1-3A	a
1898	September 28-October 1	LMV 1-3B	a
1899	January 4-6	LMV 3-7	a
1899	June 27-July 1	GM 3-4	a
1900	April 15-18	LMV 2-5	a
1900	July 14-17	MR 1-5	a
1900	October 27-30	UMV 1-7A	a
1900	October 30-November 1	UMV 1-7B	a
1901	July 1-6	UMV 1-8	a
1901	September 16-19	SA 2-5	a

*Location of center given for storms lacking assignment number.
+ "a" = approved part II data; "p" = preliminary data.

1902	February 26-March 2	GM 1-10	p
1902	March 25-29	LMV 2-7	a
1902	July 3-10	GL 1-7	a
1902	September 24-27	SA 1-5	a
1903	May 25-31	MR 1-9	a
1903	June 7-15	GL 4-8	a
1903	July 12	SA 1-6	a
1903	August 24-28	MR 1-10	a
1903	August 25-30	GL 1-9	a
1903	September 28-October 1	SW 1-4	a
1903	October 7-11	GL 4-9	a
1904	March 24-26	UMV 2-4	a
1904	September 12-15	NA 1-9	a
1904	September 26-30	SW 1-6	a
1904	October 24-26	GM 3-11	a
1905	February 11-13	SA 3-9	a
1905	June 3-8	GL 2-12	a
1905	June 9-10	UMV 2-5	a
1905	July 18-21	SW 1-7	a
1905	July 18-21	SW 1-7A	a
1905	July 18-21	SW 1-7B	a
1905	July 21-25	GM 3-13	a
1905	September 12-19	UMV 2-18	a
1905	October 16-19	UMV 2-6	a
1906	May 21-26	SA 4-9	a
1906	June 6-8	MR 5-13	a
1906	August 24	SA 1-20	p
1906	November 17-21	LMV 1-4	a
1907	January 1-3	LMV 1-5	a
1907	May 28-31	LMV 3-13	a
1907	July 13-16	MR 1-23	a
1908	May 22-25	SW 1-10	a
1908	June 4-10	MR 1-24 (Zone A)	a
1908	June 4-10	MR 1-24 (Zones C, D, E)	a
1908	July 26-August 2	LMV 3-14	a
1908	August 23-28	SA 2-6	a
1908	October 19-24	SW 1-11 (Zones A, B, C, D, E, F, L)	a
1908	October 19-24	SW 1-11 (Zones G, H, I, J, K)	a
1909	May 30-June 4	LMV 2-10	a
1909	June 2-5	GL 1-11A	a
1909	June 2-5	GL 1-11B	a
1909	July 4-7	UMV 2-8	a

1909	July 18-23	UMV 1-11A	a
1909	July 18-23	UMV 1-11B	a
1909	September 19-22	LMV 3-16	a
1909	November 10-16	MR 1-29	a
1910	October 3-6	OR 4-8	a
1911	February 13-19	MR 2-1	p
1911	August 28-31	SA 3-11	a
1912	March 14-15	SA 2-7	a
1912	May 19-22	GL 3-1	a
1912	July 19-24	GL 2-29	a
1913	January 10-12	LMV 1-9	a
1913	March 23-27	OR 1-15	a
1913	June 6-12	SW 1-14	a
1913	July 12-15	OR 3-7	a
1913	August 8-10	GL 3-2	a
1913	December 1-5	GM 1-5	a
1914	March 24-28	LMV 3-19	p
1914	April 29-May 2	SW 1-16	a
1914	May 10-12	GL 2-15	a
1914	June 25-28	MR 4-14A	a
1914	August 31-September 1	GL 2-16	a
1914	October 13-16	SA 2-8	a
1915	May 25-29	MR 2-7	a
1915	August 1-3	SA 4-15	a
1915	August 16-21	LMV 1-10	a
1915	August 21-22	SA 1-7	a
1915	September 6-9	MR 2-11	a
1915	September 11-16	UMV 1-15	a
1916	January 26-31	MR 2-13	a
1916	March 21-27	GL 4-14	a
1916	June 2-5	GL 1-16	a
1916	June 26-30	MR 2-13	a
1916	July 5-10	GM 1-19	a
1916	July 13-17	SA 2-9	a
1916	July 13-19	SA 2-9A	a
1916	July 13-17	UMV 1-16	a
1917	January 3-5	UMV 3-3	a
1917	July 21-23	GL 2-30	a
1918	March 13-14	GL 2-17	a
1918	May 22-23	UMV 3-5	a
1918	October 24-27	SA 2-10	a
1918	November 6-8	MR 2-18	a
1919	March 14-16	MR 2-19	a
1919	March 15-17	LMV 1-12	a
1919	July 18-23	NA 1-11	a
1919	August 13-14	NA 1-12	a
1919	September 14-15	GM 5-15A	a
1919	September 15-17	GM 5-15B	a

