GENERALIZED EVALUATION OF FLASH-FLOOD POTENTIAL

A Report by

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for

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TABLE OF CONTENTS

Tables

(Table of Contents cont.)

Figures

Appendices

GENERALIZED EVALUATION OF FLASH-FLOOD POTENTIAL

INTRODUCTION

Problem Identification

A flash flood is considered to be a flood that occurs with very little warning and that constitutes an unusual event. In general, flash floods are defined as damaging floods that occur within 4 to 6 hours of the time that the causative rainfall occurs. Neglecting artificially induced hazards such as dam failures, flash floods are generally the result of relatively intense rainstorms. Precise estimation of the critical rainfall intensity that is capable of producing flash flooding on any specified watershed is difficult, as many watershed and seasonal factors influence the hydrologic response, however, those areas susceptible to rainfall intensities of severe magnitude may be considered to be areas with potential hazards due to flash flooding.

If rainfall intensities of severe magnitude can be considered to be the causative mechanism of flash flooding, then almost all areas of the United States can be considered to be areas of possible flash flooding, as most areas of the United States have experienced rainfall intensities of severe magnitude. Even so, flash floods are most common in the arid and semi-arid regions of the west and southwest. This is due, in part, to the meteorological and physiographic conditions that frequently can lead to the development of large convective thunderstorm cells that are capable of producing large amounts of rainfall in short periods of time.

Flash Flood Forecast Program

One duty of the National Weather Service is the development and operation of the Flash Flood Forecast Program. The Flash Flood Forecast Program must provide communities in the United States with information concerning the flash-flood potential of streams in the communities and surrounding areas.

In addition, when approaching storms or other conditions deem it necessary, flash-flood warnings are issued to appropriate community authorities and media so that actions to reduce property damage and loss of life may be initiated. Three basic methods of providing flash-flood warnings have been used or proposed by the National Weather Service (U. S. Weather Bureau, 1969). The first approach employs conventional flood forecast techniques at the community level. Under the guidance of the local River District Office of the National Weather Service, the community establishes a network of rainfall and river observation stations. As conditions warrant, information concerning rainfall rates, stream stages, and observed storm movement is collected by a warning representative. Flash-flood warnings are issued by the warning representative as necessary. If radar is available in the area, warnings may be based on radar tracking and rainfall measurement, as well as observational reports from the observer network.

The second approach involves use of a recently developed flash-flood alarm mechanism. As rising stages in headwater streams or tributaries reach a predetermined height, an alarm located at a continuously occupied public authority is activated by telephone or radio signal. The trigger of the alarm system is an automatic stage measuring device located some distance upstream of the community. The positioning of the triggering device, both geographically and vertically, must be determined from consideration of expected warning times and required evacuation times.

The third approach is dependent upon the skill and alertness of the rainfall forecaster. Warnings of possible flash floods are issued on the basis of rainfall reports received by the meteorologist during the progress of the storms and the meteorologist's estimate of the continuing intensity of the storm. Telemetered rain gages can provide information on storm intensities, and radar surveillance can provide information concerning time of onset, duration, areal extent, and intensity.

The Need for Generalized Criteria

Application of any of the three flash-flood warning systems requires an expenditure of capital and manpower, which must be justified by the size of the community involved and potential damages from flash flooding. Since an estimated 30,000 locations in the United States might warrant investigation as potential flash-flood locations under the Flash Flood Warning Program of the National Weather Service, the determination of the most effective type of warning program for application in each community would require far greater manpower resources than are currently available to the National Weather Service. Since highly detailed hydrologic and economic analyses of the 30,000 locations is not feasible, the establishment of generalized criteria by which a preliminary evaluation of the relative severity of flash-flood potential can be made with a minor amount of study is of critical importance. Accordingly, the objective of the research reported on herein is the establishment of criteria for making a relative evaluation of flash-flood potential in a short time using readily available information. Using these criteria, effective allocation of limited flash-flood forecast and warning resources may be made, so that those communities where the potential of flash flooding is most severe may be served most effectively.

Scope of Research

Hydrologic Factors. Because of special uncertainties associated with flash flooding due to events such as the failure of water control structures, earthslides, ice jams etc, development of generalized criteria for the evaluation of flash-flood potential reported on herein is limited to flash floods that result directly from rainfall. In addition, the study is limited to surface runoff phenomena and does not include treatment of coastal flooding problems such as hurricane surges. Hydrologic factors that would bear on the determination of flash-flood potential within the scope of this study are rainfall and runoff intensity-duration frequency relationships and drainage basin characteristics such as area, slopes, stream configurations, etc.

Damage Factors. In evaluating the flash-flood potential at any location, consideration of hydrologic factors must be supplemented by the evaluation of potential property damage and hazard to life within the flood-plain areas. In the preliminary investigations, it was determined that it was not feasible to establish generalized criteria for the evalution of potential damage within flood-plain areas. Any preliminary evaluation of damage potential would require inspection of developments within the flood-plain areas either through use of aerial photographs, or personal visits to the area.

Study Procedures

If generalized criteria for the evaluation of flash-flood potential are to be developed so that application to any locality in the United States is possible, then the information used to develop the criteria should be of a type generally available for all localities of interest. Consequently, available literature and data sources should be searched for information concerning flash flooding, the flash-flood process, and appropriate flash-flood data. Based on the results of this search, development of criteria that quantify the flash-flood potential of a location should be accomplished. Following the development of the criteria, some method of generalization should be established so that the flash-flood potential of ungaged streams may be evaluated. Based on the demonstrated effectiveness of the proposed generalized criteria, some method of application should be developed so that ranking of locations according to flash-flood potential magnitudes can be accomplished.

DEVELOPMENT OF CRITERIA FOR EVALUATING FLASH-FLOOD POTENTIAL

Development of Proposed Criteria

Background Information. The generalized indicators of flash-flood potential should relate to the following:

1. Magnitude of flash flooding
2. Frequency of flash flooding
3. Available warning time

While it is considered that rainfall depth-area-duration-frequency relationships would be good indicators of the hydrologic potential of flash flooding, detailed studies of these relationships were not pursued for various reasons. First of all, the information search indicated that systematic annual data on rainfall amounts for short durations is not available in a form that could be readily accessed at a reasonable cost for thousands of stations. Secondly, generalized mapping of rainfall intensity frequency values has been completed by the National Weather Service and is available as a general guide. Thirdly, in addition to rainfall factors, basin characteristics have a great influence on the nature of flash flooding, and it is not considered that simple relationships of rainfall intensities could be developed for deriving criteria on flash-flood potential. Accordingly, emphasis was placed on the use of streamflow information in the development of the hydrologic indicators of flash-flood potential.

In the research project planning phase, it was considered that meteorological or climatological factors such as generalized dew points and air-mass instability indices would be useful in identifying regions of high flash-flood potential. However, it was subsequently determined that available maps of rainfall intensity frequency would satisfactorily integrate the effects of these meteorological factors on flash flooding. Moisture and instability measures would surely be of primary importance in the actual forecasting of conditions, because some additional warning time is possible, but their actual effects are later adequately measured in the resulting rainfall intensities.

Flash-Flood Magnitude Index. Although the damage associated with a flash flood is related to the magnitude of the flood, the potential for damage prior to the flood occurrence is related to the previous frequency of occurence associated with the flow magnitude. That is, if large flows occur frequently, development within the flood plain would be greatly inhibited, and inhabitants will be conscious of the continuing flood threat. However, if large damaging flows are fairly rare, occupants of the flood plain usually feel that development in the flood plain area is economically advantageous. Also, the floods that have occurred commonly within the memory of the residents might not be indicative of the magnitudes that can occur, and thus the flood plain occupants would not be prepared for the consequences. Accordingly, it is considered that the ratio of the magnitudes of rare flood events to common flood events is a measure of the influence of the magnitude of flash flooding on the composite hydrologic flash-flood potential of a location.

Although the ratio of the magnitudes of rare flood events to common flood events could be computed from observed streamflow records, there is no assurance that the ratio computed from a few selected events would be representative of expected ratios. Some better definition can be obtained if a complete streamflow frequency analysis is used. Such an analysis requires the selection or determination of an appropriate mathematical frequency relationship. The log Pearson Type III frequency analysis function is commonly used in hydrologic studies. Considering the relatively small variation in skew coefficients and sampling uncertainties, it is considered that the standard deviation of the logarithms of the annual maximum peak flows can be used alone as an adequate estimator of the expected ratio of rare flood events to common flood events.

Consider, for example, the two frequency curves of Figure 1. Although both curves exhibit the same mean flow logarithm, the slope of curve A is considerably larger than the slope of curve B. This implies that the increment of the logarithms from a common to an infrequent occurence computed or estimated from curve A is considerably larger than the corresponding increment from curve B. Thus, the ratio of the relatively rare flood event to common flood event for the stream represented by frequency curve A is larger than the ratio computed for the stream represented by frequency curve B. As this difference in ratios is directly related to the difference in standard deviations of the two streamflow regimes, the standard deviation should be a relatively efficient estimator of the ratio of rare flood events to common flood events.

Flash-Flood Warning Time Index. Of almost comparable importance to the index of flash flood magnitude potential is an index of flash-flood warning time. The potential for property damage and particularly loss of life is a function of the amount of time available for warning occupants of flood-plain areas that flooding is iminent. This warning time is usually considered to be a function of the time between the occurrence of rainfall and occurrence of the high flow that causes overbank flooding. Determination of this time period requires a great deal of detailed rainfall and streamflow data and highly complex studies of the relationships between rainfall and runoff. In most parts of the United States, detailed rainfall data during flood periods are inadequate to define accurately the actual time and areal patterns of rainfall that have occurred over specific drainage basins. Even if such data were generally available, the time and effort required for developing generalized indices of warning time would be prohibitive in a study of this scope. Therefore, a search was made for a better or more feasible indicator of warning time that might be available at any location. It was determined that warning time is generally closely related to the rate of rise of streamflow, and consequently an indicator was selected that related the annual maximum peak flow to the maximum volume (expressed as an average rate of flow) for a 3-day period including the day of the occurrence of the peak flow. The higher the ratio of peak to average 3-day flow is, the more rapidly the streamflow must rise during the flood period, and the less warning time would be available. An index of this form is a measure of the intensity of flooding and is, therefore inversely related to available warning times. Because available warning times are of importance in the prevention of damages due to flash flooding, the flash-flood warning time (intensity) index is a direct complement of the flash-flood magnitude index in the computation of the flash-flood potential of a specific location.

Computation of Proposed Criteria

Flash-Flood Magnitude Index. In view of the importance of the magnitude index as a flash-flood potential indicator and of the ready availability of annual maximum streamflow data, records of annual maximum unregulated flows for about 2900 streamflow stations with drainage area under 1000 square miles in extent and record length equal to or exceeding 20 years were obtained from the U.S. Geological Survey. Flood-flow frequency analyses were performed using a version of a computer program developed for the Water Resources Council that was available in preliminary form. The program accounts for the undue influence that zero flows and lower-end outliers have on the magnitude of the standard deviation (slope of the frequencey curve). In this study, lower-end outliers are defined as flows with logarithms more than 2.5 standard deviations below the computed mean logarithm (the standard deviation and mean of the logarithms are computed for non-zero flows only). Specifically, the computer program computes the mean and standard deviation of the logarithms of non-zero flows, examines and removes the logarithms of lower-end outliers. The mean and standard deviation of the remaining logarithms are then recomputed.

Flash-Flood Warning Time Index. The computation of the flash-flood warning time index, defined as the ratio of peak flow to maximum 3-day average flow including the day of the occurrence of the peak flow, requires the availability of the entire year of daily flows for the year of the peak flow. Because of the computation time requirement and the expense of obtaining complete daily records, only about 200 stations distributed throughout the U.S. were originally selected for study. The daily streamflow records analyzed were obtained from magnetic tape files of the Center for Research in Water Resources. Subsequent mapping of the 200 stations originally analyzed indicated that several large regions of the U.S. were not well represented in the original sample. As all of the data in the magnetic tape files had been exhausted, about 60 stations were analyzed using daily streamflow data as published in the U.S. Geological Survey Water-Supply Papers. The final sample obtained in this manner exhibited a more complete geographic distribution of stations than did the original smaple. In addition, as it was felt that the flash-flood warning time index should reflect the warning time available during the most significant events, computations were limited to the top 10% of the annual maximum floods. The final warning-time index was then taken as the average of the indices computed for the top 10% of the peaks. It should be re-emphasized at this point that the flash-flood warning time (intensity) index is an inverse indicator of the amount of time available for the issuance flood warnings.

GENERALIZATION OF CRITERIA

Regional Analysis of Hydrologic Parameters

Because the proposed criteria for the evaluation of flash-flood potential must be applied to many ungaged streams in the United States, it is desirable to develop some general methodology for the determination of the indices of flash-flood potential. In past studies, the determination of hydrologic parameters has been successfully accomplished using regional correlation analyses (Beard, 1962). The basic procedure is to relate the hydrologic quantity of interest to basin characteristics and climatological factors of the watershed using linear regression techniques. If the statistical significance of the relationship, usually measured by the value of the coefficient of determination, is less than acceptable, then regression residuals computed for each observation may be plotted at basin centroids on topographic maps. Lines of equal magnitude of the parameter may then be drawn, taking advantage of any topographic or geographic pattern discernable. This process also helps to ensure some degree of consistency in the estimated values of the parameter of interest. If the coefficient of determination indicates no significant relations among the variables selected for study, then the values of the parameter may be plotted directly on the topographic maps and contoured accordingly. If, on the other hand, the coefficient of determination is adequate for the proposed application, then estimates of the parameter for ungaged sites may be made by direct application of the regression relationship. Using the procedure outlined here, it is possible to generalize the results of the computation of the indices of flash-flood potential so that values of the indices may be estimated for ungaged locations.

Application of Regional Correlation and Mapping

Flash-Flood Magnitude Index. Regional correlation analyses as described in the previous paragraph were performed using the logarithms of the following drainage basin characteristics as independent variables and the logarithm of the flash-flood magnitude index as the dependent variable.

1. Drainage area in square miles
2. Main channel slope in feet per mile.
3. Length of main channel in miles
4. Area of lakes, ponds, and swamps in square miles
5. Forested area in square miles
6. Mean basin elevation in feet above MSL
7. Average annual precipitation in inches

The drainage basin characteristics used in the analysis were selected primarily on the basis of anticipated effect on the dependent variable and ease of measurement. The latter is of importance if the results of the regional correlation analyses are to be applied successfully to a large number of ungaged locations. The selection of the independent variables was also influenced by the observed availability of each variable in a magnetic tape file, obtained from the U. S. Geological Survey, containing 19 drainage basin characteristics.

The required computations were performed using a stepwise linear multiple regression computer program, BMD02R-Stepwise Regression, developed at UCLA (Dixon, 1973). The results of the correlation analyses performed for each region (each U.S.G.S. hydrologic division as used in the compilation reports was considered as a separate region) and the U.S. as a whole are shown as Table 1. The statistical importance of a variable, as used in this study, is defined as the ratio of increase in explained variance of the dependent variable, due to the inclusion of the independent variable whose significance is to be analyzed, to the unexplained variance of the dependent variable as computed prior to the inclusion of the independent variable into the relationship. For example, a variable accounting for only 5% of the total observed variance of the dependent variable might explain 10% or more of the variance when included into a regression relationship during a subsequent step of the regression analysis. A significant improvement, as defined here, of 10% was used in the selection of the correlation results.

Because of regional inconsistencies in both the magnitudes of correlation coefficients and the variables selected using the significance criterion, it was determined that no drainage basin parameter affected the logarithmic standard deviation in a consistent manner. Therefore, the unadjusted values of the flash-flood magnitude index were plotted at basin centroids on regional base maps adapted from maps used by the U.S.G.S. in their compilation reports. After mapping the values of flash-flood magnitude index, lines of equal index were drawn on each of the 18 regional base maps. No attempts were made to develop such maps for Alaska (U.S.G.S. part 15) or Hawaii (U.S.G.S. part 16) or any of the U. S. possessions, as the data available for analysis in these areas were inadequate. Rainfall frequency maps as published by the National Weather Service and topographic maps were used as general guides in the preparation of these maps, shown as Figures 2 to 19.

Flash-Flood Warning Time Index. A regional correlation analysis was also performed using the logarithms of the following set of independent variables as a set of predictors of the logarithm of the flash-flood warning time (intensity) index:

1. Drainage area in square miles
2. Main channel slope in feet per mile
3. Main channel length in miles
4. Average annual precipitation in inches

The other variables used in the correlation analyses of the flash-flood magnitude index (Forested area, Area of lakes, ponds, and swamps, and Elevation) were not included in this analysis, because their quantities were not available for a substantial number of stations in the sample. The regression analysis indicated that the size of the drainage basin slightly influenced the observed values of the flash-flood warning time index. This outcome was expected, as streams with smaller contributing drainage areas should generally exhibit more rapid rises than streams with larger contributing drainage areas. The results of the final correlation analysis are given below:

$$\text{warning time index} = 10.9\ (\text{Area})^{-.23} \qquad (1)$$

The relationship shown also reflects adjustments made to some stations in the Rocky Mountains to reduce inaccuracies due to the inclusion of some snowmelt induced peak flows into the computation of the warning time index. The adjustments were made by simply removing those peak flows occurring during the months generally associated with snowmelt. Although severe rain storms can occur during months generally associated with snowmelt, the exclusion of peak flows that occur during snowmelt months from the computation of the warning-time indices resulted in higher estimates of the warning time index. This result was in accordance with the anticipated effect of snowmelt events on the magnitude of the warning time index.

In order to reflect the influence of the drainage basin size on the value of the flash-flood warning time index and generalize the results of the analysis, values of the index, I, were related to drainage basin size, A, in accordance with the above correlation results as follows:

$$I = KA^{-.23} \qquad (2)$$

in which k, the antilogarithm of the regression constant, was 10.9. In order to reflect the geographic variation of the warning-time index independently of the drainage basin size for which it was computed in each case, values of I and A for each location were substituted in the above equation and k values were plotted at drainage basin centers on a map of the contiguous 48 states (Figure 20). The k values were generalized as shown in Figure 20, and these represent the values of the warning-time index for a 1-square-mile drainage basin and can be used to compute a warning-time index for a basin of any size, based on the best-fit exponent of -0.23 derived from available data.

VERIFICATION OF THE EFFECTIVENESS OF GENERALIZED CRITERIA

Verification Data

For study and verification purposes, the four regional offices of the National Weather Service provided a list of and data on 39 communities throughout the United States and Puerto Rico (involving 42 streams) where severe or moderate flash floods have been experienced. The names of the streams and map estimates of the flash-flood potential indices for each stream are shown in Table 2.

Verification Analysis

Simple Comparison. In order to compare the magnitudes of the flash-flood potential indices of stations analyzed in this study with the flash-flood test group shown in Table 2, statistics of the logarithms of the flash-flood potential indices were computed:

All Stations	Sample Size	Mean Logarithm of index	Logarithmic Standard Deviation of index
Magnitude Index	1606	-.4731	.1186
Warning Time Index	260	.5056	.3857
TEST			
Magnitude Index	42	-.4556	.2007
Warning Time Index	42	.7651	.3134

No statistical significance tests were applied to the observed differences in mean logarithms and logarithmic standard deviations, as it would be inappropriate to compare the test group of known classification with the group of unclassified areas. Still, it is evident that the mean logarithm of the flash-flood warning time index of the test group is considerably larger than the mean logarithm of the unclassified group, and that the mean logarithm of the flash-flood magnitude index of the test group is slightly larger than the mean logarithm of the unclassified group. Because of the difficulties associated with the comparison of mixed groups of observations, two other techniques were employed to examine the effectiveness of the proposed criteria. The first technique, summarized in this section and presented in detail in Appendix I, is an application of geomorphological concepts. The second technique, also summarized in this section and presented in detail in Appendix II, is an application of the multivariate analysis procedure of linear discriminant analysis.

Morphological Investigations. In order to evaluate the effectiveness of the maps of flash-flood potential indices presented herein and to investigate morphological differences in drainage basins selected from opposite ends of the flash-flood potential spectrum, study areas were selected from regions of relatively high flash-flood potential (larger values of flash-flood magnitude index and flash-flood warning time index) and from regions of relatively low or moderate flash-flood potential (smaller values of flash-flood magnitude index and flash-flood warning time index). In addition, one study area (north-central Utah) of high flash-flood potential was selected primarily on the basis of historically documented flash-flood hazard. Those areas selected for study are shown in the following table:

HIGH FLASH-FLOOD POTENTIAL STUDY AREAS

Central Texas (13 study basins)
North-central Utah (11 study basins)
Southern California (12 study basins)

LOW FLASH-FLOOD POTENTIAL STUDY AREAS

Indiana (10 study basins)
Appalachian Plateau (11 study basins)

Engineering and geologic literature were then surveyed to determine appropriate morphological parameters that could be related to the potential for flash flooding. It was anticipated that measures of relief, drainage density, and basin size would be appropriate parameters for investigation.

The literature survey and subsequent analysis indicated that the three parameters, basin relief, drainage density, and basin magnitude,(shreve order of the mainstream or the number of first order streams in the basin), adequately delineate differences in observed flash-flood potential. Also, basin relief and drainage density can be represented by their dimensionless product, ruggedness number. Fisher's linear discrimnant function analysis was applied to the groups of low and high flash-flood potential, using ruggedness number and basin magnitude as discriminating variables (Hoel, 1971). The results of the analysis, shown graphically in Figure 1 of Appendix I, indicate that for a given value of basin magnitude, a basin with a larger ruggedness number should demonstrate a higher flash-flood potential than a basin with a smaller ruggedness number. This outcome is reasonable, as a large ruggedness number is indicative of steep, short hillslopes and thus the effective length of overland flow should be shorter, and runoff should concentrate in stream channels more rapidly. From Figure 1 of Appendix I, it is also evident that there is some degree of overlap between the groups of high and low flash-flood potential, especially certain basins from the central Texas and Appalachian Plateau study areas. This is probably due to the relatively moderate values of ruggedness number observed in the central Texas basins, and occassional large values of ruggedness number for basins of small basin magnitude in the Appalachian Plateau. However, the discriminant analysis generally indicates that for a given storm pattern, basins with large ruggedness numbers should be expected to produce more rapid hydrograph responses.

Linear Discriminant Analysis. Linear discriminant analysis is a multivariate analysis procedure that can be used to classify sets of observations into several distinct categories. It was anticipated that two or more categories of differing degrees of flash-flood potential could be formed for 160 locations for which the following drainage basin characteristics were known and for which the flash-flood potential indices had been computed:

1. Drainage basin area in square miles
2. Main channel slope in feet per mile
3. Channel length in miles
4. Average annual precipitation in inches
5. Expected 6-hour 100-year rainfall

Subsequent classification by discriminant analysis of the 42 selected streams of the test group provided by the National Weather Service should indicate which of the categories is of more severe flash-flood potential. Because no initial groupings of the 160 locations were known, hierarchical cluster analyses were performed using the flash-flood indices and the five basin characteristics as the principal cluster-determining variables. Examination of the results of the clustering procedures indicated the presence of four significant clusters (Figure 2 of Appendix II). Discriminant functions based on these four categories were formed, and the 42 test observations were classified accordingly. Of the 42 test observations, 20 were assigned to group 2; 14 were assigned to group 3; and the remaining 8 were assigned evenly to groups 1 and 4. These group assignments indicate two possible conclusions. First, the proposed indices of flash-flood potential effectively discriminate differing degrees of flash-flood potential, as over 80% of the test group were assigned to two of the four categories of flash-flood potential. Second, the hypothesis that increasing magnitudes of both flash-flood potential indices indicate increasing flash-flood potential is substantiated by the assignment of 20 of the 42 test locations to group 2, as illustrated by the group average values of the indices presented in the following table:

GROUP	AVERAGE MAGNITUDE LOGARITHM	AVERAGE INTENSITY LOGARITHM
1	-.474	.249
2	-.349	.818
3	-.644	.566
4	-.739	.248

METHOD OF APPLICATION OF GENERALIZED CRITERIA

The analyses of the morphometric and hydrologic indices of flash-flood potential presented in the Appendices generally indicate that larger values of the hydrologic indices of flash-flood potential (magnitude index and warning time (intensity) index) and larger ruggedness numbers are representative of higher flash-flood potential. Basins that have relatively large values of all three indices are, therefore, of the most severe flash-flood potential, and basins that have relatively large values of any single index deserve special consideration. To be totally effective, procedures for determining a priority list of flash-flood-prone locations should be influenced by the interrelationships of the hydrologic and morphometric indices of flash-flood potential. Because of the resource constraints of the project, it was not possible to obtain morphometric data in amounts necessary for the determination of these interrelationships. However, the ranking procedures described in the following sections can be used to determine two independent priority lists (hydrologic and morphometric) of flash-flood-prone locations. Those basins that rank high on both lists are considered to be locations of the most severe potential for flash flooding.

Hydrologic Indices of Flash-Flood Potential

Locations may be ranked in order of decreasing magnitude of flash-flood potential using the following procedures that were developed on the basis of the verification analysis presented in Appendix II.

For each basin to be analyzed,

1. Locate the basin centroid on the appropriate flash-flood magnitude index map and on the flash-flood warning time (intensity) index map (Figure 20).
2. Compute the common logarithm, LMI, of the magnitude index, MI (the magnitude index can be read directly from the appropriate map).

3. Compute the common logarithm, LWTI, of the warning time (intensity) index, WTI , estimated using K from Figure 20 and equation 2.

4. Compute the following discriminants and assign the basin to the category corresponding to the largest discriminant, or classify the location using Figure 21.

$$D1 = -46.72 \text{ (LMI)} + 20.12 \text{ (LWTI)} \quad (3)$$

$$D2 = -35.91 \text{ (LMI)} + 63.20 \text{ (LWTI)} \quad (4)$$

$$D3 = -64.03 \text{ (LMI)} + 44.66 \text{ (LWTI)} \quad (5)$$

$$D4 = -72.52 \text{ (LMI)} + 20.63 \text{ (LWTI)} \quad (6)$$

5. Compute the hydrologic ranking factor, HRF, using (7) or (8) depending on the categorization of the basin.

   If the basin is assigned to category 2 (D2 from (4) is is the largest discriminant),

$$HRF = -[(LMI + .739)^2 + (LWTI - .248)^2] \quad (7)$$

   otherwise,

$$HRF = [(LMI + .349)^2 + (LWTI - .818)^2] \quad (8)$$

All of the locations to be analyzed can then be ranked in ascending order of ranking factor computed in step 4. Those locations with smaller positive, or negative, values of ranking factor are closer to the mean of group 2 (if not assigned to group 2), or more distant from the mean of group 4 (if assigned to group 2). Small positive, or negative, ranking factors thus represent relatively high potentials for flash flooding. The 42 members of the test group were ranked in descending order of flash-flood potential using the procedure outlined above. The resulting priority list is shown in Table 3.

Morphometric Indices of Flash-Flood Potential

Because the limited research resources available prevented the collection of sufficient amounts of morphometric data necessary for the establishment of procedures for the identification of composite morphometric-hydrologic indices of flash-flood potential, the morphological studies were directed toward the validation of the hydrologic criteria and generalization techniques. However, the morphometric techniques discussed in Appendix I can be used to supplement the hydrologic ranking procedures. Based on the discriminant analysis presented in Appendix I, the following ranking procedures can be used to establish a morphometric priority list of locations.

For each basin to be analyzed,

1. Compute the common logarithm, LM, of the basin magnitude, M. The basin magnitude used in this report is the Shreve order number of the principal stream exiting from the basin. The shreve order of a stream is defined as the number of contributing first order streams, or unbranched stream segments. Thus, the magnitude of a basin is the number of first order streams in the basin.
2. Compute the common logarithm, LHD, of the ruggedness number, HD. As defined in Appendix I, ruggedness number is the dimensionless product of relief and drainage density. Relief is defined as the difference of outlet elevation and the average elevation of the highest basin divide. Drainage density is the ratio of the total length of all definable channels in the basin to the total surface area of the basin. Drainage density can be estimated rapidly using the approximate relationships discussed on page I-6.
3. Compute Fisher's discriminate FD

$$FD = (0.072)\ (LHD) - (0.066)\ (LM) \qquad (9)$$

4. Assign the basin to the category of high flash-flood potential if,

$$\left| FD + .114 \right| \leq \left| FD + .221 \right| \qquad (10)$$

5. Compute the morphometric ranking factor (MRF) using 11 or 12 depending on the categorization of the basin.

   If the basin is assigned to the category of high flash flood potential

$$MRF = -[(LM - 3.063)^2 + (LHD + .3622)^2] \tag{11}$$

Otherwise,

$$MRF = [(LM - 2.344)^2 + (LHD - .6025)^2] \tag{12}$$

The locations can then be ranked in ascending order of morphometric ranking factor. Small positive and negative values of MRF are indicative of relatively high morphometric flash-flood potential.

Although the morphometric studies of Appendix I closely approximated the results achieved with the warning time and magnitude indices, the morphometric approach also identified the flash-flood potential of the Wasatch Front in north-central Utah. This is an area where summer cloud-burst events are potentially hazardous but are usually of secondary magnitude as compared to the annual snowmelt induced flood. Thus, the morphometric ranking procedures are most useful in areas where annual snowmelt severely influences the record of annual peak flows.

CONCLUSIONS

Evaluation of the results of this study leads to the following conclusions:

a. The maps of the flash-flood potential indices provided in this report can be used effectively in the determination of the relative hydrologic potential for flash flooding at a specified location.

b. The suggested ranking procedures based on these indices can be effective in the determination of a priority list of areas to be studied in greater detail.

c. The morphometric parameters, ruggedness number and basin magnitude, can be used to identify those basins whose drainage systems are conducive to the development of flash floods.

d. The multivariate analysis techniques of hierarchical cluster analysis and linear discriminant analysis can be used in the identification of areas of comparable hydrologic properties.

Procedures for evaluating flash-flood potential are outlined in detail in the preceding section.

SUMMARY

This study conducted in the Center for Research in Water Resources at the University of Texas at Austin, under the guidance and financial assistance of the National Weather Service of NOAA, was directed toward developing a rapid and practical means for preliminary evaluation of flash-flood potential at thousands of locations throughout the United States.

The first criterion developed in this study is the flash-flood magnitude index. This index is defined as the ratio of the magnitudes of rare flood events to common flood events, and is indicative of the relative severity of rare flood events. Because of the relatively small variation in observed skew coefficients for use in annual maximum stream flow frequency analyses, the standard deviation of the logarithms of annual maximum streamflows is considered to be an adequate estimator of the flash-flood magnitude index. This index was generalized for application in the contiguous 48 states by regional mapping.

The second criterion developed is the flash-flood warning time index. This index is an inverse measure of the average warning time available during relatively rare flood events, and is, therefore, a direct measure of the intensity of expected flash-flood magnitudes. The warning time (intensity) index of a location is defined as the average of the ratios of peak flow to 3-day flow, computed for the top 10% of the observed annual peak flows of the location. A larger value of flash-flood warning time (intensity) index indicates less average warning time and higher intensity of flooding than does a smaller value. A map of the generalized flash-flood warning time (intensity) index was prepared for the contiguous 48 states.

The effectiveness of the criteria and of suggested ranking procedures are demonstrated using appropriate data determined for 42 streams from 39 flash-flood prone communities provided by the National Weather Service for

this purpose. In addition, apparent morphologic differences in drainage basins selected from opposite ends of the flash-flood potential spectrum are investigated, and appropriate morphometric indicators of those drainage basin characteristics conducive to flash-flooding are presented.

The regional maps of generalized flash-flood magnitude index, the map of generalized flash-flood warning time (intensity), and the ranking procedures provided in this report can be used to effectively determine a preliminary priority list of areas to be studied in greater detail.

SUGGESTIONS FOR FUTURE STUDY

The primary deficiency encountered in pursuing this study is inadequate documentation of past flash-flood events. To the extent feasible, a brief report should be prepared on each major flash-flood event. This report should include hyetographs of rainfall and hydrographs of runoff or such substitute information on magnitude and relative timing of rainfall and runoff as is obtainable. A contour map of the drainage basin showing storm isohyets, if obtainable, and extent of any urbanized area, should be included. Also of importance would be amount of damages incurred and, if available, a flow-damage relationship. Available aerial photographs of the area subject to damage would be particularly useful.

Since the warning-time (intensity) index appears to be of particular significance in identifying flash-flood-prone locations, and since a relatively small number of stream-gage locations were used in establishing the map of this index, regional studies of this index using all available station data on unregulated flows should improve evaluations considerably over the simple use of Figure 20.

As experience in the use of the indices and criteria provided herein accumulates, some manner of better combining the magnitude, intensity and morphometric indices should become evident. Special studies to establish a single combined index should be helpful at that time.

ACKNOWLEDGMENT

This study was supported technically and financially by the National Weather Service of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Particular guidance and assistance was furnished by Lee Larson, Research Hydrologist with the Hydrologic Research Lab and Technical Representative for this project, and Bob Ellis, Gerald Williams, Larry Longsdorf and Joe Goldman, Regional Flash Flood Hydrologists of the National Weather Service. The technical studies were conducted by Dr. Shin Chang and David Lott under the guidance of Leo R. Beard at the University of Texas, Center for Research in Water Resources. Appendix I was developed and written by Peter Patton under the guidance of Dr. Victor Baker, both of the Department of Geological Sciences of the University of Texas at Austin.

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TABLE 1

RESULTS OF REGIONAL CORRELATION OF FLASH-FLOOD MAGNITUDE INDEX

Sample	USGS Part	Drainage Area	Channel Slope	Channel Length	Elevation	Area of Lakes	Forested Area	Average Precip.	Correlation Coefficient	Constant
248	1	x	x	x	x	-.0544	x	x	.4197	-.4956
210	2	x	x	-.0679	x	x	x	x	.2814	-.3429
248	3	x	x	-.0477	x	x	x	x	.2437	-.4494
95	4	x	x	x	x	.0612	-.0995	x	.5170	-.4135
149	5	x	x	x	x	-.0411	x	.7311	.6657	-.6903
195	6	x	x	x	x	x	-.0758	x	.6146	-.3050
61	7	x	.1555	x	x	x	.0371	.6594	.5350	-1.7380
112	8	x	x	.1078	NA	NA	NA	x	.2601	-.4620
74	9	x	x	x	x	-.0734	x	-.3213	.5471	-.1291
28	10	x	x	x	-.9261	x	x	x	.5123	3.0771
153	11	x	x	x	NA	NA	x	-.5593	.6748	-.5730
131	12	x	.0504	x	x	x	x	x	.5338	-.6570
36	13	.0762	x	x	-.2418	x	-.1185	NA	.8189	-.4198
135	14	x	x	x	x	x	x	-.1842	.4187	-.2020
1606	USA	.0681	x	x	x	x	-.0854	x	.4991	-.4767

X - Variable not significant

NA - Variable not used in analysis

TABLE 2

STREAMS SELECTED FOR VERIFICATION PURPOSES

LOCATION NAME	AREA	MAGNITUDE	WARNING
WHETSTONE BROOK AT BRATTLEBORO VERMONT	28.10	.22	2.29
WESTERN RUN IN BALTIMORE COUNTY MARYLAND	59.80	.23	8.82
FOUR MILE RUN NEAR ALEXANDRIA VIRGINIA	14.40	.40	11.24
CHESTER CREEK NEAR CHESTER PENNSYLVANIA	61.10	.29	5.72
GREENBROOK NEAR PLAINFIELD NEW JERSEY	9.75	.22	6.45
CRABTREE CREEK AT RALEIGH NORTH CAROLINA	146.00	.24	2.18
WHEELING CREEK AT WHEELING WEST VIRGINIA	282.00	.21	3.87
KILLBUCK CREEK NEAR WOOSTER OHIO	462.00	.31	2.85
ELKIN RIVER (BIG ELKIN CREEK) NEAR ELKIN NORTH CAROLINA	35.00	.25	6.09
REEDY RIVER AT GREENVILLE SOUTH CAROLINA	486.00	.19	2.11
MINGO CREEK AT TULSA OKLAHOMA	61.20	.28	5.72
BOGGY CREEK NEAR ENID OKLAHOMA	6.91	.51	9.54
DARK CANYON DRAW NEAR CARLSBAD NEW MEXICO	442.00	.70	14.40
HACKBERRY DRAW NEAR CARLSBAD NEW MEXICO	214.00	.72	15.64
ROCKY ARROYO NEAR CARLSBAD NEW MEXICO	285.00	.65	18.61
SEVEN RIVER NEAR CARLSBAD NEW MEXICO	532.00	.72	13.78
BIG CEDAR CREEK NEAR CEDARTOWN GEORGIA	109.00	.19	3.00
WEST FORK LITTLE PIGEON RIVER NEAR GATLINBURG TENNESSEE	32.00	.19	7.10
PEACHTREE CREEK AT ATLANTA GEORGIA	86.80	.26	2.81
DRY COMAL CREEK AT NEW BRAUNFELS TEXAS	112.00	.65	13.90
SINK CREEK AT SAN MARCOS TEXAS	48.30	.60	16.93
PURGATORY CREEK AT SAN MARCOS TEXAS	37.20	.60	18.00
PAPILLON CREEK AT OMAHA NEBRASKA	402.00	.45	2.45
LENA GULCH NEAR DENVER COLORADO	12.20	.47	16.69
RALSTON CREEK NEAR DENVER COLORADO	91.00	.38	7.64
BOULDER CREEK NEAR BOULDER COLORADO	140.00	.25	6.28
RAPID CREEK NEAR RAPID CITY SOUTH DAKOTA	410.00	.45	5.13
JACKS FORK OF THE CURRENT RIVER NEAR EMMINENCE MISSOURI	398.00	.39	9.34
LITTLE PLATTE RIVER NEAR SMITHVILLE MISSOURI	234.00	.41	1.95
CEDAR RIVER NEAR AUSTIN MINNESOTA	425.00	.28	2.42
WEST BAYS FORK BARREN RIVER NEAR SCOTTSVILLE KENTUCKY	7.47	.20	5.31
LITTLE POPO AGIE RIVER NEAR LANDER WYOMING	125.00	.29	3.87
CARMEL RIVER NEAR ROBLES DEL RIO	255.00	.33	4.09
SOUTH FORK EEL RIVER NEAR MIRANDA CALIFORNIA	537.00	.25	2.29
SMITH RIVER NEAR CRESCENT CITY CALIFORNIA	609.00	.19	1.78
SAN FRANCISCO RIVER NEAR CLIFTON ARIZONA	350.00	.43	7.60
TONTO CREEK ABOVE GUN CREEK NEAR ROOSEVELT ARIZONA	675.00	.41	4.13
SABINO CREEK NEAR TUCSON ARIZONA	35.50	.42	15.16
LAS VEGAS WASH NEAR LAS VEGAS NEVADA	1571.00	.72	8.02
COTTONWOOD CREEK NEAR BOISE IDAHO	16.00	.35	7.83
WILLOW CREEK AT HEPPNER OREGON	87.80	.33	3.51
CANYONS 1 AND 2 WENATCHEE WASHINGTON DATA FOR 12461500	18.60	.17	3.78