1919	September 16-19	MR 2-23	a
1919	October 25-28	LMV 1-13A	a
1919	October 30-November 1	LMV 1-13B	a
1920	January 21-24	OR 6-23	a
1920	June 15-18	GL 1-18	a
1920	July 16-17	MR 4-18	a
1920	August 18	SA 1-8	a
1921	June 2-6	SW 1-23	p
1921	June 17-21	MR 4-21	a
1921	September 8-10	GM 4-12	a
1921	October 29-November 2	OR 3-12	a
1921	November 16-19	SW 1-24	a
1922	February 19-23	GL 4-17	a
1922	June 8-11	GL 2-21	a
1922	July 9-12	MR 2-29 (Zones A, B)	a
1922	July 9-12	MR 2-29 (Zones C, D)	a
1922	September 1	UMV 3-9B	a
1922	September 2-3	UMV 3-9A	a
1922	October 9-10	SA 1-9	a
1923	June 6-11	SW 1-25	a
1923	July 27-August 1	SA 1-15	a
1923	September 13-19	SW 1-26	a
1923	September 27-October 1	MR 4-23	a
1923	October 11-16	SW 1-27A	a
1923	October 11-16	SW 1-27B	a
1924	May 7-12	SA 1-24	a
1924	June 24-29	GL 1-20	a
1924	August 3-6	GL 2-22	a
1924	August 18-20	UMV 4-11	a
1924	September 13-17	SA 3-16 (Zones B, C, D, F, G)	a
1924	September 12-18	SA 3-16 (Zones A, E, H, I)	a
1924	October 4-11	SA 4-20	a
1925	May 27-29	GM 4-21	a
1925	August 8	SA 1-10	a
1925	September 23-26	SW 1-29	a
1926	August 23-26	LMV 4-5	a
1926	August 31-September 5	MR 3-8	a
1926	September 2-5	SW 1-30	a
1926	September 8-9	OR 4-22	a
1926	September 17-19	MR 4-24	a
1926	September 11-16	SW 2-1	a
1927	February 28-March 1	LMV 4-7	a
1927	April 12-16	LMV 4-8	a
1927	April 17-21	SW 2-4	a

1927	March 11-13	LMV 1-14	a
1927	May 17-19	UMV 4-12	a
1927	July 12-15	SW 2-5	a
1927	September 28-October 2	MR 3-14	a
1927	November 2-4	NA 1-17	a
1928	June 1-5	LMV 2-18	a
1928	June 12-17	LMV 2-19	a
1928	June 16-20	MR 3-15	a
1928	June 28-30	OR 7-10	a
1928	July 5-8	UMV 1-18	a
1928	July 27-29	GL 4-21	a
1928	August 10-13	NA 1-18	a
1928	August 13-17	SA 2-13	a
1928	September 4-7	SA 2-14	a
1928	September 16-19	SA 2-15	a
1928	October 15-17	MR 3-20	a
1928	November 15-17	MR 3-20	a
1929	March 11-16	LMV 2-20	a
1929	May 29-June 3	MR 3-25	a
1929	August 1-2	UMV 2-17	a
1929	September 23-28	SA 3-20	a
1929	September 29-October 3	SA 3-23	a
1930	January 6-11	LMV 2-22	a
1930	May 15-19	LMV 2-24	a
1930	June 12-15	UMV 2-14	a
1930	October 9-12	SW 2-6	a
1930	October 18-20	GL 1-26	a
1931	July 20-25	GL 1-27	a
1932	January 11-13	LMV 4-16	a
1932	June 2-6	SW 2-7	a
1932	June 2-6	SW 2-7A	a
1932	June 30-July 2	GM 5-1	a
1932	August 1-3	OR 2-8	a
1932	August 15-17	SW 2-8	a
1932	August 30-September 5	GM 5-16A	a
1932	September 16-17	NA 1-20	p
1932	October 4-6	NA 1-21	a
1932	October 14-18	SA 5-11B	a
1932	October 15-18	SA 5-11A	a
1932	November 4-9	SA 4-28	p
1933	April 11-14	NA 1-23	a
1933	June 28-29	UMV 2-15	a
1933	July 22-27	LMV 2-26	a
1933	July 24	SA 1-11	a
1933	August 20-24	NA 1-24	a