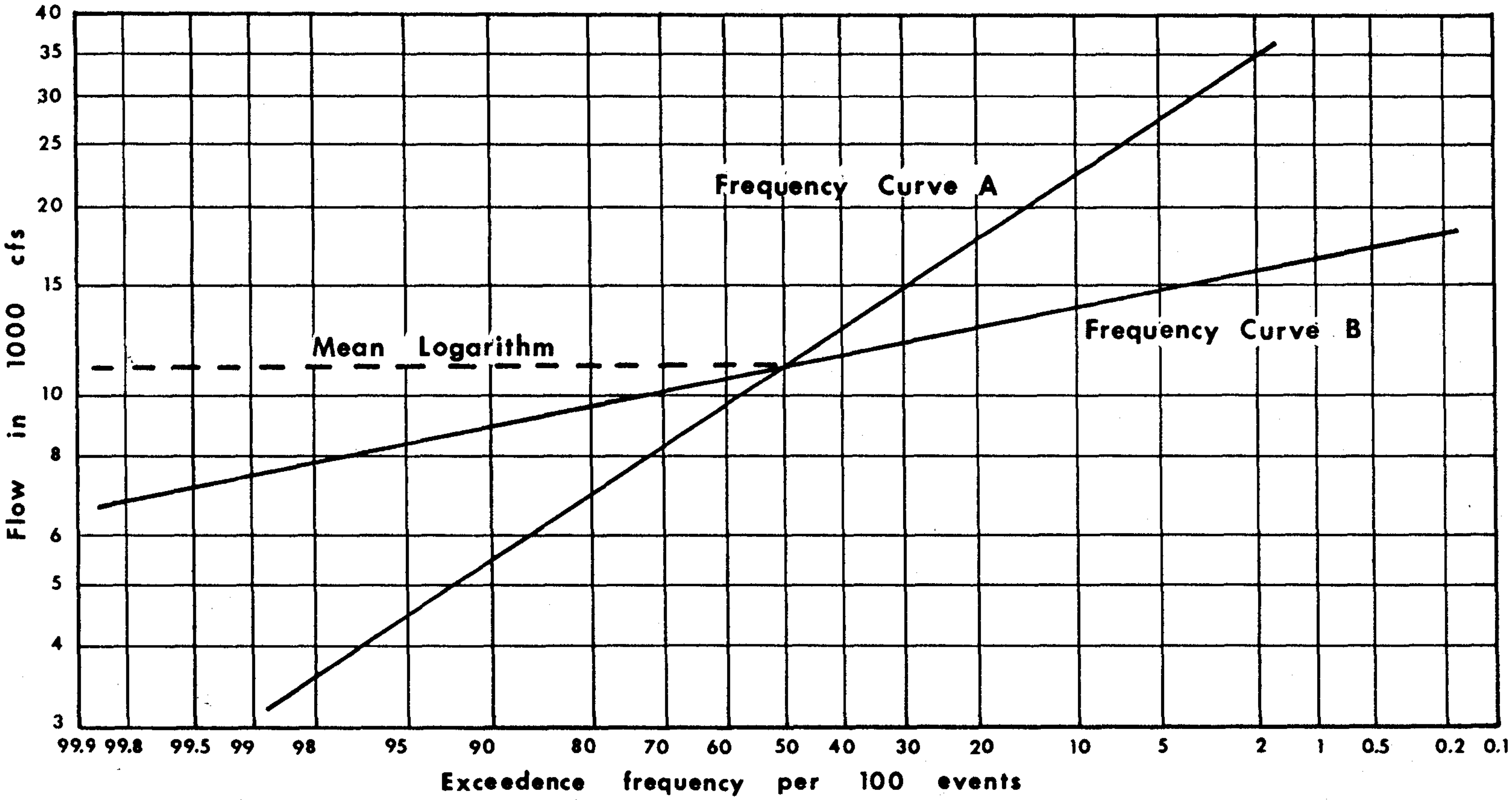
TABLE 3

PRIORITY LIST OF VERIFICATION GROUP

LOCATION NAME	RANK	MAGNITUDE	WARNING	CATEGORY
ROCKY ARROYO NEAR CARLSBAD NEW MEXICO	1	.650	18.614	2
PURGATORY CREEK AT SAN MARCOS TEXAS	2	.600	17.997	2
HACKBERRY DRAW NEAR CARLSBAD NEW MEXICO	3	.720	15.641	2
SINK CREEK AT SAN MARCOS TEXAS	4	.600	16.929	2
DARK CANYON DRAW NEAR CARLSBAD NEW MEXICO	5	.700	14.395	2
SEVEN RIVER NEAR CARLSBAD NEW MEXICO	6	.720	13.784	2
LENA GULCH NEAR DENVER COLORADO	7	.470	16.693	2
DRY COMAL CREEK AT NEW BRAUNFELS TEXAS	8	.650	13.901	2
SABINO CREEK NEAR TUCSON ARIZONA	9	.420	15.163	2
LAS VEGAS WASH NEAR LAS VEGAS NEVADA	10	.720	8.021	2
FOUR MILE RUN NEAR ALEXANDRIA VIRGINIA	11	.400	11.240	2
BOGGY CREEK NEAR ENID OKLAHOMA	12	.510	9.536	2
JACKS FORK OF THE CURRENT RIVER NEAR EMMINENCE MISSOURI	13	.390	9.344	2
SAN FRANCISCO RIVER NEAR CLIFTON ARIZONA	14	.430	7.602	2
RALSTON CREEK NEAR DENVER COLORADO	15	.380	7.644	2
COTTONWOOD CREEK NEAR BOISE IDAHO	16	.350	7.833	2
WESTERN RUN IN BALTIMORE COUNTY MARYLAND	17	.230	8.818	2
RAPID CREEK NEAR RAPID CITY SOUTH DAKOTA	18	.450	5.128	2
CHESTER CREEK NEAR CHESTER PENNSYLVANIA	19	.290	5.722	2
TONTO CREEK ABOVE GUN CREEK NEAR ROOSEVELT ARIZONA	20	.410	4.128	2
MINGO CREEK AT TULSA OKLAHOMA	21	.280	5.720	3
CARMEL RIVER NEAR ROBLES DEL RIO	22	.330	4.094	3
BOULDER CREEK NEAR BOULDER COLORADO	23	.250	6.282	3
ELKIN RIVER (BIG ELKIN CREEK) NEAR ELKIN NORTH CAROLINA	24	.250	6.085	3
LITTLE POPO AGIE RIVER NEAR LANDER WYOMING	25	.295	3.871	3
GREENBROOK NEAR PLAINFIELD NEW JERSEY	26	.225	6.451	3
WILLOW CREEK AT HEPPNER OREGON	27	.330	3.512	3
WEST BAYS FORK BARREN RIVER NEAR SCOTTSVILLE KENTUCKY	28	.200	5.306	3
WEST FORK LITTLE PIGEON RIVER NEAR GATLINBURG TENNESSEE	29	.190	7.102	3
KILLBUCK CREEK NEAR WOOSTER OHIO	30	.310	2.849	3
WHEELING CREEK AT WHEELING WEST VIRGINIA	31	.210	3.865	3
PAPILLON CREEK AT OMAHA NEBRASKA	32	.450	2.453	1
PEACHTREE CREEK AT ATLANTA GEORGIA	33	.260	2.811	3
CEDAR RIVER NEAR AUSTIN MINNESOTA	34	.280	2.421	1
CANYONS 1 AND 2 WENATCHEE WASHINGTON DATA FOR 12461500	35	.170	3.781	3
BIG CEDAR CREEK NEAR CEDARTOWN GEORGIA	36	.190	2.998	3
SOUTH FORK EEL RIVER NEAR MIRANDA CALIFORNIA	37	.250	2.292	1
LITTLE PLATTE RIVER NEAR SMITHVILLE MISSOURI	38	.410	1.949	1
CRABTREE CREEK AT RALEIGH NORTH CAROLINA	39	.240	2.177	4
WHETSTONE BROOK AT BRATTLEBORO VERMONT	40	.220	2.288	4
REEDY RIVER AT GREENVILLE SOUTH CAROLINA	41	.190	2.112	4
SMITH RIVER NEAR CRESCENT CITY CALIFORNIA	42	.190	1.781	4