1934	February 27-March 4	LMV 4-19	a
1934	April 3-4	SW 2-11	a
1934	June 12-16	SA 5-1	a
1934	September 5-9	SA 5-12	a
1934	November 19-21	LMV 1-18	a
1935	January 18-21	LMV 1-19	a
1935	May 27-June 2	MR 3-28B	a
1935	May 30-31	MR 3-28A	a
1935	May 31	GM 5-20	a
1935	June 10-15	GM 5-2	a
1935	June 12-18	SW 2-13	a
1935	June 25-26	UMV 3-14	a
1935	July 6-10	NA 1-27	a
1935	September 2-6	SA 1-26	a
1935	August 6-7	OR 9-11	a
1935	December 5-8	GM 5-4	a
1936	February 1-5	GM 2-18	p
1936	March 9-13	NA 1-29A	p
1936	March 16-22	NA 1-29B	p
1936	September 14-18	GM 5-7	a
1937	January 5-25	OR 5-6	a
1937	April 24-28	SA 5-13	a
1937	May 26-30	GM 5-17	a
1937	July 11-16	UMV 1-20	a
1937	August 31-September 3	GL 3-5	a
1937	September 6-10	SW 2-15A	a
1937	September 6-10	SW 2-15B	a
1937	October 16-21	SA 5-14	a
1938	February 9-14	GL 2-27	a
1938	February 14-19	SW 2-17	a
1938	May 17-20	MR 5-6	a
1938	May 30-31	MR 3-29	a
1938	June 10-11	UMV 3-17	a
1938	June 29-July 1	GL 3-11	a
1938	July 19-25	GM 5-10	a
1938	August 30-September 4	MR 5-8	a
1938	September 16-21	SA 5-16	a
1938	September 17-22	NA 2-2	a
1939	February 2-3	Deer Lodge, Tenn.	p
1939	June 19-20	(Snyder, Tex.)	p
1939	July 4-5	OR 2-15	p
1939	August 19	NA 2-3	a
1939	August 21	NA 2-13	p
1939	August 25	UMV 3-19	a
1940	August 6-9	LMV 4-24	a

1940	August 10-17	SA 5-19A	p
1940	September 1	NA 2-4	a
1940	September 2-6	SW 2-18	a
1940	November 22-25	GM 5-13	a
1941	May 20-25	GM 5-18	a
1941	May 22	UMV 2-19	a
1941	August 28-31	UMV 1-22	a
1941	September 20-23	GM 5-19	a
1941	September 30-October 7	UMV 3-20	a
1941	October 17-22	SA 5-6	a
1941	October 18-22	MR 6-2	a
1942	May 19-23	NA 2-5	a
1942	June 23-26	MR 6-1	a
1942	July 2-6	GM 5-12	a
1942	July 7-9	UMV 3-21	a
1942	July 17-18	OR 9-23	a
1942	August 7-10	NA 2-8	a
1942	September 15-19	UMV 1-25	a
1942	October 11-17	SA 1-28A	a
1942	October 11-17	SA 1-28B	a
1943	March 13-17	MR 6-11	a
1943	May 6-12	SW 2-20	a
1943	May 12-20	SW 2-21	a
1943	August 4-5	OR 3-30	a
1944	March 26-31	MR 6-12	p
1944	June 10-13	MR 6-15	a
1945	March 28-April 2	SW 3-5	a
1945	June 24-27	Georgetown, S.C.	p
1946	August 12-16	MR 7-2B	a
1948	June 23-24	Del Rio, Tex (nr)	p
1948-49	December 29-January 1	NA 2-18	p
1951	July 9-13	MR 10-2	a

APPENDIX B
CONTROLLING STORMS

Some of the major controlling storms for each month are shown in this list, by location of storm center, date, and assignment number. A brief synoptic description is given along with the zones in which the storm was considered. The moisture adjustment (in percent) for transposition to the center of the zone for the actual date of storm occurrence is listed in parenthesis after the zones concerned.

The Ironton, Mo., storm of January 26-31, 1916 (MR 2-13), was the result of interaction of the circulation around two large high pressure areas of contrasting heat and moisture properties. The opposing flows were locally intensified by the remnants of two Pacific cyclones with their attendant upper-air troughs. One resulting wave formation took place on the 26-27th, the other on the 30th. Such a situation is not uncommon for zones 2 (86), 3 (71), 4 (116), and 7 (128).

In the Pinkham Notch, N. H. storm of March 9-13, 1936 (NA 1-29A), a Low which formed in the southern Gulf of Mexico moved up the East Coast to New England and amalgamated with another Low from the west with a cold front oriented north-south. The first Low set up a strong inflow of warm moist air which was lifted over the front of the second Low and caused the major precipitation. This storm was not transposed out of zone 1 (156).

The previous storm was followed soon by the storm of March 16-22, 1936 (NA 1-29B), also centered at Pinkham Notch, N. H. A deep Low developed in the Gulf Coast States and moved northward along the Atlantic Coast, quite slowly causing a prolonged inflow of modified tropical air into New England. The precipitation was greatly augmented by orography. Transposition was confined to zone 1 (172).

The storm centered at Elba, Ala., on March 11-16, 1929 (LMV 2-20), was characterized by exceptionally strong inflow from the south between a warm High off the Atlantic Coast and a slowly moving frontal trough in the Mississippi Valley. This type of storm was considered possible in zones 5 (121), 8 (127), and 9 (127).

The storm of March 21-27, 1916 (GL 4-14), with centers at Beloit, Wis., and Washington, Iowa, began with a snow cover deposited by a fast-moving deepening Low. A continental polar air mass followed after it had reached the East Coast and directed a flow of warm moist air from the Gulf of Mexico around its western periphery. A second Low from the west intensified the warm air inflow. This

Low, as it slowly traversed the Midwest, released the moisture contained in the air from the Gulf of Mexico. This storm was transposed to zones 2 (142), 4 (182), and 7 (186).

The storm of March 23-27, 1913 (OR 1-15), centered at Bellefontaine, Ohio, was the result of waves on a quasi-stationary front which stretched from New England to Texas. The significant meteorological feature of this storm was the persistence of a polar continental High over the Northern States and an equally persistent mass of moist air over the western Gulf States. The intense interaction between the air masses along the front produced lifting and convergence to supply the initial impulse to probably convectively unstable air. The transposition of this storm was limited to zones 2 (111) and 7 (148).

The Cheyenne, Okla., storm of April 3-4, 1934 (SW 2-11), accompanied wave action along a quasi-stationary front. The storm type has widespread occurrence, but the orographic effects involved in this storm confined transposition to general areas with elevations between 1000 and 3000 feet. This storm was therefore limited to zones 4 (132) and 5 (164).

The storm centered at Warner, Okla., May 6-12, 1943 (SW 2-20), was due to repeated wave action along a quasi-stationary front which persisted in the same vicinity for several days. Association of a trailing front and circulation about the Mexican Low appears to be conducive to development of heavy-rain-producing wave cyclones. The orientation is generally northeast-southwest with an elongated High to the north of the front. Considering the possible interrelations among the Mexican Low, quasi-stationary front, and the elongated High, transposition was limited to zones 4 (125) and 7 (125).

The surface charts for the storm of May 30-June 1, 1889, centered at Wellsboro, Pa., (SA 1-1) show that on the 29th and 30th of May an occluded wave cyclone moved northeastward from Arkansas to Lake Erie. By the evening of May 30 the trough containing the new quasi-stationary front extended southward through extreme western Pennsylvania to northwestern Florida. Repeated wave developments then moved northward along the front as the front itself moved slowly eastward. Although the usual factors of frontal lifting and other mechanisms were present, orographic lifting of the warm moist air east of the front played an important part in the rainfall production. The transposition was therefore limited to zones 1 (152) and 6 (180).

The storms centered at Warrick, Mont., June 6-8, 1906 (MR 5-13), Springbrook, Mont., June 17-21, 1921 (MR 4-21), and Savageton, Wyo., Sept. 27-Oct 1, 1923 (MR 4-23), are representative of many eastern Montana and Wyoming storms in which tropical air undergoes cyclonic turning around a Low. Since topography also plays an important role in these storms, transposition was limited to zone 3. The adjustment factors are 199, 128, and 141 respectively. The Savageton, Wyo., storm (MR 4-23), was particularly heavy and for zone 3 is responsible for keeping the probable maximum precipitation values high in September and October. The Springbrook, Mont., storm (MR 4-21) influences the precipitation values for the same zone by its unusually high values in June.