FIGURE 1

Relation of Logarithmic Standard Deviation and Magnitude Index



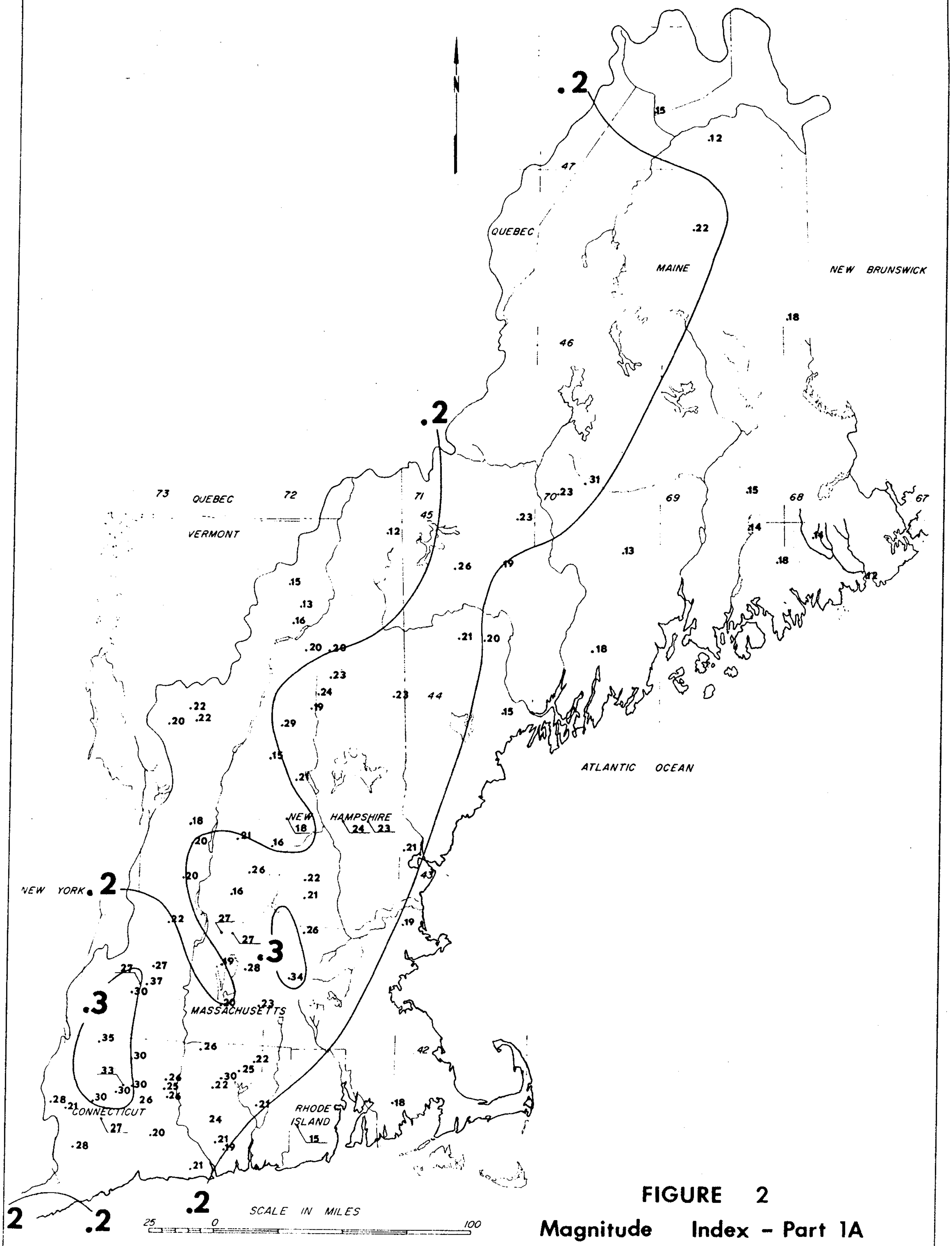


FIGURE 2

Magnitude Index – Part 1A

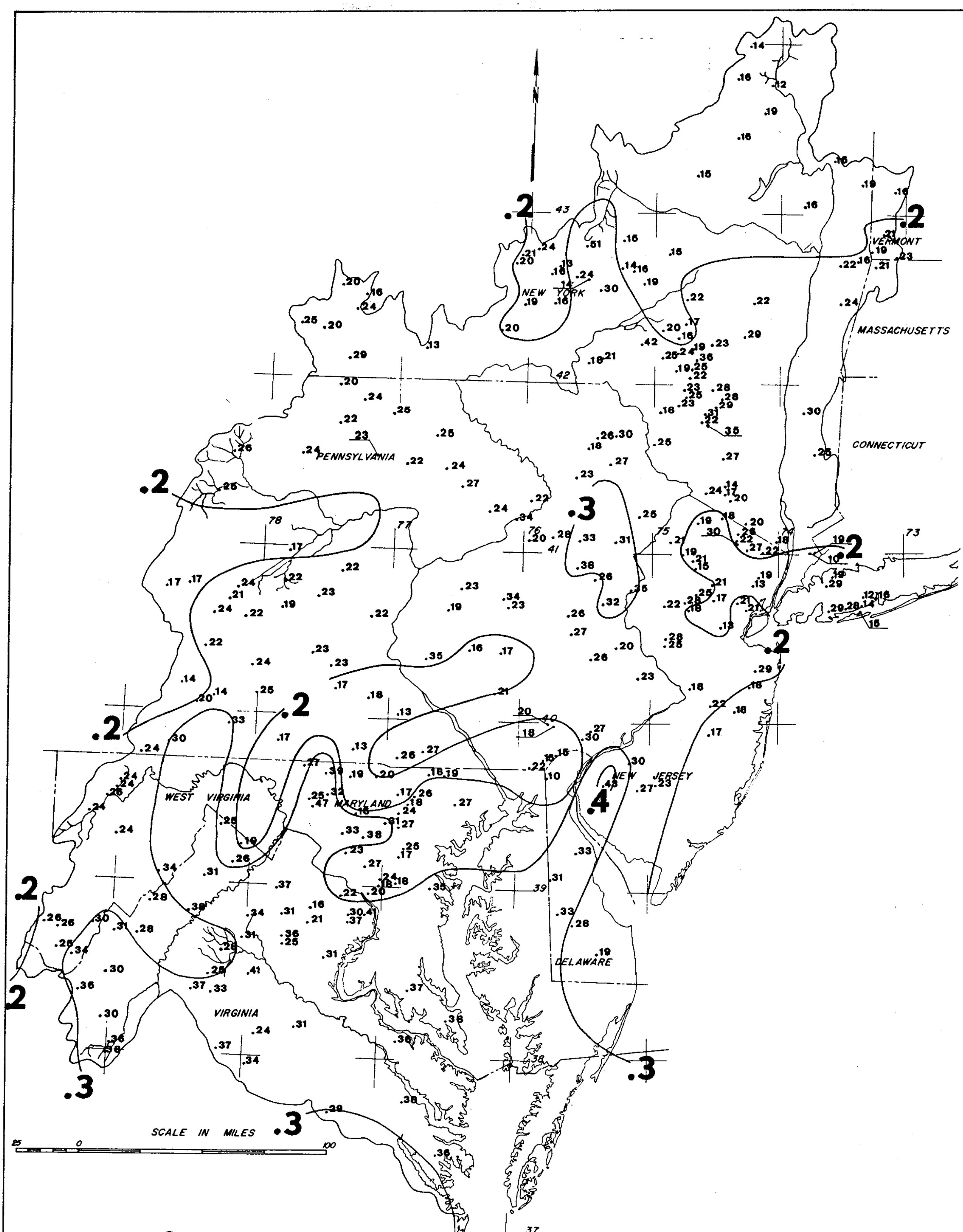


FIGURE 3

Magnitude Index - Part 1B

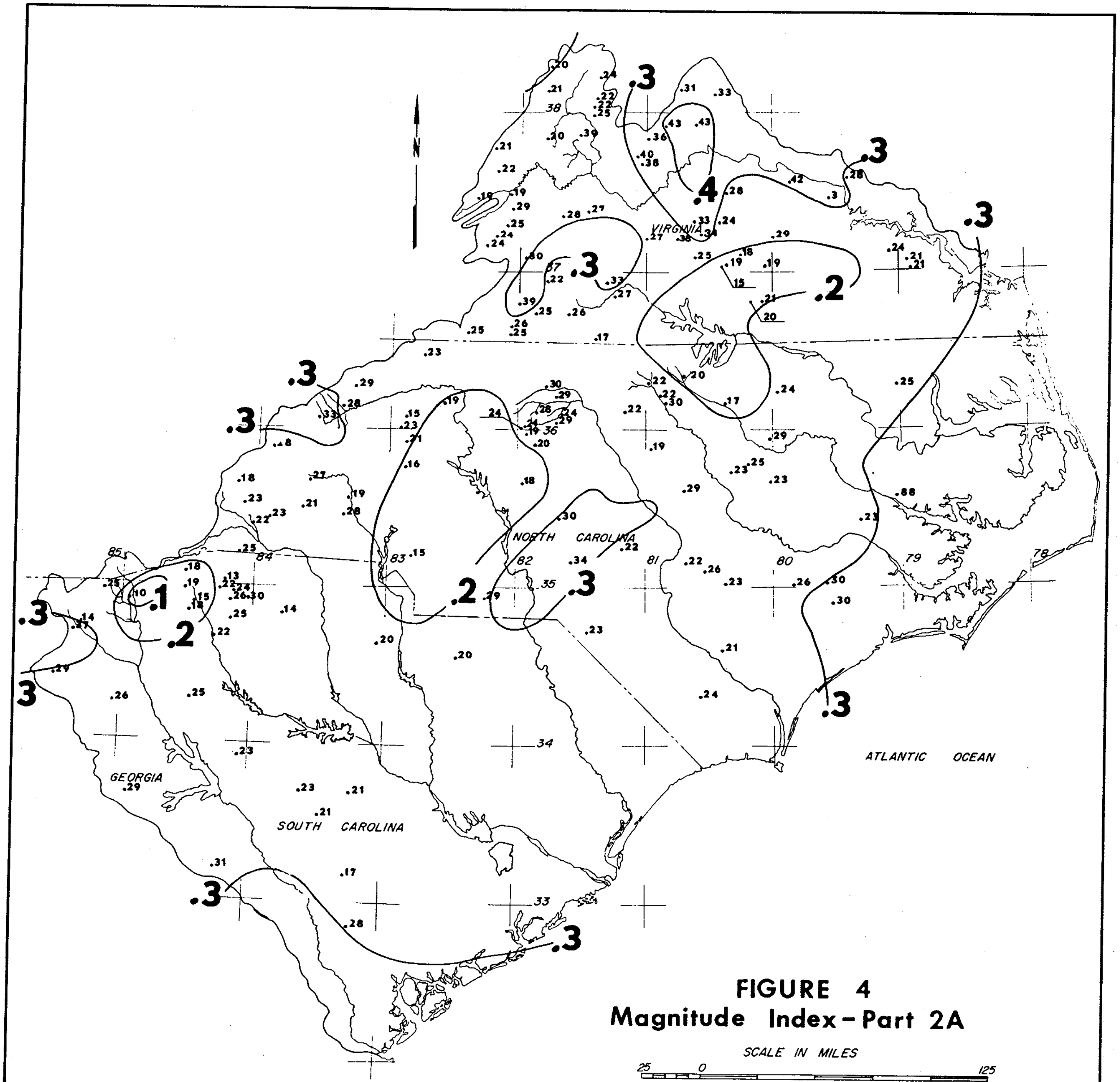


FIGURE 4
Magnitude Index - Part 2A

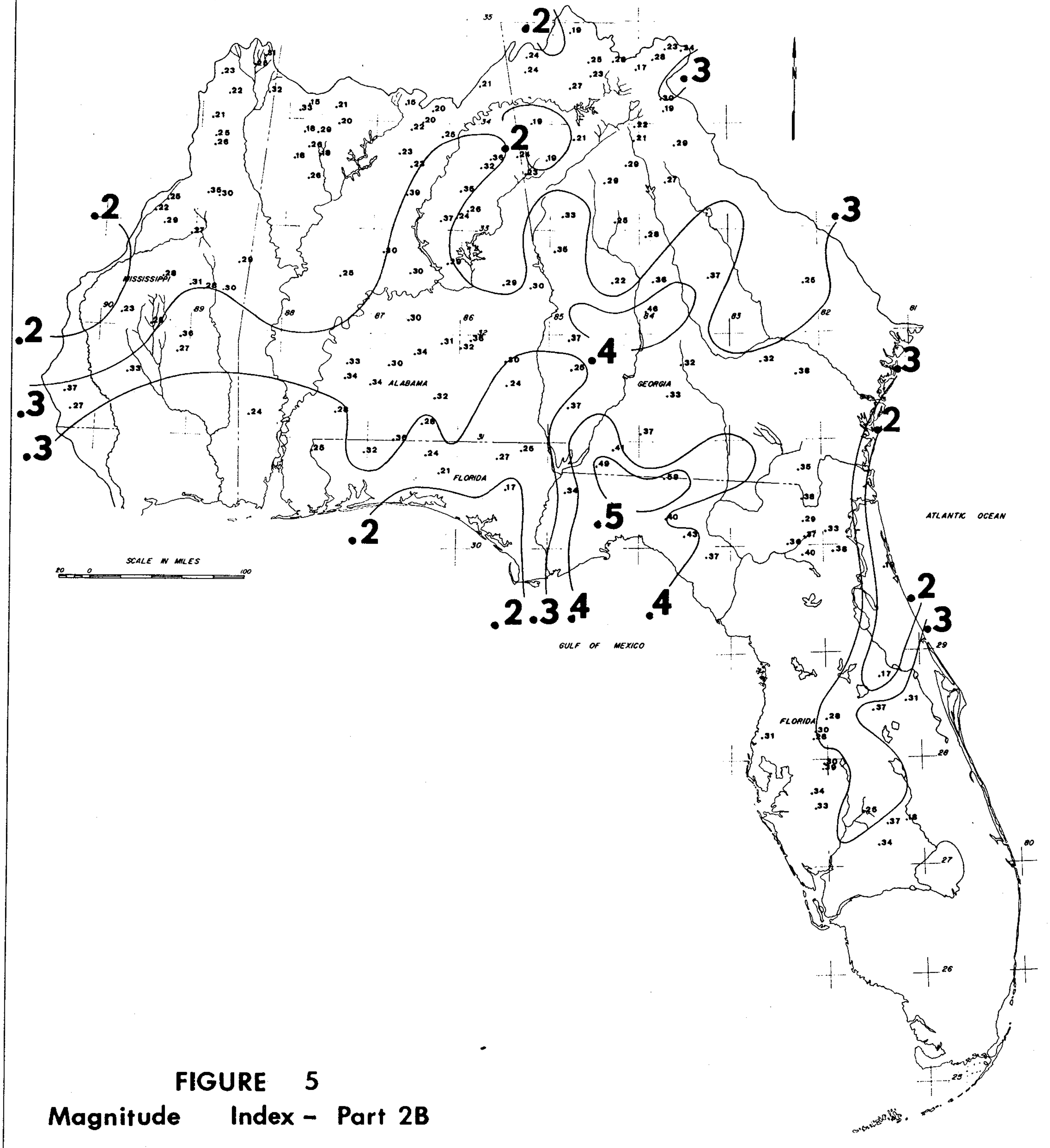


FIGURE 5

Magnitude Index – Part 2B

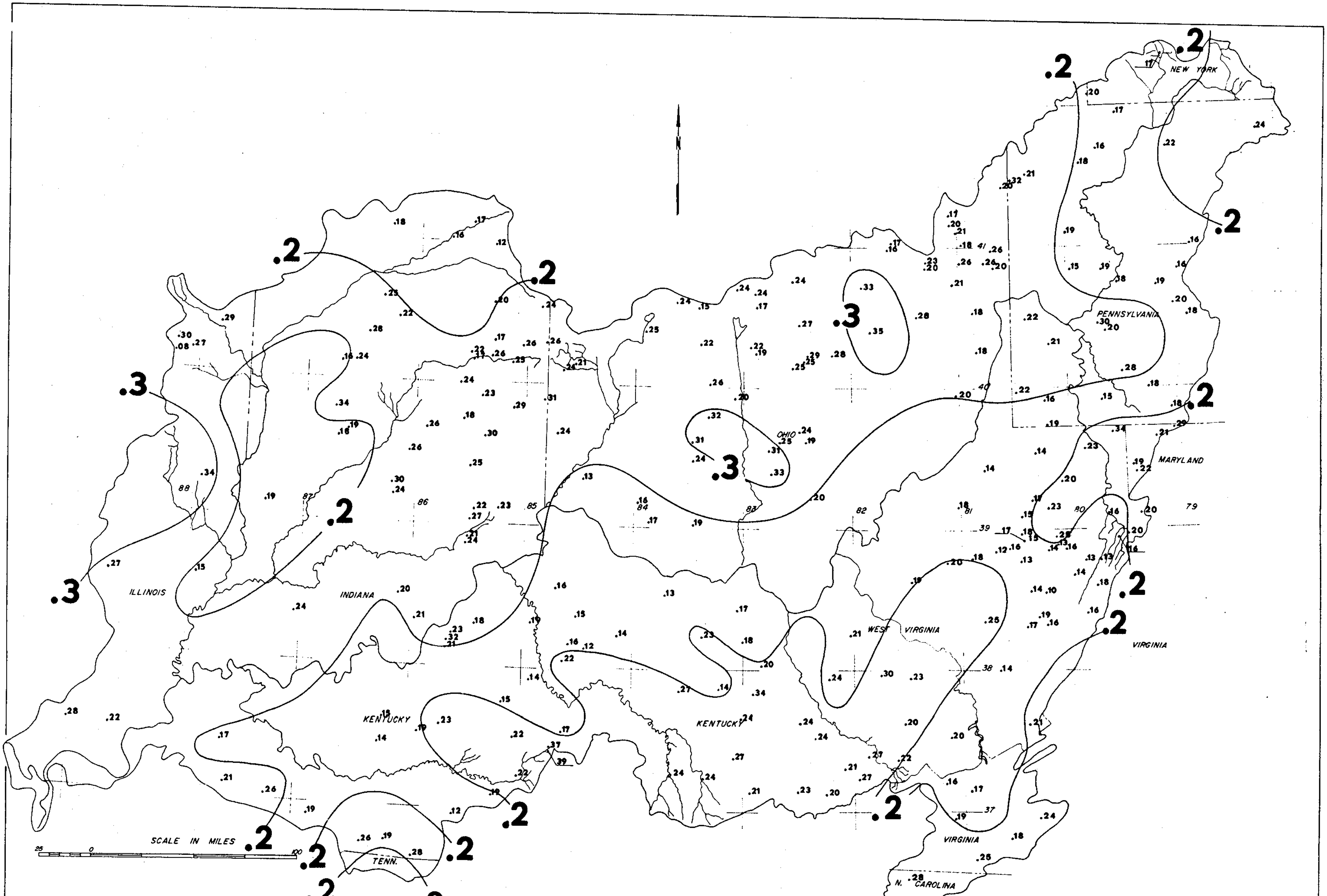


FIGURE 6

Magnitude Index - Part 3A

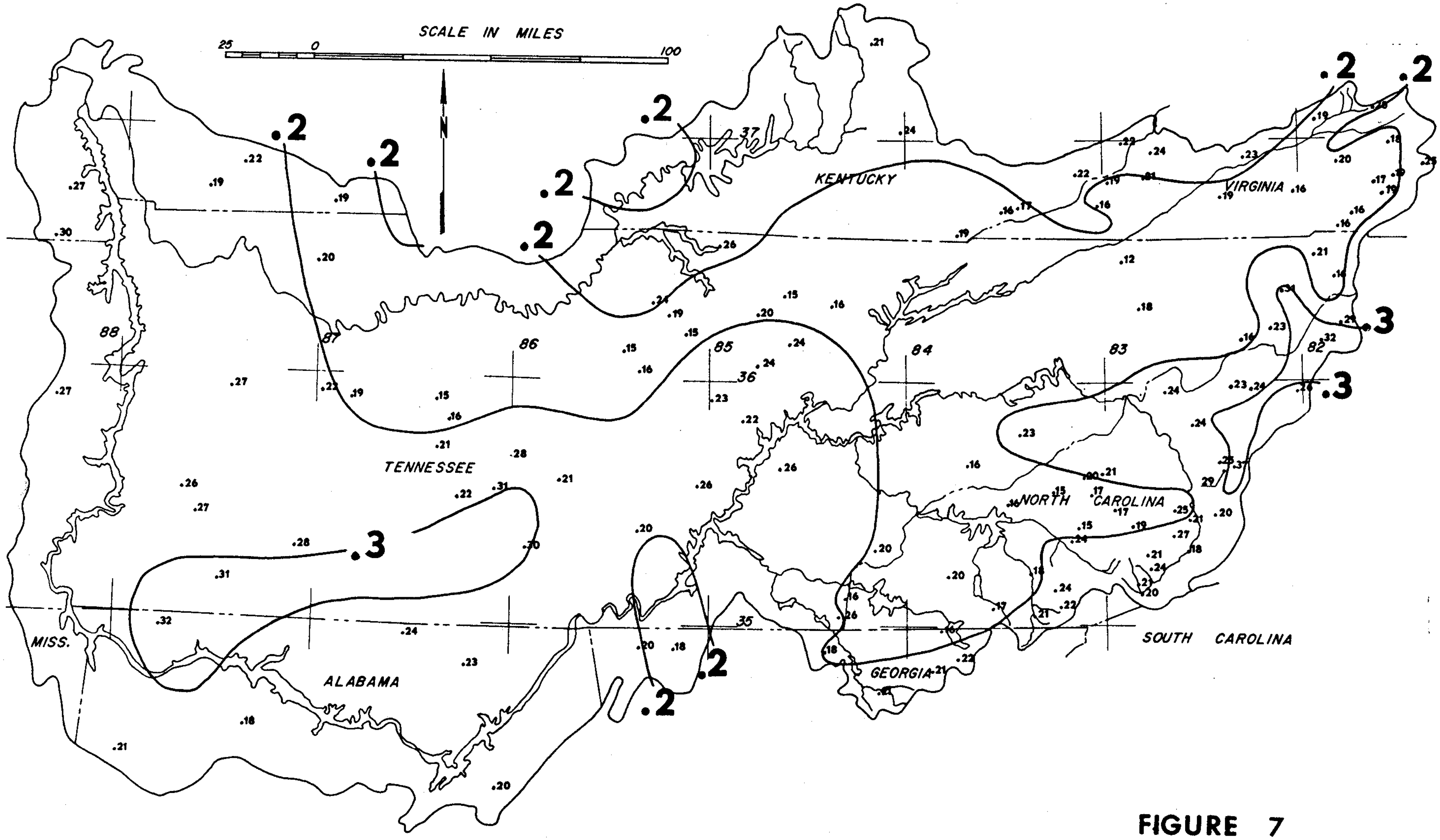


FIGURE 7
Magnitude Index – Part 3B

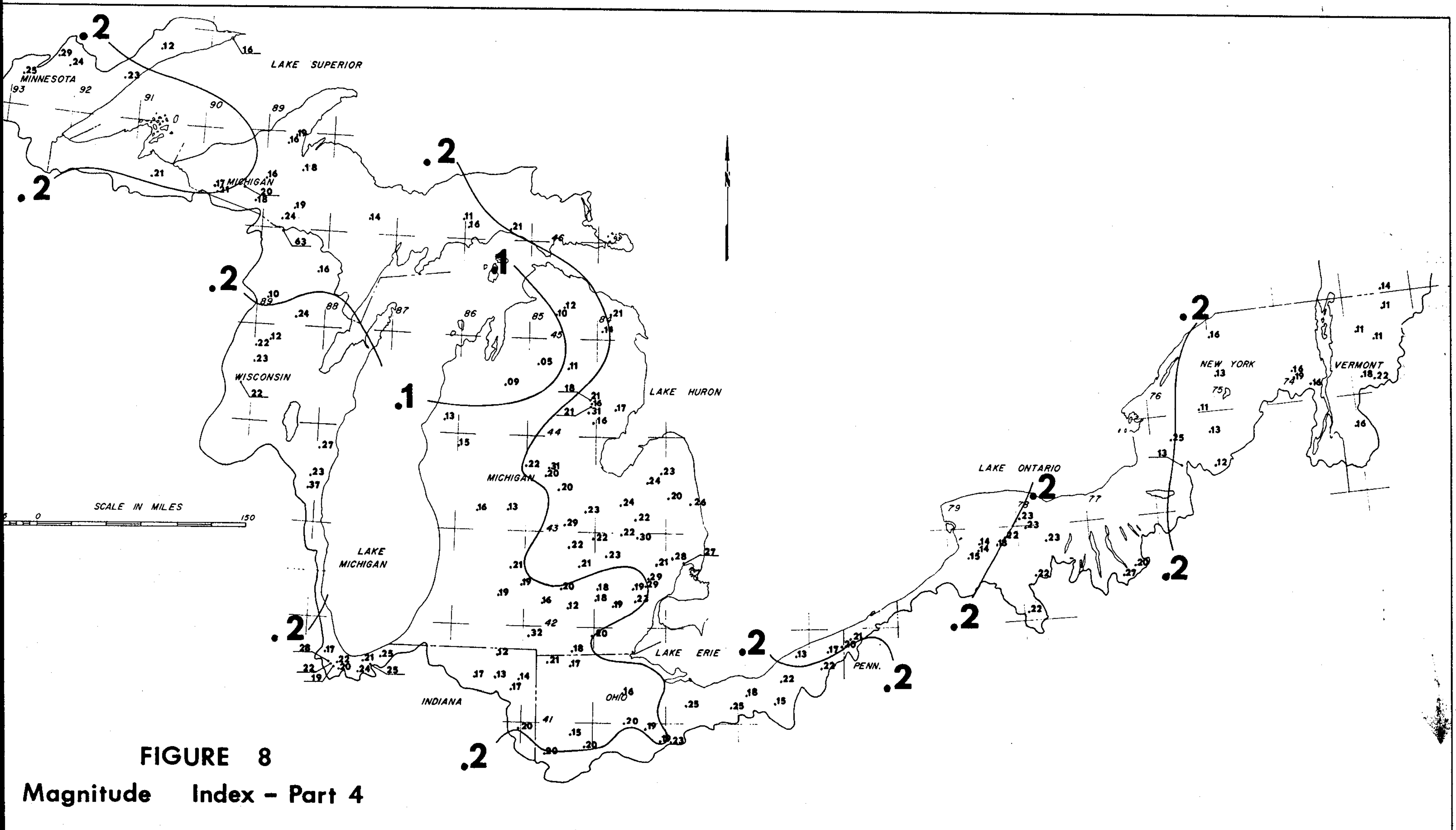


FIGURE 8

Magnitude Index - Part 4

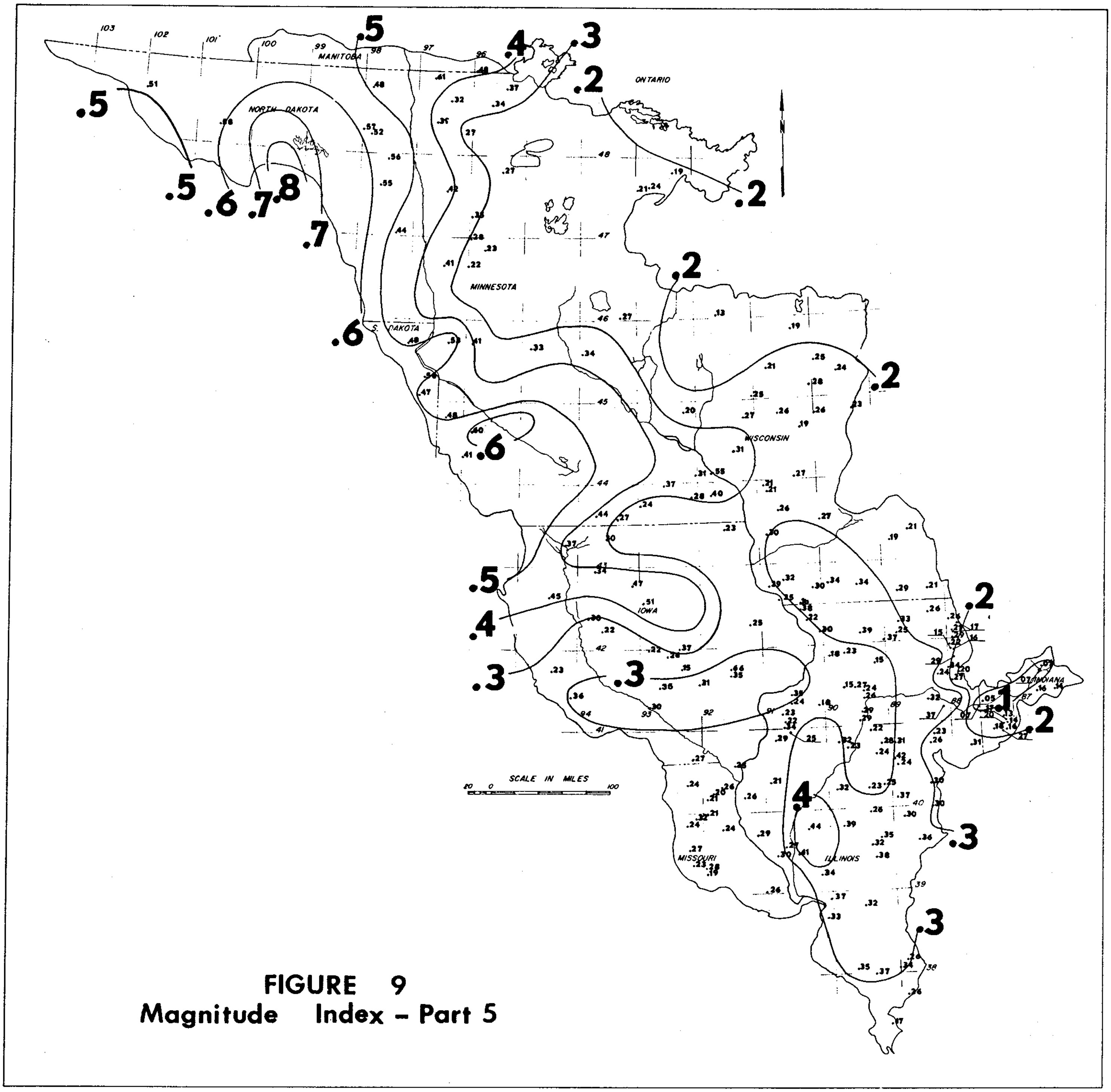


FIGURE 9
Magnitude Index – Part 5

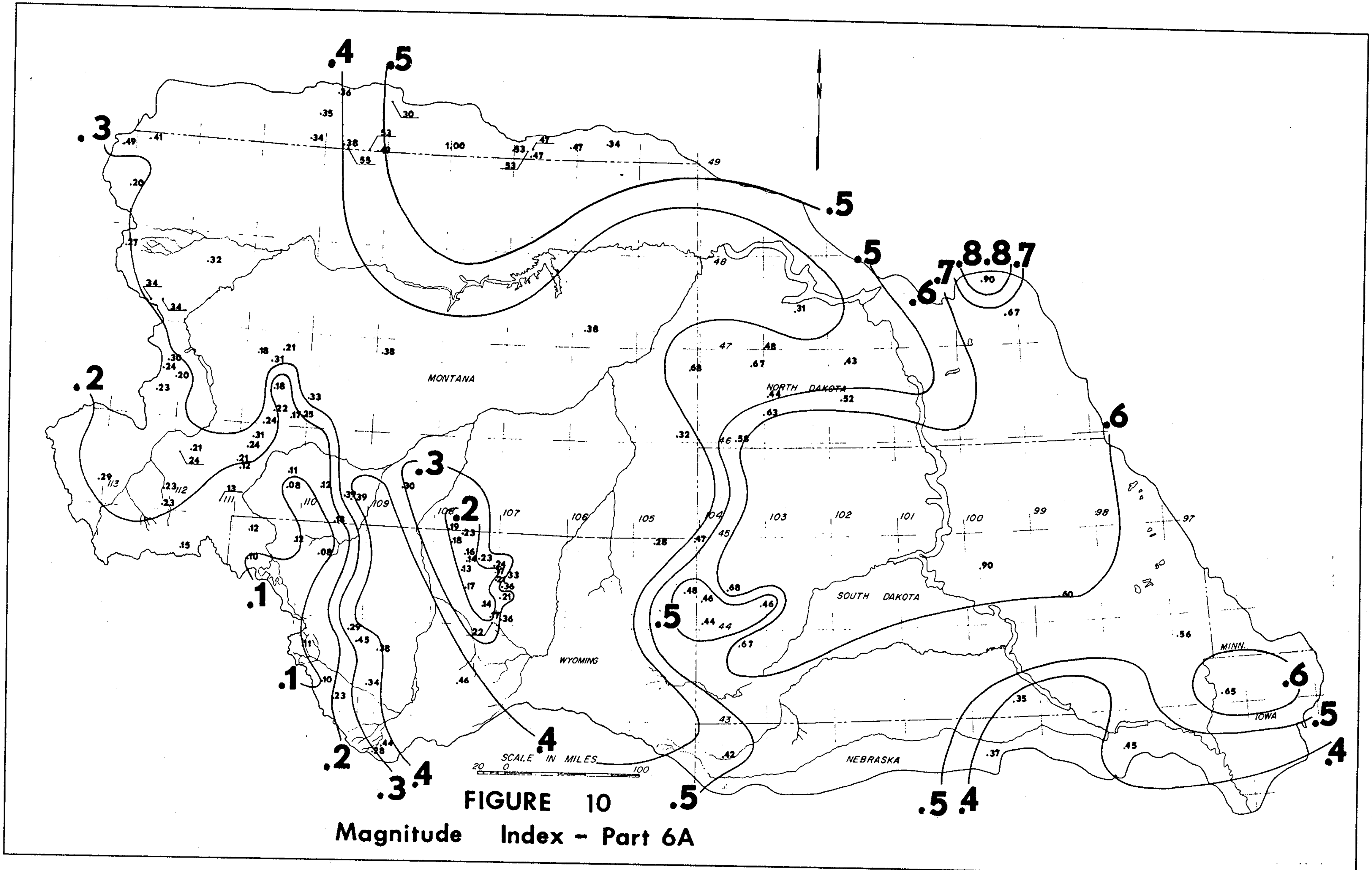


FIGURE 10
Magnitude Index - Part 6A

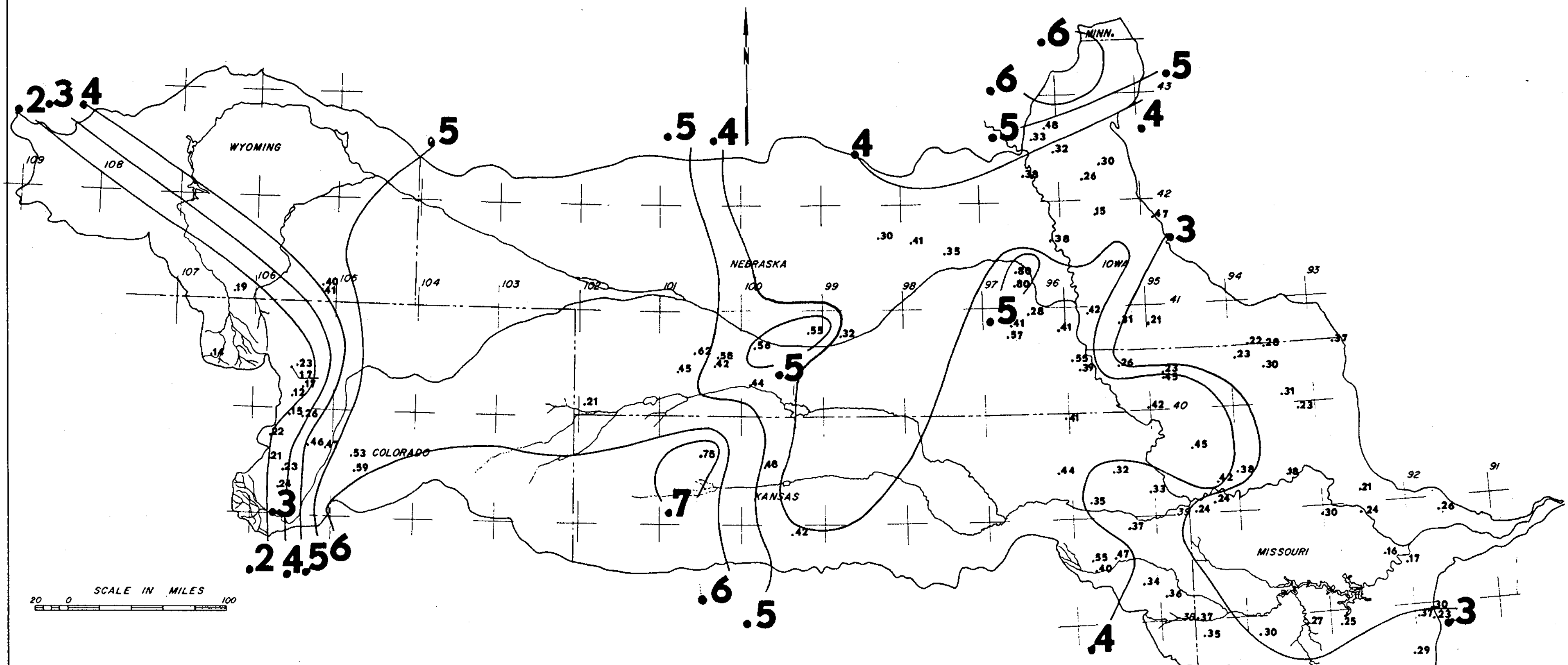


FIGURE 11
Magnitude Index - Part 6B

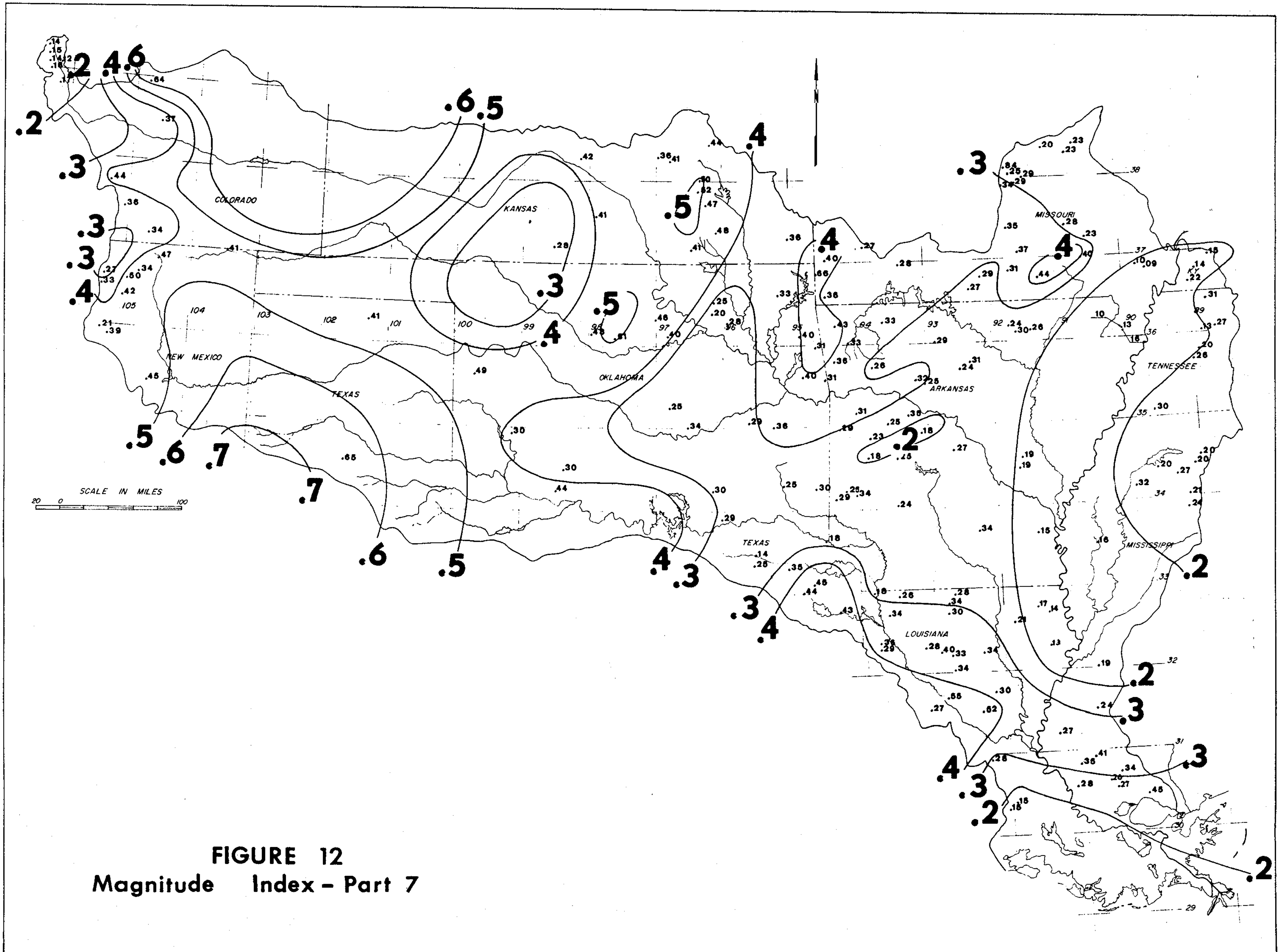