The Bonaparte, Iowa, storm of June 9-10, 1905 (UMV 2-5), is especially noteworthy for the large precipitation amounts for short durations. The storm began with an extra-tropical cyclone over the Dakotas and Nebraska which moved slowly over Iowa where it reached its maximum intensity. The convergence associated with the cyclonic center, wave action along the front, and overrunning warm air were the factors causing the heavy rain. This storm was considered transposable within zones 2 (141), 3 (128), 4 (145), and 7 (145).

The storms centered at Stanton, Nebr., June 10-13, 1944 (MR 6-15), and at Boyden, Iowa, Sept. 17-19, 1926 (MR 4-24) may be considered of the same type. The centers of intense rainfall in each storm occurred in the vicinity of a frontal wave in a well-defined Low. The strength of the circulation depends upon the temperature contrast between the interacting air masses. This type of storm is considered possible in zones 2, 3, 4, and 7. The adjustments for MR 6-15 are 131, 134, 148, and 145. Those for MR 4-24 are 125, 122, 138 and 141.

The rainfall centered at Georgetown, S. C., June 24-27, 1945, was the result of a tropical storm which passed a short distance off the South Carolina coast. This storm was limited to zone 6 (138).

The rain in the Hearne, Tex., storm of June 27-July 1, 1899 (GM 3-4), was associated with a decadent tropical storm which moved inland between Corpus Christi and Galveston. The remains of the Low later became part of a quasi-stationary frontal trough extending west-southwestward from a Low which had moved across the Great Lakes to the Atlantic. As in many major Texas storms, an ill-defined Low persisted in northern Mexico. Two factors, not altogether independent, served to restrict the transposition of this storm. The Mexican Low appears to be an essential part of the storm. Also, there is a tendency, apparently associated with this Mexican Low, for trailing cold fronts to develop heavy-rain-producing waves or cyclonic systems in the region. Transposition was therefore confined to zone 5 (116).

The moisture for the Kerville, Tex., storm of June 30-July 2, 1932 (GM 5-1), was supplied by sustained flow around the westward extension of the Bermuda High. The movement into the area of interest of a cold front trailing southwestward from a Low in the Great Lakes region brought about a change in isobaric curvature from anticylonic to cyclonic with the resulting marked convergence responsible for the heavy rain. The orographic influence was so marked that it was not transposed out of zone 5 (116).

The Altapass, N. C. storm of July 13-17, 1916 (SA 2-9), resulted from a hurricane moving inland on the South Carolina coast on the 13th and 14th. There was heavy rain along the coast but the center of heaviest rainfall was in North Carolina at an elevation between 2000 and 3000 feet, near the crest of the Appalachians. Because of the orography associated with this storm, it was not transposed out of zone 6 (128).

The Smethport, Pa., storm of July 17-18, 1942 (OR 9-23), is characterized by a moist northeastward-flowing current aloft. In storms of this type, one immediate cause of the heavy precipitation is cyclonic turning into a trough aloft in the vicinity of the Appalachians. Another is the western slope of the Appalachians. For these reasons transposition was limited to zones 2 (116) and 7 (121).

The Miller Island, La., storm of August 6-9, 1940 (LMV 4-24), occurred in connection with a tropical hurricane which crossed Florida on August 2 and continued moving westward approximately along the 29th parallel. On the 7th, the storm arrived at a point just south of Lake Charles, La., and started recurving inland. The rainfall in southern Louisiana, already heavy, became torrential. Because of the modifications imposed on the storm's structure as a result of its slow westward movement parallel to the coast line its transposition was limited to zones 5 (110) and 8 (110).

The Collinsville, Ill., storm of August 12-16, 1946 (MR 7-2B), resulted from the lifting of a continuous inflow unstable tropical maritime air which accompanied an open wave moving eastward over Kansas and Missouri. Because of the persistence of a polar High over the Eastern States and the absence of an inflow of cold air west of the wave center, the wave moved very slowly and did not occlude. This storm was considered transposable within zone 2 (116) and 7 (121).

The Manahawken, N. J., storm of August 19, 1939 (NA 2-3), was a decadent tropical storm. The Low passed inland over extreme northwestern Florida on August 12-13. After remaining practically stationary over Alabama until the 17th, it began to move slowly northeastward attended by heavy rains. By the time of the heavy rain in New Jersey on the 19th, the cyclonic circulation was quite weak. Two days later, when practically no indication of the Low remained, a severe local storm occurred at Baldwin, Maine, apparently as a result of the moisture brought in by the same tropical storm. Since the storm was accompanied by heavy rain along most of its path, and since heavy rains caused by tropical storms have been observed as much as several hundred miles inland, the area of transposition was limited to zones 1 (103), 6 (122), and 9 (128).

A storm important because of its adjustment potential occurred at Hallett, Okla., on Sept., 2-6, 1940 (SW 2-18). Because the dominant feature of this storm was a northeastward-flowing current of moist air aloft, it was considered transposable to zones 4 (134), 5 (141), 7 (134), and 8 (141).

The Thrall, Tex., storm of Sept. 8-10, 1921 (GM 4-12), is one of the greatest storms of record. Many of the maximum observed U. S. values for assigned areas and durations occurred in this storm. The mechanism producing the exceptionally heavy rain appeared to be convergence caused by a change from the anticyclonic (with higher than geostrophic velocities) to straight flow. A tropical storm moving inland over Tampico, Mexico, provided moisture supply in great depth, while another tropical storm moving west-northwestward from the vicinity of Barbados served to warp the isobars of the wedge between the Lows into the shape of extreme effectiveness for the convergence process. Because such a pattern, particularly since it includes a warm anticyclonic wedge, belongs to Gulf State latitudes, this storm was limited to zones 5 (105) and 8 (105).

The storms centered at Patterson, N. J., October 7-11, 1903 (GL 4-9), and at Kinsman Notch, N. H., November 2-4, 1927 (NA 1-17), are essentially of the same type, not an uncommon one for producing heavy rain over the Atlantic coastal region south of latitude 33. The principle features of this storm type in its early stages are high pressure over New England and the Middle Atlantic States, with low pressure centered over the Great Lakes region and an associated cold front extending southward. The cold front decelerated as it moves eastward and becomes quasi-stationary in the vicinity of the Hudson Bay Valley. Cyclogenesis then takes place along the front over the Southeastern States, north of which an inverted-V low-pressure trough may develop well into New England. The resulting circulation carries moist unstable tropical air from the southern portion of the North Atlantic over the colder air west of the front. The resulting convergence and frontal lifting of the moist air produces heavy rains over the region. These storms were transposed to zones 1 and 6. GL 4-9 has the adjustment 125 for each zone and NA 1-17 the adjustments 141 and 145. The storm centered at Patterson, N. J., (GL 4-9), is the chief reason for the comparable high precipitation values in October over New England.

The Trenton, Fla., storm of October 17-22, 1941 (SA 5-6), was associated with a mild tropical disturbance first noticed in the Caribbean on the 17th, subsequently moving into the eastern Gulf, and then recurving into the Florida Peninsula near Cedar Keys on the 19th. After moving very slowly northeastward, it became practically stationary near the east coast of Florida during the 20th and 21st. By the 22nd it had practically lost its identity as a tropical disturbance. There is abundant observational evidence demonstrating that tropical storms can move inland anywhere along the Gulf Coast and along the Atlantic Coast northward to Cape Cod. Sluggish movement, though more characteristic of low than middle latitudes, is not unknown farther north. For example, a tropical storm, not of hurricane force, remained in the vicinity of Cape Hatteras for several days in July 1901. Thus, this storm was considered transposable to zones 5 (110), 6 (100), 8 (113) and 9 (113).

The Meekner, Okla., storm of October 19-24, 1908 (SW 1-11), occurred in a trough of low pressure west of an intense High centered over the northeastern part of the country. Much of the peak rainfall was due to thunderstorm activity. This storm was limited in transposition to zones 4 (144) and 7 (137).

The storm centered at Satsuma, Tex., December 5-8, 1935 (GM 5-4), was due to the lifting of maritime tropical air over a quasi-stationary front which lay near the Gulf Coast of Texas. This type of storm is considered possible in zones 5 (152), and 8 (152).

A feature of the storm of December 16-20, 1895 (MR 1-1), centered at Phillipsburg, Mo., was a polar front extending from Texas northeastward into the Lakes region with little variation from its mean position during the period. Minor waves travelled along its length. An elongated High predominated off the eastern seaboard carrying moist air from the Gulf into the storm area. Convergence, frontal lifting, and wave action combined to produce heavy and continuous rains. The Phillipsburg storm was considered transposable within zones 4 (153), and 7 (157).

In the Berlin, N. Y., storm of December 29, 1948-January 1, 1949 (NA 2-18), a cyclone moved from Colorado to New England where it became elongated and oriented in a north-south direction. Intense inflow from the southeast resulted and upon striking a front in eastern New York was lifted with heavy rainfall ensuing. This storm was not transposed beyond zone 1 (100).

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(Nos. 6-22 numbered retroactively)

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