FIGURE 12
Magnitude Index – Part 7

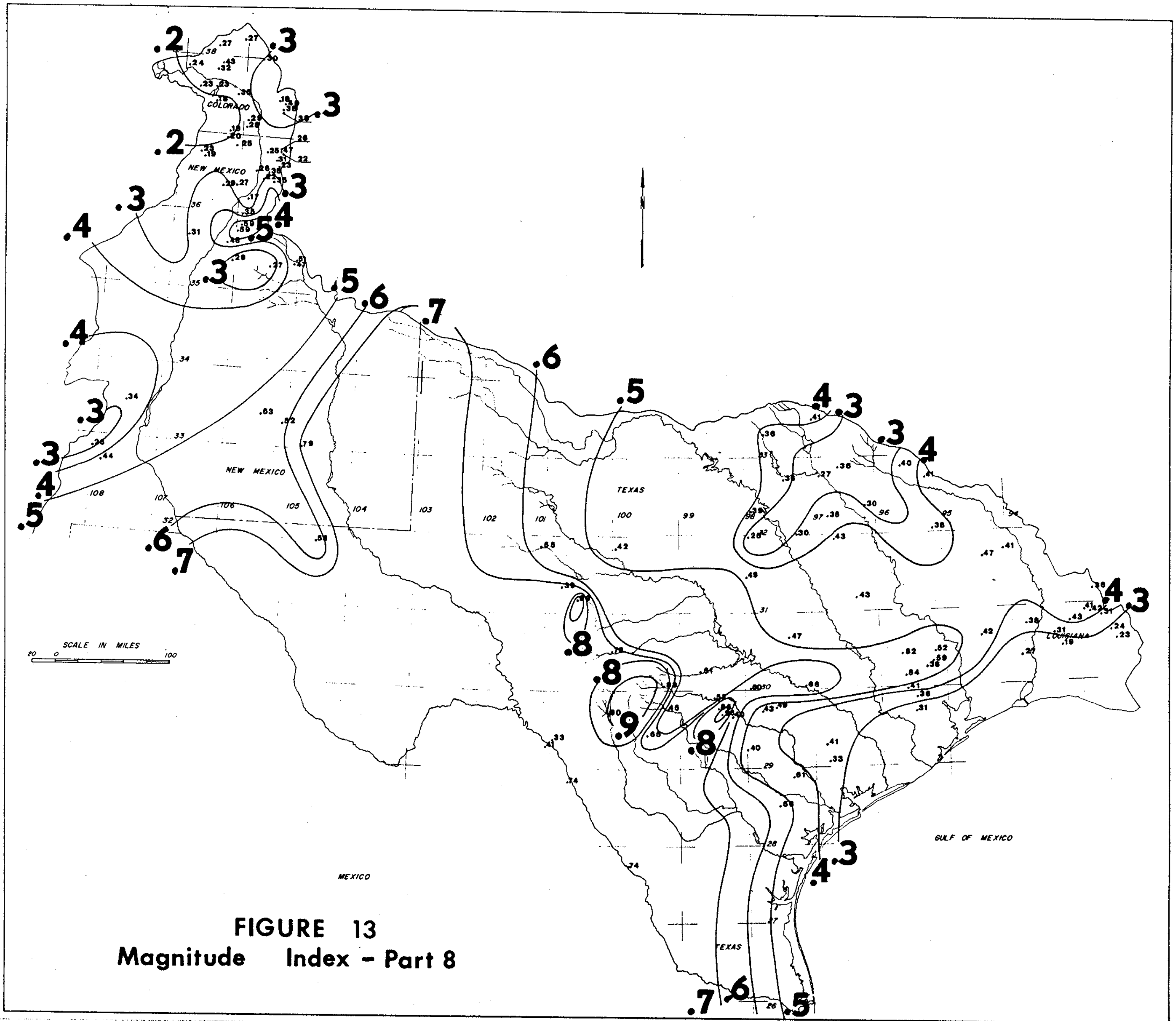


FIGURE 13
Magnitude Index - Part 8

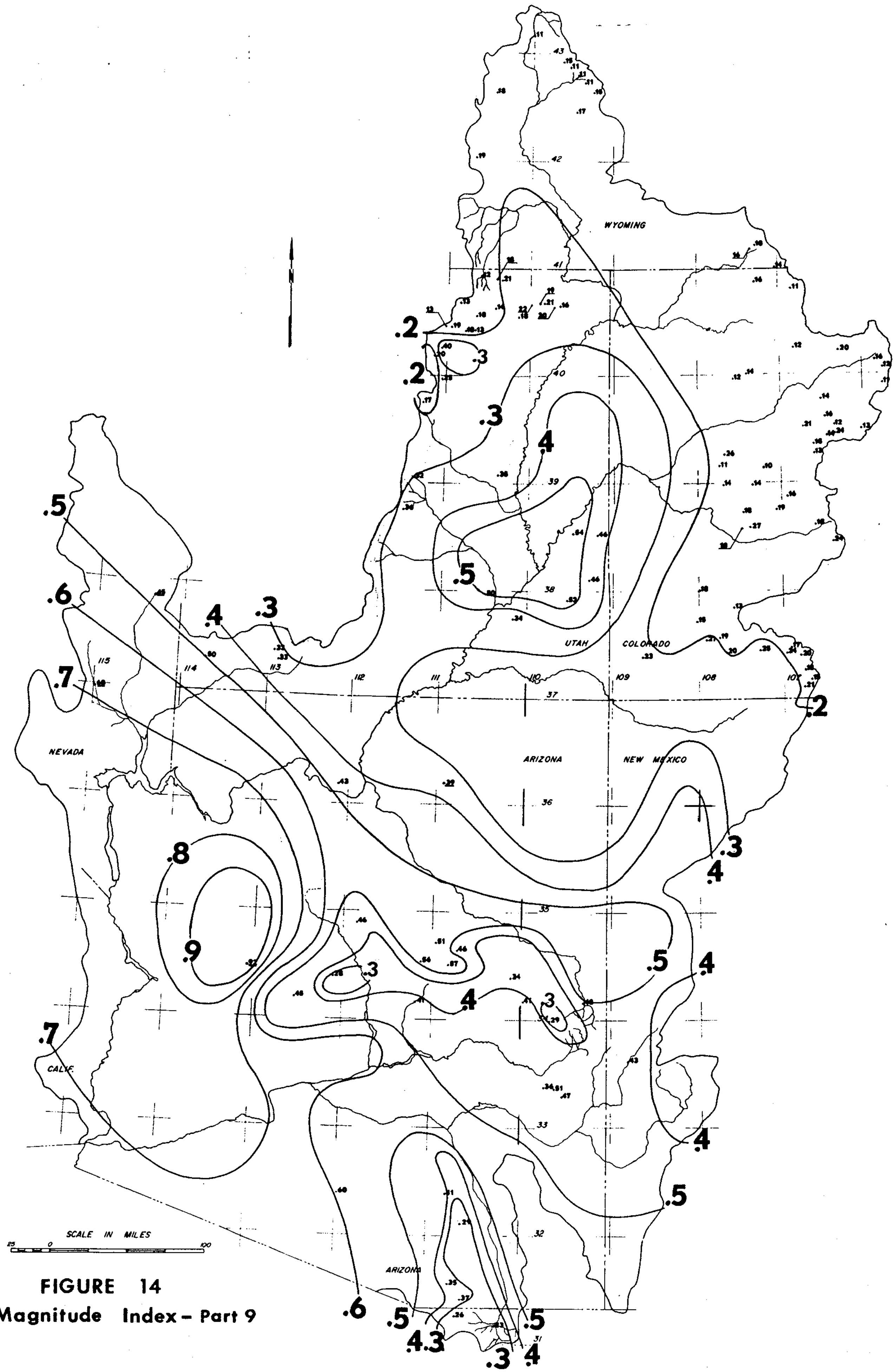


FIGURE 14
Magnitude Index - Part 9

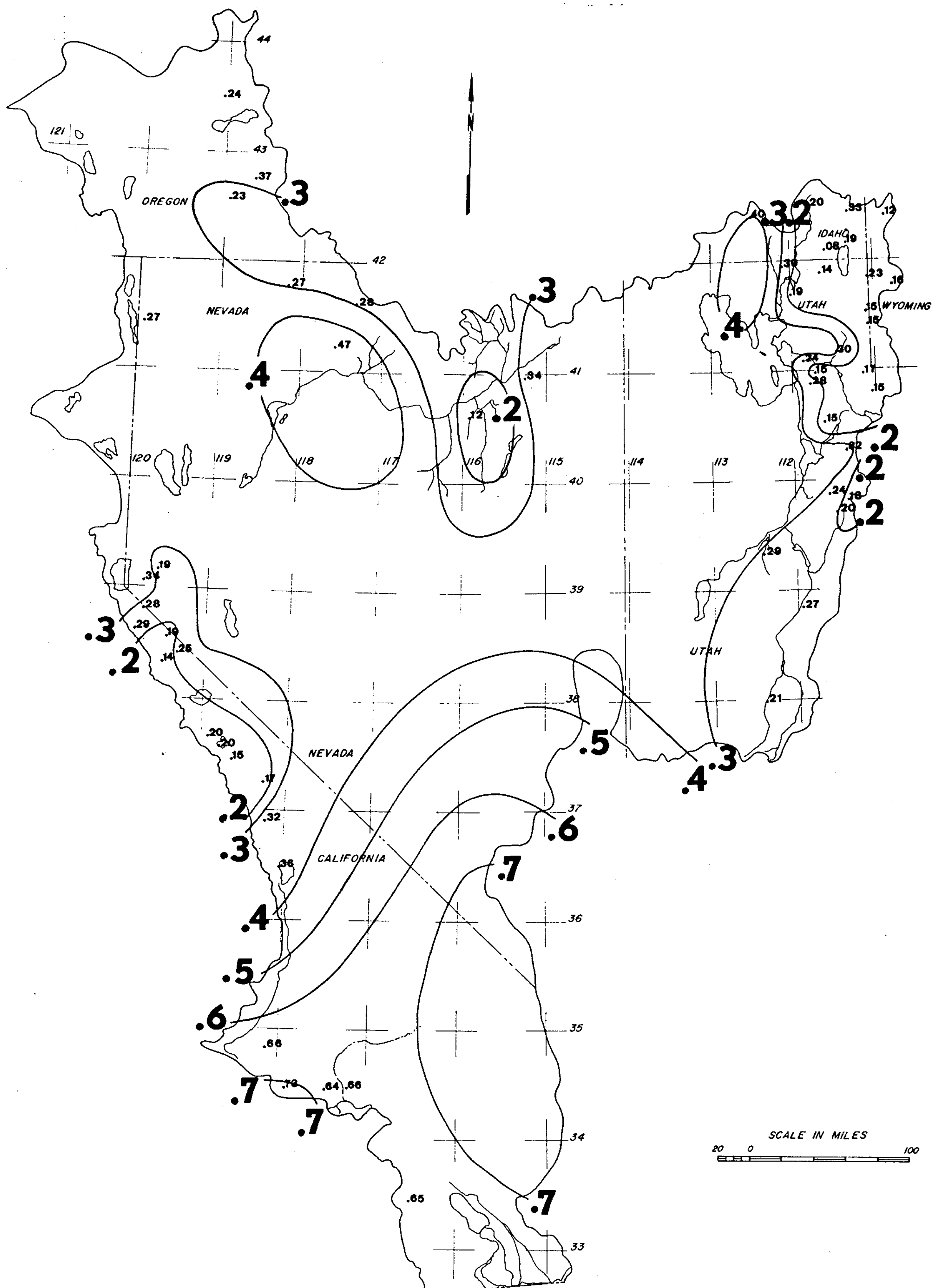


FIGURE 15
Magnitude Index - Part 10

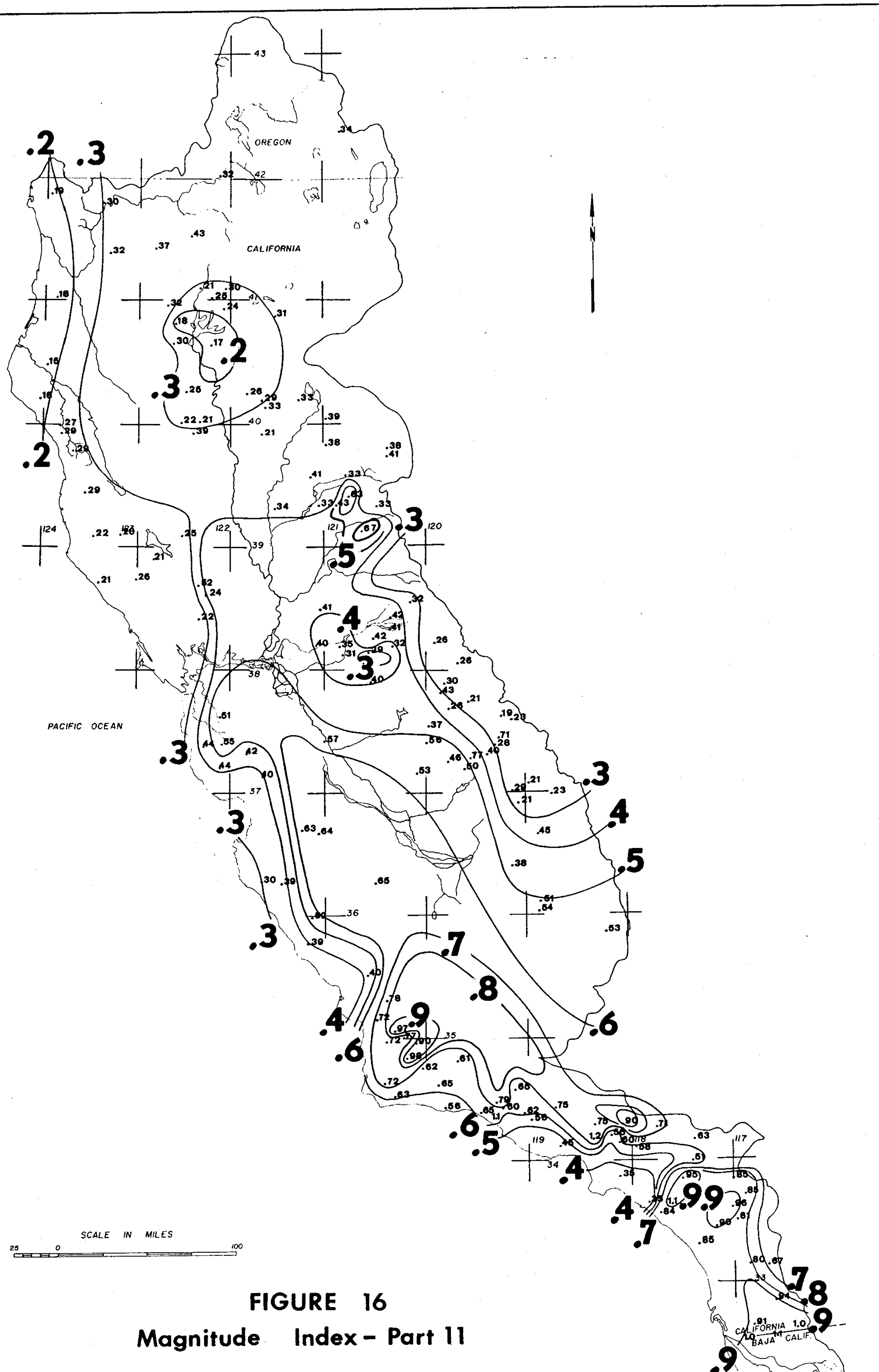


FIGURE 16
Magnitude Index – Part 11

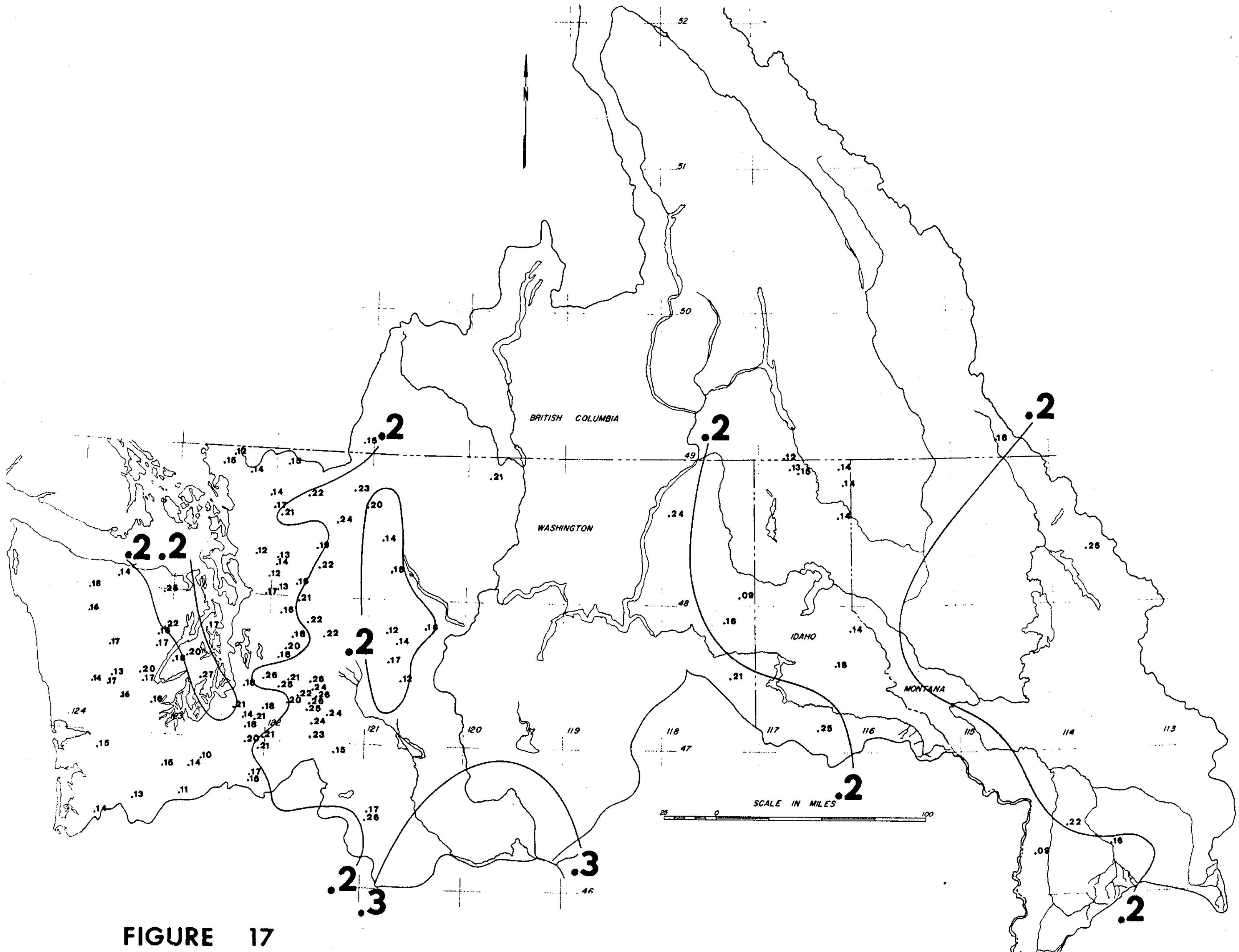


FIGURE 17
Magnitude Index - Part 12

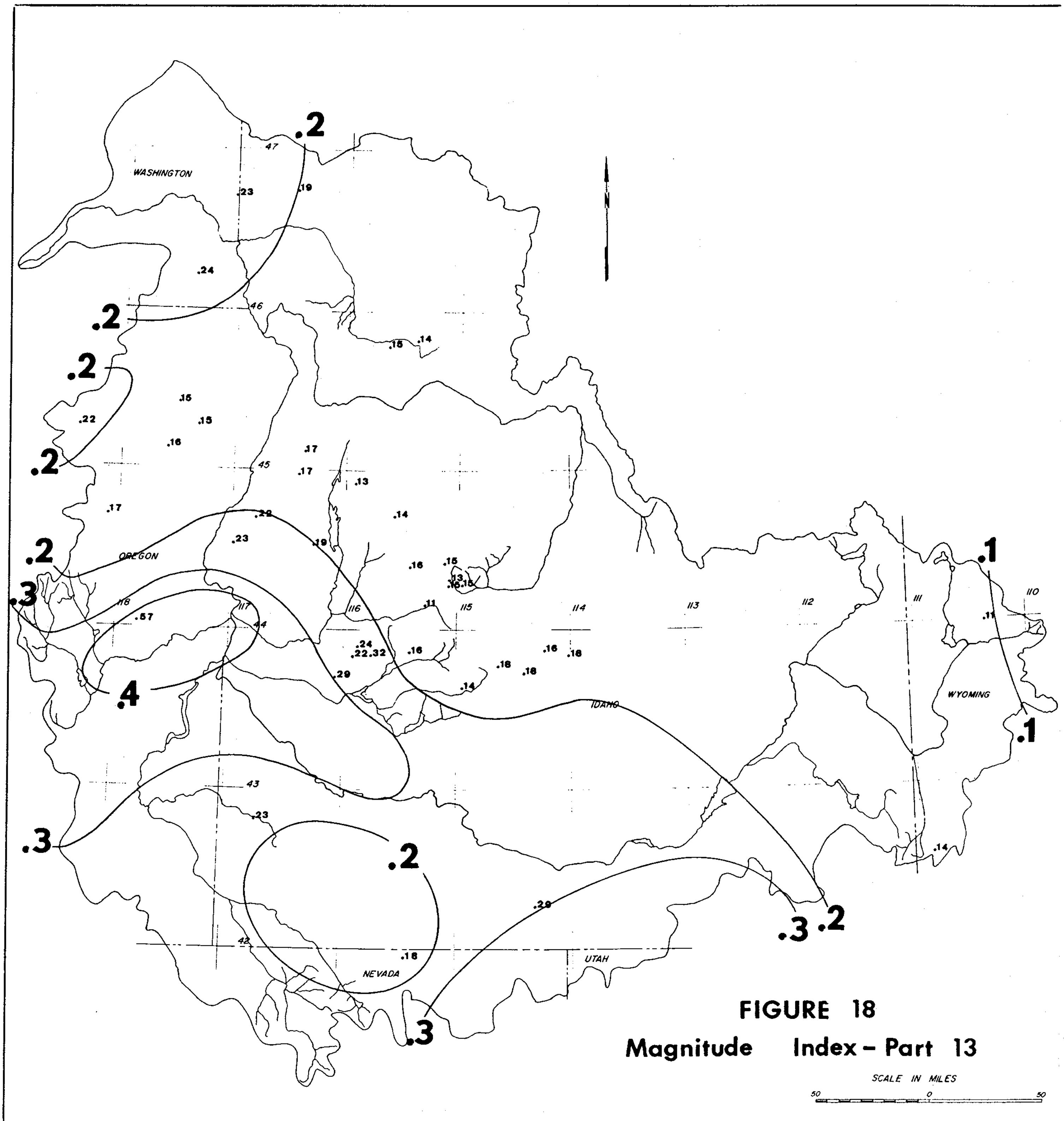


FIGURE 18

Magnitude Index – Part 13

SCALE IN MILES

50 0 50

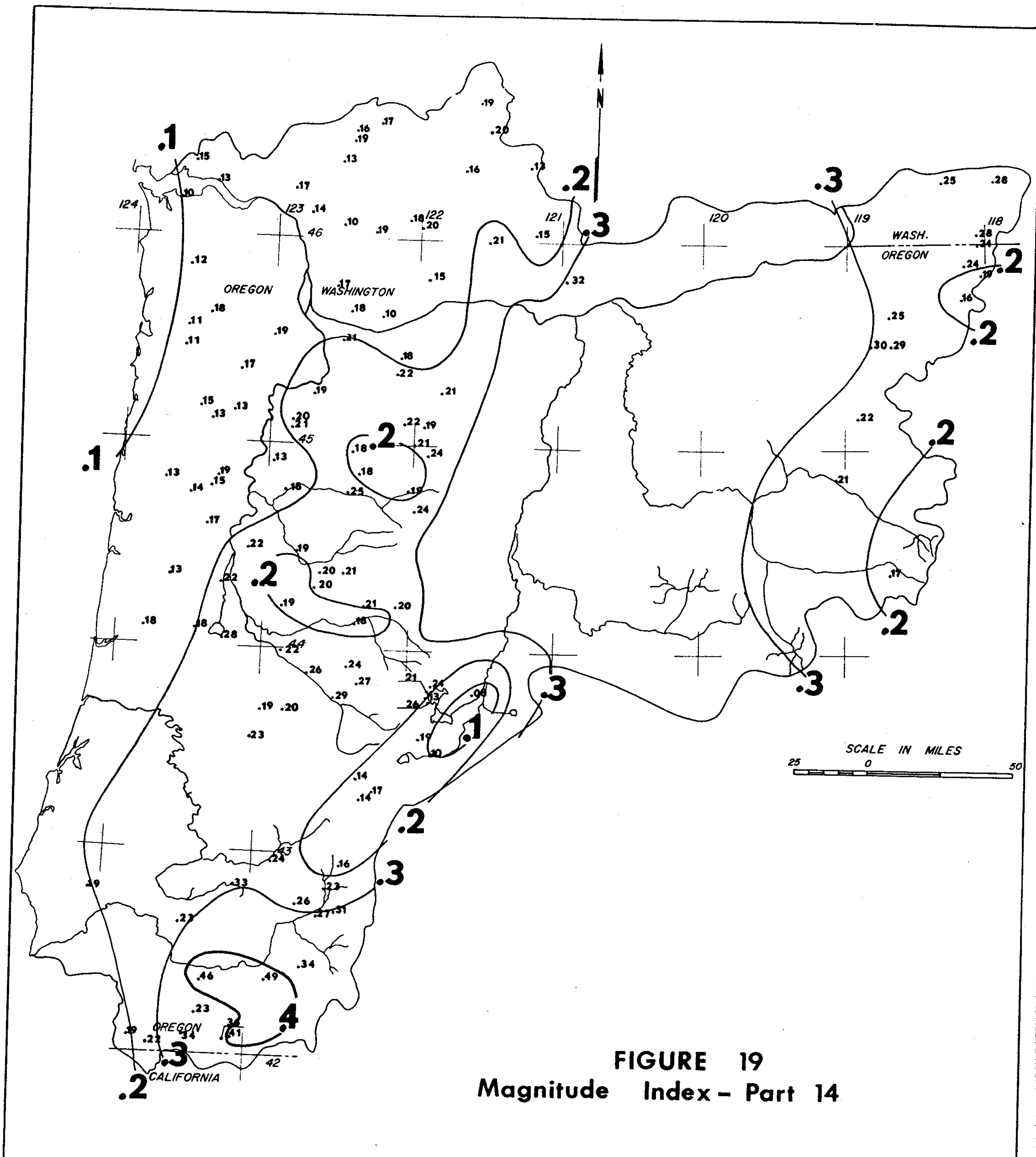
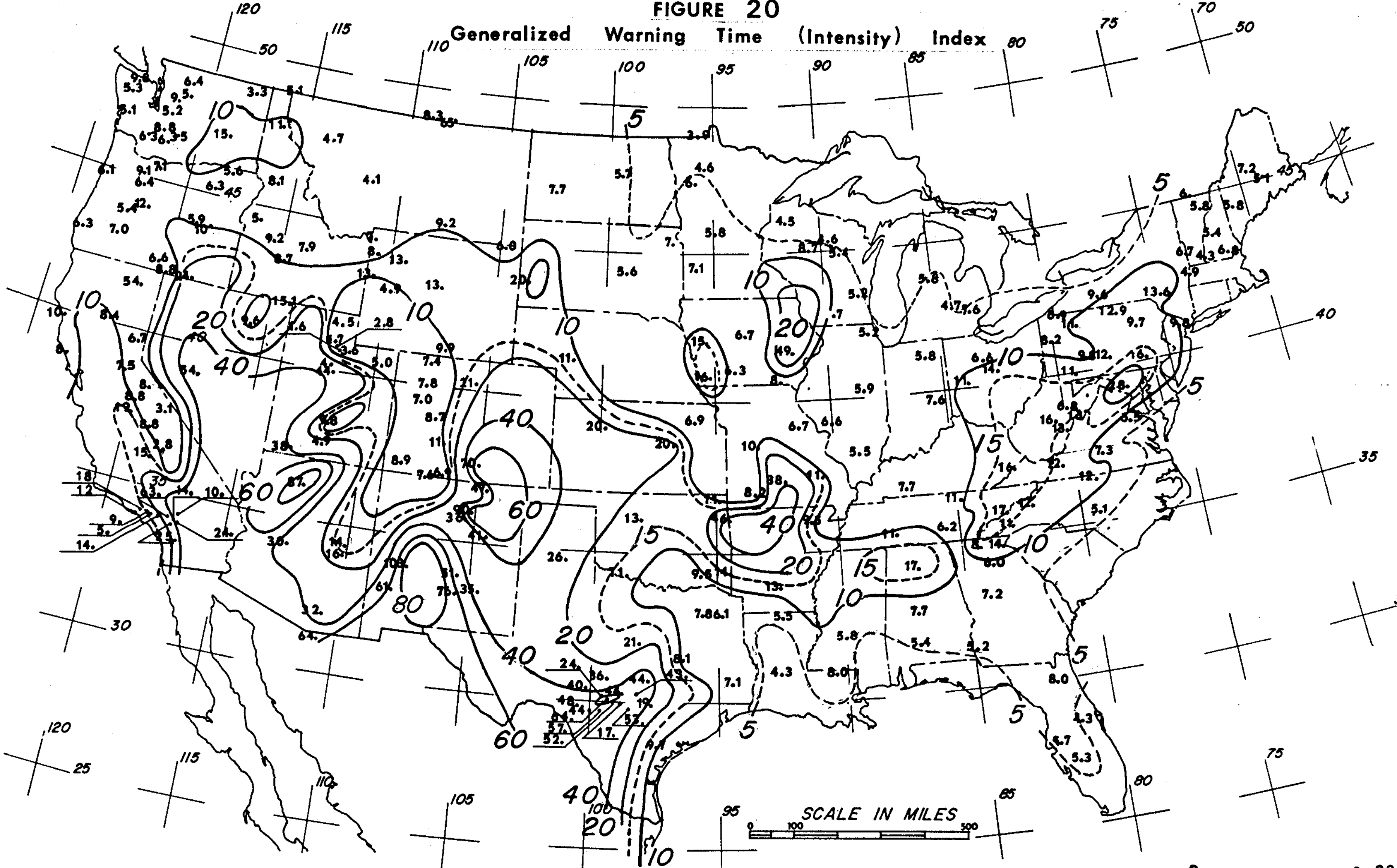


FIGURE 19
Magnitude Index – Part 14

FIGURE 20

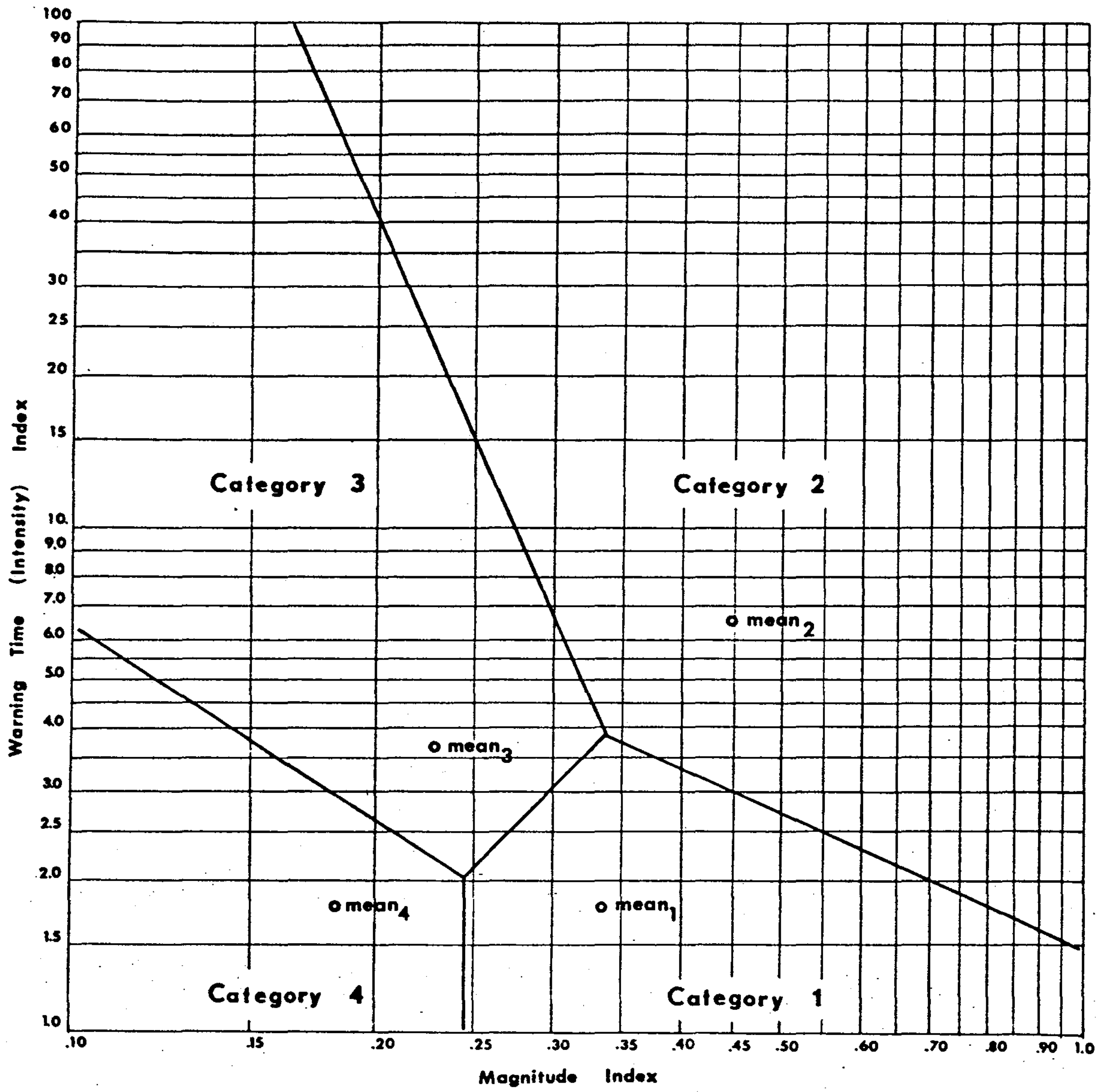
Generalized Warning Time (Intensity) Index



Contours of: Warning Time Index [Drainage Area]$^{.23}$

FIGURE 21

Discriminant Estimates of Categories of Flash-Flood Potential



APPENDIX I

GEOMORPHIC MEASURES OF FLASH-FLOOD POTENTIAL

Background

Geomorphic studies can contribute to flood hazard evaluation through a variety of approaches and techniques. Estimation of flood potential along a particular river reach can involve the qualitative correlation of flood stages of differing recurrence interval a) with terrace levels (Glenn, 1911; Jahns, 1947; Wolman and Eiler, 1956) b) with botanic associations (Sigafoos, 1961) and c) with different soil series associations (Reckendorf, 1973; Wolman; Baker, in press). More quantitative approaches involving channel geometry have been applied for estimating mean annual runoff for streams in California (Hedman, 1970) and in the Appalachian Mountains (Kilpatrick and Barnes, 1964). Extension of the channel geometry concept enabled Emmett (1970) to construct dimensionless rating curves for ungaged Alaskan streams and thereby estimate runoff of varying recurrence interval.

An alternative approach to flood discharge estimation is the consideration of the morphology of the drainage basin. Quantitative measurement of drainage basin morphology for discharge estimation involves an understanding of both transient and permanent variables (Rodda, 1969). Transient parameters include mainly climatic factors of rainfall duration and intensity, areal distribution of rainfall, and storm movement, (Gray, 1974). Permanent variables include the physical characteristics of the drainage basin, its size and shape, topographic relief, network topology, and geology. Horton (1932, 1945) provided the pioneering work in the quantification of fluvially eroded landforms. His work was subsequently expanded by Strahler (1957) and his students (Chorley, 1957; Maxwell, 1960; Miller, 1963; Melton, 1957; Morisawa, 1959, 1962; Schumm, 1958).

Objectives

The purpose of this study is to develop geomorphic parameters for estimation of flash-flood potential for the continental United States. Flash floods are variously defined as 1) a sudden flood resulting from a cloudburst (American Geological Institute, 1957) or 2) a local flood of great volume and short duration generally resulting from heavy rainfall in the immediate vicinity (Webster's Seventh New Collegiate Dictionary, 1967). The hydrologic implications of these vague definitions are that 1) the rate of rise of the flood hydrograph is extremely rapid, and 2) because of the intensity of rainfall required for the generation of a flash flood, the drainage area affected is relatively small. Leopold (1942), for example, demonstrated for New Mexico and Arizona, a negative correlation between cumulative depth of intense rainfall and area covered by the storm. Woolley (1946) in his description of flash floods along the Wasatch Mountains in Utah, included hydrographs for Price River (drainage area = 530 $mi.^2$) and San Rafael River (drainage area = 1690 $mi.^2$), which demonstrated the rapid rise of flood stage as a result of cloudbursts. However, these rapid rises were probably a result of runoff from only a few much smaller tributaries. Similarly, in central Texas, rapid runoff from Bleiders Creek (drainage area = 16 $mi.^2$) on May 11 and 12, 1972 as a result of 16 inches of rain, caused a rapid rise on Dry Comal River hours before the runoff from the Dry Comal River basin peaked (Baker, 1974). Furthermore, flash floods may produce record discharges on small streams whereas the runoff in the major drainages may be of a far lower recurrence interval. Therefore to predict flash flood potential for a given region one should consider the climate and morphometry related to peak discharges in small drainage basins. Because of the broad regional scope of the problem, field observations are not practical. On the other hand, morphometric data can be collected efficiently and accurately from topographic maps (Morisawa, 1957; Mark, 1974) and remote sensing imagery (Baker, in press; Baker, Holz, and Patton, in press). Given these limitations, the objectives of this study are:

a) to survey the geomorphic and engineering literature for parameters related to peak discharge, which also have the advantage of ease of measurement from topographic maps or remote sensing imagery.

b) to compare and contrast the morphometric properties of drainage basins in regions of high flash-flood potential with drainage basins in regions of low flash-flood potential.

c) to develop equations predicting peak discharge from small drainage basins employing morphometric parameters.

Methodology

The literature was surveyed to determine morphometric parameters related to peak discharge from small drainage basins. In addition to physical significance, ease of measurement was also considered.

Regions of differing flash-flood potential were determined by employing several criteria. Historical accounts of flash floods were considered, although lack of historical data does not necessarily preclude the threat of flash flooding. Hydrologic considerations were based on the maps prepared for this report. Regions with high values of flash-flood magnitude index and high flash-flood warning index were considered potential flash-flood areas. Because nearly all the drainage basins examined in this study have stream gaging records, the flash flood magnitude index was computed for each individual drainage basin.

Where possible, published morphometric data were used to generate predictive equations. For two regions, central Texas and north-central Utah, data was specifically generated for this study by topographic map analysis. The drainage net was interpreted using Strahler's (1957) crenulation method. The stream network was ordered both by the Strahler (1957) and Shreve (1966) methods. Areal measurements were made with a polar planimeter, linear measurements were made with a map wheel. The technique for measuring each parameter will be outlined in the following section.

Stream discharge records were gathered from published U.S.Geological Survey records (data was on U.S.G.S. computer tapes) and U.S. Forest Service open file reports. The Log Pearson III frequency analysis was used to calculate exceedence probabilities from the annual peak data (Beard, 1974).

Where discharge data was not available, regional runoff equations were employed (Patton and Baker, 1975). Morphometric and discharge data were reduced and analyzed by the standard statistical techniques of correlation, discriminant analysis and multiple regression methods (Krumbein and Graybill, 1965; Snedecor and Cochran, 1967).

Selection of Variables

Area. Drainage area is perhaps the most frequently employed variable in estimating stream discharge. Area has been correlated with both low magnitude frequent runoff events (Hack, 1957) and with high magnitude infrequent runoff events (Patton and Baker, 1975); it has been used with runoff in humid (Benson, 1962) and arid (Burkham, 1966) regions. Gray (1974) reviewed numerous examples for regions throughout the world. In this study area, data was collected from U.S.G.S. Water Supply Papers or, when necessary, by measurement from topographic maps with a polar planimeter.

Drainage System. Horton (1945) reintroduced the concept of stream ordering, which Strahler (1957) subsequently modified. The Strahler system designates all unbranched fingertip streams as first order streams; two first order streams combine to form a second order stream; two second order streams join to form a third order stream; and so on until the entire basin is ordered. Although there have been regional correlations of Strahler order with discharge (Leopold and Miller, 1956), it is unsatisfactory for several reasons. First, it does not adequately portray the drainage net. For example, first order streams flowing directly into second or higher order streams are essentially unaccounted. Secondly, there is the technical problem that stream gaging stations are rarely located at the end of a particular order stream (Morisawa, 1962), rather the gages are located intermediate along a Strahler order reach making comparison of discharge with Strahler order difficult. Nevertheless, Stall and Fok (1967) noted an increase in "goodness of fit" between runoff and stream order with decreasing frequency of runoff. This suggests that Strahler order determined from the number of recognizable streams in a given basin is related to extreme runoff events.

A better measure of the hydrologic characteristics of the drainage net is basin magnitude. Proposed by Shreve (1966), the ordering system again designates unbranched fingertip streams as first order (or first magnitude) streams, and there-after the order of the stream is the sum of the contributing first order streams. The importance of basin magnitude is that it is a measure of the maximum drainage development which Blyth and Rodda (1973) have demonstrated is hydrologically significant; for with increasing intensity and duration of rainfall the length and number of flowing streams increases. These results agree with the speculation of Chorley and Morgan (1962) that stream networks are adjusted to maximum rather than mean runoff. Therefore the hydrologic significance and the ease of measurement make basin magnitude an important variable. The frequency of first order streams, basin magnitude divided by basin area, was also computed. Because it is a measure of the number of first order streams per unit area, it enables a comparison between basins of differing size. Basins with high first order stream frequency probably concentrate runoff rapidly.

In addition to proposing the laws of stream numbers and stream lengths, Horton (1932, 1945) developed the parameter known as drainage density. Drainage density is calculated by dividing total stream length by drainage area; it is the length of channel per square unit of drainage area. Drainage density is a complex parameter because it incorporates relief, rainfall, infiltration capacity of the terrain, and the resistance of the land to erosion (Horton, 1945). Strahler (1958) employed dimensional analysis to demonstrate that drainage density is a function of runoff intensity, relief, Horton's erosion proportionality factor, density and viscosity of the fluid medium, and the acceleration of gravity. Drainage density has been correlated with a measure of relief, relief ratio, (Schumm, 1958; Hadley and Schumm, 1961), with Thornthwaites precipitation-effectiveness index and runoff intensity (Melton, 1957); with intensity of precipitation (Chorley, 1957) and with infiltration capactiy (Hadley and Schumm, 1958). Although it is difficult to quantify resistance to erosion, a qualitative inverse relationship has been recognized (Schumm, 1958; Miller, 1953).

Drainage density has been correlated with stream base flow (Carlston, 1963; Trainer, 1969) and the mean annual flood (Carlston, 1963; Hadley and Schumm, 1961). However, other studies have demonstrated that drainage density by itself is not sufficient to define the runoff characteristics of a basin (Morisawa, 1962; Maxwell, 1960). Nevertheless, because of the interactions between process and form variables summarized by the drainage density measure (Horton, 1945; Strahler, 1958) and the wide range of naturally occurring values of drainage density (Schumm, 1958) it is an important variable.

In an analysis of flash-flood potential one might expect flash-flood prone regions to be characterized by high drainage density values reflecting low infiltration capacity, relatively short steep slopes, and low vegetative cover, all of which would lead to rapid concentration of flood runoff. Low potential flash-flood regions might be expected to have low drainage density values reflecting the inverse of the above conditions. However, these hypothetical relationships are actually end members of a continuous series of possible environments. The erodibility of the terrain, a function of local geology; or relict drainage systems as a result of paleo-climates can add considerable complexity to the above generalization.

A technical problem with the use of drainage density is its difficulty of measurement, particularly when large basins are considered. This problem can be circumvented by employing the line intersection estimating procedure. First introduced by Carlston and Langbein (1960) and later modified by McCoy (1971) and Mark (1974), the technique involves superimposing a grid over the drainage net and counting the number of intersections of drainage lines along a traverse line. Drainage density can then be calculated from several empirical equations employing the quotient of the number of intersections (N) and traverse length (L):

$Dd = 1.414\ N/L$ (1) Carlston and Langbein (1960)

$Dd = 1.8 + 1.27\ N/L$ (2) McCoy (1971)

$Dd = 1.571\ N/L$ (3) Mark (1974)

This technique was used for calculating drainage density for basins in north-central Utah. For comparison, drainage density for the six basins was also calculated by measuring total stream length and dividing by drainage area. Equation 2 gave the best results having less then 10% error (Table 1). Considering the rapidity of the technique, the error was considered acceptable.

Relief. The importance of basin relief as a hydrologic parameter has been noted by numerous investigators (Sherman, 1932; Horton, 1945; Strahler, 1958). With increasing relief, steeper hillslopes and higher stream gradients, time of concentration of runoff decreases thereby increasing flood peaks. Thus, all other conditions equal, the greater the relief of a basin, the greater the rate of hydrograph rise. In order to compare relief among basins of varying size two dimensionless parameters were calculated. Relief ratio (Schumm, 1958) is the ratio of basin relief to basin length. Basin relief is measured by averaging the elevation of the highest divide and subtracting the elevation of the outlet. Basin length is measured parallel to the main stream. Relief ratio has been directly correlated with sediment yields (Schumm, 1958) and employed in multiple regression models of peak discharge (Morisawa, 1959, 1962). Because it is directly related to the magnitude of mass removed from a basin it should be an important consideration in estimating flood magnitudes. Similarly basins with high values of relief ratio may be susceptible to flash flooding. Ruggedness number (Melton, 1957) is the dimensionless product of drainage density and relief; and therefore areas of high drainage density and low relief are as rugged as areas of low drainage density and high relief. However, areas of potential flash flooding might be expected to have the highest ruggedness numbers, incorporating a fine drainage texture, with minimal length of overland flow across steep slopes, and high stream channel gradients. The combination of these factors might result in larger flood peaks for an equivalent rainfall input than for basins having a low ruggedness number.

Areas Selected For Study

In order to test the significance of these morphometric parameters, data was collected from both high and low potential flash-flood regions. Regions of high flash-flood potential chosen were central Texas, the Wasatch Mountains in north-central Utah, and the San Gabriel Mountains in southern California. Regions of low potential selected are Indiana and the Appalachian Plateau province in western Pennsylvania, Maryland, Ohio, West Virginia, and Tennessee.

Central Texas. Central Texas is within perhaps the most catastrophic rainfall-runoff regime in the conterminous United States. Texas rainfalls for up to 24 hours duration approach the world maxima (Hoyt and Langbein, 1955). In addition, it is one of the two regions in the U.S. which has the highest 10 year flood magnitudes for 300 square mile drainage basins (Leopold, Wolman, and Miller, 1964). Often, the flooding is the result of intense thunderstorms, and therefore the spatial and temporal distribution of flooding is extremely unpredictable. As a result, effective flood control with large detention structures is not always successful. An example is the May 11 and 12, 1972 New Braunfels flood where the center of intense precipitation was immediately downstream from Canyon Dam, the major flood prevention structure on the Guadalupe River (Baker, in press). The erratic temporal distribution of floods is reflected in the flash flood magnitude index which commonly exceeds .5 .

In addition to loss of life, preperty damage from individual flood events exceeds $50,000,000 (U.S. Water Resources Council, 1968). For these reasons central Texas is an appropriate region in which to relate drainage basin morphometry to flash flooding.

Morphometric data was collected for thirteen study basins throughout central Texas (Table 2). The drainage basins are located in diverse physiographic regions on a variety of rock types. Basins are located on the Precambrain metamorphic and igneous rocks of the Llano uplift, on the Paleozoic limestones in north central Texas, on the Cretaceous limestones of the Edwards Plateau, and on the Cretacious and younger sediments of the Gulf Coastal Plain.

As a result of this diversity there is a wide range in drainage basin morphometric characteristics. Relief, measured as relief ratio, is highly variable ranging from low values on the Coastal Plain (.010) and in north central Texas (.007) to higher values in the Llano region (.020) and Edwards Plateau (.030). The same trend is consistent with values of drainage density, first order stream frequency, and ruggedness number.

Runoff data was available for six of the study basins and runoff for the remaining basins was estimated from a regional equation which relates maximum discharge to drainage area for central Texas (Patton and Baker, 1975). To avoid spurious correlations between morphometric variables and discharge, area and variables highly correlated with area (e.g. basin length) were eliminated from any analysis of stream runoff.

North-Central Utah. The Wasatch front in north-central Utah is another area of historical flash flooding. Woolley (1946) noted that between 1847 and 1938 over 500 cloudburst floods were reported along with reports of extensive crop damage, highway, bridge, and building destruction. A more recent report (Butler and Marsell, 1972) details the 836 flash floods reported between 1938 and 1969, the majority of which occurred along the Wasatch Front. The floods are the result of intense rainfalls, up to 4 inches in 12 hours, from severe thunderstorms created by the orographic effect of the Wastach Front (Butler and Marsell,1972). Although the volume of flood runoff is considerably less than that for central Texas for example, flash floods in the Wasatch Range commonly cause mud and debris flows which greatly increase property damage (Woolley, 1946). The flash-flood magnitude index for this region is low, ranging from .15 to .35 . The magnitude index, however, is calculated from the distribution of the annual peak flows. Along the Wasatch Front the annual peak flows are related to snowmelt events (U.S. Geol. Survey Water Supply Paper 1927), and therefore cloudburst floods represent secondary runoff events. This is perhaps one region where a more detailed analysis of the runoff records is required to clearly identify the magnitude index.

Woolley (1946) recognized the direct relationship between regional population growth and flash flood reports throughout Utah, a trend which tends to obscure any statewide pattern of flash flood incidence. This trend is accentuated because instrumentation for measuring rainfall and runoff is concentrated near population centers. Although flood reports from the Wasatch Front may be proportionately high for the region as a whole, it remains a documented area of flash-flood potential and was therefore included in the study. Furthermore, with the rapid population growth along the Wasatch Front the problem is likely to become more environmentally acute and property damage is likely to increase (Marsell, 1971).

Eleven drainage basins along the Wasatch Front were selected for study (Table 3). The geologic framework of the Wasatch Front is complex. The drainages investigated have their headwaters east of the Wasatch fault and flow westward eroding steep canyons into the fault scarp. Where the streams exit from the mountain front broad alluvial fans have formed on top of lacustrine Pleistocene sediments. Most of the small drainage basins are underlain by the Precambrain Farmington Canyon complex composed of metamorphic sedimentary rocks, metamorphic igneous rocks, and intrusive gneisses (Eardley, 1944). The larger basins are eroding into the Triassic clastic sediments, and in places cross narrow belts of Paleozoic clastic and carbonate rocks (Eardley, 1944). In general, the drainage basins have high relief (relief ratio .08 - .27), high drainage density (6.68 - 10.01 mi./mi.^{2}) and extremely high ruggedness numbers (4.60 - 10.95). Also, U.S.G.S. stream gaging records are available for each basin analyzed. These data were reduced by standard Log Pearson III frequency analysis (Beard, 1974).

Southern California. Southern California was the third flash-flood prone region selected for study. Intense precipitation in southern California is controlled by extra-tropical North Pacific cyclones which move inland generating storms with recorded intensities of up to 11.5 inches in 1 hour 20 minutes (Anderson, 1949). The mountainous regions of southern California are particularly affected by flash flooding, with runoff of up to 1260 cubic feet per second per square mile from a 17 square mile drainage basin (Anderson, 1949). Therefore the San Dimas Experimental Forest on the southern slope of the San Gabriel Mountains near Los Angeles was an excellent locality for analysis. The regional flash-flood magnitude index is 0.7 . Runoff in the San Dimas region is even more erratic with the flash-flood magnitude index approaching or exceeding 1.0 for many basins.

The San Gabriel Mountains are a fault block range bounded by three major fault zones (Maxwell, 1960). The mountains themselves are highly faulted and consist of pre-Cretaceous schist, gneiss and granitic rocks surrounded by Tertiary and Quaternary alluvial deposits (Maxwell, 1960).

The analysis of the morphometric data was greatly facilitated by the excellent quantitative geomorphology study by Maxwell (1960). Maxwell (1960) provides morphometric data for twelve basins (Table 4) within the San Dimas Experimental Forest. Relief is high (relief ratio .130 - .390), and drainage density is extremely high (13.50 - 32.94 mi./mi.^{2}). As a result, ruggedness number is again high (1.86 - 10.16), indicating extremely high relief, fine textured drainage basins. The fine texture of the drainage network is demonstrated by the frequency of first order streams which exceeds 3600/mi.^{2} in one basin. This demonstrates that as drainage density increases, the increase in total channel length is created as the result of a far greater increase in first order streams, and not by an increase in the length of higher order channels. Runoff data was obtained from the U.S. Forest Service in Glendora, California. Analysis of the runoff data was by standard Log Pearson III frequency analysis (Beard, 1974).

It is more difficult to identify regions of low or moderate flash-flood potential. Because historical reports of large magnitude floods abound throughout the United States, one obvious, but subjective criteria is to use the definition of a flash flood. The rapid rise of the flood hydrograph is one criterion which can be employed to distinguish flash floods from more slower-cresting flood events. The regional flash-flood warning index was therefore evaluated in selecting regions of low and moderate flash-flood potential. Secondly, both the regional and at a station flash-flood magnitude indices were scrutinized.

Drainage basins in Indiana, Ohio, Pennsylvania, Maryland, West Virginia, and Tennessee were chosen on this basis. The flash-flood magnitude index ranged from .2 to .3 . The collection of morphometric data was greatly facilitated by the previous quantitative geomorphic studies of Lee and Delleur (1972) and Morisawa (1962).

Indiana. Ten Indiana basins for which stream runoff and drainage basin morphometric data were available were selected for study (Table 5). With the exception of south central Indiana, the entire state is covered by a thickness of more than 50 feet of glacial ground and end moraine (Indiana State Geol. Survey 1961 - 1972). Of the basins investigated, only one crosses significant outcrop of Mississippian shale, siltstone, and sandstone; the others are underlain by Wisconsinan and Illinoisan glacial material (Indiana State Geol. Survey 1961 - 1972). Basin relief is extremely low in Indiana (relief ratio .0008 - .016) but drainage densities (2.17 - 11.80 mi./mi.^{2}) can be as high as values in the Wasatch Front and are generally comparable to values for central Texas. This can in part be related to the easily eroded, impermeable till underlying most of the drainage basins (Indiana State Geol. Survey, 1961 - 1972). Ruggedness number is slightly lower for Indiana than for the previously discussed regions of high flash flood potential. Runoff data was collected from U.S.G.S. stream gaging records and Log Pearson III frequency analysis was performed (Beard, 1974).

Appalachia. Eleven basins were chosen for study within the Allegheny Mountain, unglaciated Allegheny Plateau, and Cumberland Plateau division of the Appalachian Plateau (Morisawa, 1962). The region contains Paleozoic rocks, gently folded in the Allegheny Mountain region, becoming more horizontal westward and southward onto the unglaciated Allegheny Plateau and Cumberland Plateau. In this region, values of basin relief are low to intermediate (relief ratio .005 - .067), but drainage density is consistently low (2.58 - 5.75 mi./mi.^{2}) and as a result ruggedness numbers have intermediate values (.17 - 1.11). The low drainage density values in basins with intermediate relief probably reflect greater infiltration capacity of thicker soils and increased vegetative cover prohibiting erosion. For example, several central Texas streams have lower values of relief ratio but greater values of drainage density. Ruggedness numbers, however, are nearly identical for the two regions.

General Relationships

Flash-Flood Potential. Several general trends are apparent from the morphometric data collected in this study. With the exception of central Texas, basin relief is higher for the flash-flood prone regions than for regions of low or moderate potential. The higher relief is obviously a factor in concentrating runoff rapidly. Furthermore the north-central Utah and southern California drainage basins have the highest drainage density values. High basin relief combined with high drainage density creates steep short hillslopes minimizing the length of overland flow and again more rapidly concentrating runoff. Central Texas has intermediate values of basin relief and drainage density but perhaps the greatest flood discharges. The coarser drainage texture and lower basin relief is probably offset by the more extreme rainfall events, and the thin impervious lithosols developed on the Edwards Plateau.

Conversely, low or moderate potential flash-flood regions have either low (Appalachian Plateau) or intermediate (Indiana) values of drainage density, and low to intermediate basin relief. The combined effect of these two variables will be greater length of overland flow across gently to moderately sloping interfluves, a condition which will generally result in more attenuated flood hydrographs.

Because relief and drainage density are apparently the two most distinguishing variables, ruggedness number, the dimensionless product of relief and drainage density, should adequately summarize their interaction. Southern California and north-central Utah have the highest values of ruggedness number while central Texas, Indiana, and the Appalachian Plateau province have low to intermediate values. However, as Figure 1 of this appendix demonstrates, for a given value of basin magnitude, high flash-flood potential regions are more rugged. This suggests that for a given drainage basin magnitude, basin relief and drainage density are higher for flash-flood prone regions than for low flash-flood potential regions. That is, for the same number of first order streams, a more rapid response is the result of greater stream gradients, steeper hillslopes, and a finer drainage texture. Thus, flash-flood prone regions are at least partly geomorphically controlled. The relationship can be statistically verified by discriminant function analysis. The analysis performed involved the calculation of the linear distance function. (Table 7). Although there is a significant break between the two groups, with increased sampling this separation may become less distinct.

A large number of basins fall near the line separating the two groups, forming an intermediate band. One possible explanation is that geomorphic controls may be the most effective at either end of the spectrum. Extremely dissected high relief drainage basins have a rapid hydrograph response with even relatively low intensity rainfall inputs, and conversely low relief poorly dissected basins have a much slower response even for high intensity rainfalls. However, basins with intermediate values of dissection and relief may be more dependent on the nature of the storm input. Regions characterized by high intensity storms may cause a more rapid response or flash flood in one basin, whereas in a region characterized by lower intensity storms, a topologically similar basin may have a far different slower response. The morphometry of the basins is of course controlled to a great extent by climate. In a region where the rainfall inputs are temporally erratic, but severe when they do occur, as in Texas, a feedback mechanism enhancing the rapid drainage response can be visualized. Erratically distributed rainfall does not enhance vegetation or soil development, and, as a result, with greater overland flow the creation of hillslope rills is instead enhanced, which are eventually incorporated into the channel network. These newly formed first order channels contribute to further increase the response of the drainage system. The reverse would occur in a region where rainfall is temporally and spatially more uniform. There the feedback mechanism would continually work to dampen the basin response by aiding the development of thick soils and dense vegetation thereby increasing infiltration rates and retarding surface runoff.

Flood Magnitudes. Morphometric data can be equally effective in predicting flood magnitudes from small drainage basins. Basin magnitude is one parameter directly related to the maximum runoff from a drainage basin (Blyth and Rodda, 1973). Measures of relief, either relative relief or relief ratio, should also be important in estimating flood peaks. Measures of drainage texture, either drainage density or first order stream frequency, are important measures of the overall channel efficiency. Finally ruggedness number which summarizes the interaction of topologic and relief variables should be a valuable measure for predicting runoff magnitudes.

Correlation analysis of the morphometric and runoff data was performed. Stream discharges having exceedence probabilities of .1, .5, and .01 and the maximum discharge of record were the discharge values selected for comparison with the morphometric data. For the central Texas watersheds it was feasible to include only the maximum discharge of record. The correlation matrices are presented in Tables 8, 9, 10, 11, and 12.

Basin magnitude is better correlated with infrequent runoff events in the San Dimas and Wasatch watersheds, whereas in the Indiana and Appalachian Plateau watersheds the correlation coefficients between basin magnitude and discharge increase with increasing frequency of runoff. This suggests that regions characterized by infrequent high intensity storms adjust their drainage net to the infrequent high magnitude runoff events. Regions characterized by more frequent less intense regional storms adjust their drainage nets to the resulting more frequent lower magnitude floods, such as the mean annual flood. Basin magnitude is also highly correlated with drainage area and either could be substituted in a regression analysis. In the following example basin magnitude was employed along with drainage density, first order stream frequency, relief ratio, and ruggedness number. Drainage density was not employed in the same equations with first order stream frequency as they are highly correlated (Melton, 1957). The equations developed by stepwise least squares regression methods are presented in Table 13. The results are significant with the exception of Indiana watersheds. Equations involving basin magnitude, ruggedness number, and first order stream frequency generally provided the best results. For watersheds having low flash-flood potential (Indiana and Appalachian Plateau) morphometric parameters were better estimators of the mean annual flood ($Q_{.5}$) than the maximum discharge of record (Q_{max}). This further suggests that drainage networks adjust to and reflect the magnitude and frequency of the dominant runoff events, which in turn reflect the intensity, duration, areal extent, and frequency of the rainfall inputs. Although this morphometric adjustment is probably due to a range of discharges, the values of Q_{max} and $Q_{.5}$ serve as useful measures of the end members of the discharge spectrum.

Summary and Conclusions

Morphometric parameters are practical measures of flash flood potential. Study basins were selected on the basis of flash-flood magnitude index, flash-flood warning time index, historical records, and stream gaging records. In general high potential areas had greater relief, drainage density, and thus greater ruggedness numbers than low flash-flood potential watersheds. For a given number of first order channels (basin magnitude) flash-flood regions have greater ruggedness numbers indicating that flash-flood regions have higher drainage densities combined with steep hillslopes and stream channel gradients. Data on precipitation intensity might enhance this relationship.

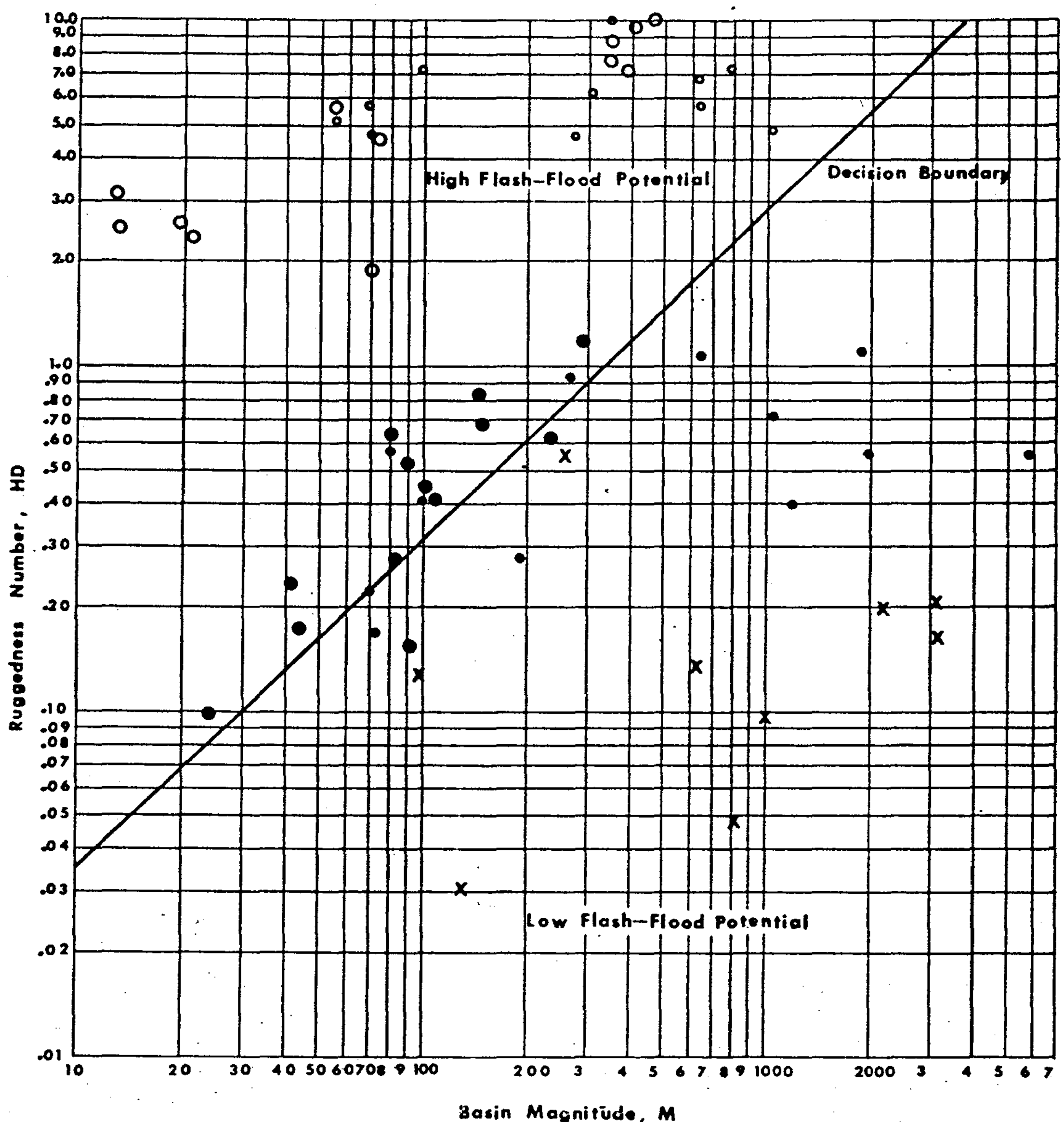
Morphometric data is also a practical technique for estimating maximum discharge magnitudes for small watersheds. Basin magnitude, ruggedness number and first order channel frequency were generally the most effective variables. Morphometric parameters for low potential flash flood regions were better estimators of frequent low magnitude runoff events (mean annual flood) further suggesting that drainage basin morphometric parameters are controlled by the magnitude and frequency of the climatic processes and resulting runoff events.

LIST OF SYMBOLS

Symbol		Units
A	drainage basin area	square miles
S	Strahler basin order	enumerative
M	basin magnitude	enumerative
R	basin relief	feet
BL	basin length	miles
HD	ruggedness number	miles
Rr	relief ratio	miles
Dd	drainage density	miles/square mile
F_1	first order channel frequency	number/square mile
$Q_{.5}$	discharge having an exceedence probability of .5	cubic feet/second
$Q_{.1}$	discharge having an exceedence probability of .1	cubic feet/second
$Q_{.01}$	discharge having an exceedence probability of .01	cubic feet/second
Q_{max}	maximum peak discharge	cubic feet/second

FIGURE 1 (Appendix I)

Morphometric Categories of Flash-Flood Potential



Legend

LOW POTENTIAL

X– Indiana

•– Appalachian Plateau

HIGH POTENTIAL

●– Central Texas

O– Southern California

o– North Central Utah

TABLE 1 (APPENDIX I)

DRAINAGE DENSITY ESTIMATION RELATIONSHIPS

Basin	N/L	1.571N/L	1.414N/L	Dd
City Creek	6.04	9.49	8.54	8.87
Centerville	4.72	7.50	6.65	6.67
Framington	5.37	8.44	7.60	7.47
Ricks	4.93	7.74	6.97	7.50
Parrish	4.72	7.44	6.68	7.36
Holmes	6.53	10.26	9.23	8.96

C = 1.571 error ranges from 1.1% to 13%

C = 1.414 error ranges from .3% to 9.2%.

The coefficient derived by regression analysis for these basins is

Dd = 1.442 N/L $R^2 = .9979$ $P < .0001$.

TABLE 2 (APPENDIX I)

MORPHOMETRIC AND RUNOFF DATA FOR CENTRAL TEXAS

	A	S	M	R	BL	HD	Rr	Dd	F_1	Qmax
Deepcreek Subwatershed No. 3	3.42	4	42	270	2.77	.23	.018	4.37	12.28	3060
Deepcreek Subwatershed No. 8	5.41	3	44	270	3.86	.17	.013	3.30	8.13	5660
Wilbarger Creek	4.61	3	24	165	3.05	.10	.010	3.24	5.20	4279
Rebecca Creek	11.41	6	237	512	4.36	.61	.022	6.14	21.27	9300
Dry Creek at Buescher Lake	1.57	4	84	142	1.94	.27	.014	10.26	53.50	1870
Mukewater Subwatershed No. 9	4.02	4	91	135	3.61	.15	.007	5.66	22.64	1440
Upshaw Creek	4.89	5	105	340	3.72	.41	.017	6.20	21.47	4460*
Helms Creek	5.92	5	147	505	4.64	.66	.020	7.01	24.83	5120*
Dry Creek	1.79	4	81	375	1.68	.64	.040	8.90	45.25	2145*
Burleson Creek	4.16	5	90	437	3.39	.52	.024	6.51	21.63	3985*
Little Barton Creek	5.95	5	101	442	4.69	.44	.018	5.24	16.97	5150*
Miller Creek	5.71	6	291	661	3.43	1.19	.036	9.68	50.96	5010*
Bee Creek	3.43	4	145	540	3.34	.81	.030	8.10	42.27	3395*

* Estimated from regional runoff equation: $Qmax = 1403\ A^{.73}$ (Patton and Baker, 1975)

TABLE 3 (APPENDIX I)

MORPHOMETRIC AND RUNOFF DATA FOR NORTH CENTRAL UTAH

Basin	A	S	M	R	BL	HD	Rr	Dd	F_1	$Q_{.5}$	$Q_{.1}$	$Q_{.01}$	Q_{max}
City Creek	19.2	5	602	4150	10.23	6.71	.080	8.54	31.35	64	109	167	163
Hardscrabble Creek	28.10	5	1028	3230	7.65	4.84	.080	8.02	36.58	242	416	638	464
Centerville Canyon	3.15	4	71	3600	3.77	4.60	.180	6.75	22.54	12	28	62	30
Farmington Canyon	10.60	5	276	3170	6.29	4.56	.095	7.60	26.03	142	300	598	298
Emigration Creek	18.00	5	629	3575	8.33	5.72	.081	8.65	34.94	25	63	137	156
Salt Lake City Mill Creek nr.	21.70	5	785	4540	9.65	7.26	.089	8.61	36.17	50	91	151	152
Rick Creek	2.35	4	68	4300	3.04	5.67	.270	6.97	28.94	17	48	130	51
Parrish Creek	2.08	3	55	4252	3.63	5.10	.220	6.68	26.44	12	31	72	30
Holmes Creek	2.49	4	98	4100	2.84	7.17	.270	9.23	39.35	17	39	85	36
Dry Creek	9.82	6	354	5785	5.27	10.95	.210	10.01	36.04	210	385	682	597
Bountiful Mill Creek nr.	8.79	5	307	3945	6.07	6.08	.120	8.15	34.92	40	103	248	140

TABLE 4 (APPENDIX I)

MORPHOMETRIC[1] AND RUNOFF DATA FOR CALIFORNIA

SAN DIMAS EXPERIMENTAL FOREST

Basin	A	S	M	R	BL	HD	Rr	Dd	F_1	$Q_{.5}$	$Q_{.1}$	$Q_{.01}$	Q_{max}
Wolfskill Canyon Watershed I	2.49	5	409	2695	2.56	9.83	.199	19.26	164.25	24	202	1311	1010
Fern Canyon Watershed II	2.20	5	465	2900	2.46	10.16	.223	18.50	211.36	10	149	1040	215
Upper East Fork Watershed III	2.18	5	347	2560	2.56	8.63	.189	17.81	159.17	13	118	905	160
Bell Canyon Watershed VIII	2.01	5	386	1520	2.21	7.02	.130	24.40	192.03	15	165	1710	217
Volfe Canyon Watershed IX	1.18	5	344	1610	1.86	7.59	.163	24.91	291.52	2	83	1862	145
<u>Subwatersheds</u>													
II - 1	.054	4	19	727	.41	2.51	.337	18.27	351.85	1	11	95	22
II - 2	.065	3	22	647	.48	2.28	.252	18.61	338.76	2	20	190	22
II - 3	.085	2	13	990	.55	2.53	.337	13.50	152.94	1	19	233	51
VIII - 1	.122	4	55	992	.68	5.52	.277	29.38	450.81	.5	14	827	22
VIII - 2	.061	5	75	719	.38	4.48	.360	32.94	1229.5	.7	26	862	33
VIII - 3	.10	4	39	1031	.54	5.62	.358	28.81	390.0	.6	10	150	18
VIII - 4	.061	3	13	921	.45	3.14	.390	18.02	213.1	.4	8	139	10

1) Morphometric data from Maxwell (1960)

TABLE 5 (APPENDIX I)

MORPHOMETRIC[1] AND RUNOFF DATA FOR INDIANA

Basin	A	S	M	R	BL	HD	R_r	D_d	F_1	$Q_{.5}$	$Q_{.1}$	$Q_{.01}$	Q_{max}
Little Indian Creek	33.43	6	129	77	8.82	.031	.0016	2.17	3.85	343	500	726	500
Lawrence Creek	2.64	4	97	120	2.17	.139	.0100	6.10	36.74	527	1350	3247	2650
Bear Creek	5.80	5	259	310	3.66	.575	.0160	9.80	44.65	603	1573	3792	1830
Bean Blossom Creek	13.40	6	785	373	5.22	.833	.0130	11.80	58.58	1792	4651	11108	8140
Big Blue River	169.70	6	3066	240	26.39	.222	.0017	4.88	18.07	4265	8807	17006	12900
Hinkle Creek	18.20	6	624	110	4.83	.138	.0043	6.62	34.28	1346	4206	12291	4920
Cicero Creek	205.70	7	3066	200	18.40	.163	.0020	4.30	14.90	3311	7548	15942	9800
Buck Creek	33.84	6	817	45	9.72	.048	.0008	5.69	24.14	810	1792	3760	1780
Salamonie River	80.55	7	2159	182	12.03	.200	.0028	5.82	26.80	2155	3803	6686	3460
Little Cicero Creek	42.06	6	1003	110	9.68	.096	.0021	4.64	23.85	1242	2960	6701	3980

[1] Morphometric data from Lec and Delleur (1972)

TABLE 6 (APPENDIX I)

MORPHOMETRIC[1] AND RUNOFF DATA FOR THE APPALACHIAN PLATEAU

Basin	A	S	M	R	BL	HD	R_r	D_d	F_1	$Q_{.5}$	$Q_{.1}$	$Q_{.01}$	Q_{max}
Tar Hollow Creek	1.5	4	74	330	3.2	.17	.048	2.79	49.33	127	337	803	957
Home Creek	1.6	5	70	210	3.4	.23	.035	5.75	43.75	123	293	618	378
Mill Creek	2.7	4	104	400	4.3	.44	.030	5.66	38.52				
Green Lick Run	3.1	4	79	860	2.2	.59	.067	3.65	25.48	263	607	1244	1400
Beech Creek	18.7	5	186	550	14.8	.29	.007	2.84	9.95	1062	2083	4124	2210
Piney Creek	24.5	5	271	1650	14.9	.95	.021	3.04	11.06	1093	2685	5834	6850
Casselman River	62.5	6	653	1700	25.1	1.07	.013	3.34	10.45	2320	4442	8034	8400
Emory River	83.2	7	1936	540	25.8	.57	.004	5.57	23.27	7233	13759	24095	18700
Youghlogheny River	134.0	6	1798	1590	25.1	1.11	.012	3.68	13.41	4375	8535	15447	11800
Daddys Creek	93.5	6	1181	730	27.8	.40	.005	2.87	12.63	7612	9346	17430	11600
Little Mahoning Creek	87.4	6	1058	1500	25.8	.73	.011	2.58	12.10	3059	5056	7879	5300
Allegheny River	550	7	5966	1010	27.4	.56	.007	2.92	10.84	7562	5708	29182	55000

[1] Morphometric data from Morisawa (1962)

TABLE 7 (APPENDIX I)

DISCRIMINANT FUNCTION ANALYSIS

Discriminant Function: $D = M^{-.066}\ HD^{.072}$

Mahalanobis D Square = 5.848

$F\ (2,54) = 38.08 \quad p = 0.0001$

Population	Sample Size	Mean Z	Variance Z	Std. Dev. Z
High potential flash flooding	36	-.11436	.00186	.04318
Low potential flash flooding	21	-.22069	.00205	.04532

TABLE 8 (APPENDIX I)

CORRELATION MATRIX OF LOGARITHMS OF MORPHOMETRIC PARAMETERS -- CENTRAL TEXAS

	A	S	M	R	BL	HD	Rr	Dd	F_1	Qmax
A	1.0000									
S	.4334	1.0000								
M	.3442	.8647	1.0000							
R	.4539	.6729	.6821	1.0000						
BL	.8934	.3606	.3078	.3852	1.0000					
HD	.1371	.7682	.8494	.8841	.0947	1.0000				
Rr	-.0659	.5037	.5451	.8256	-.2019	.8853	1.0000			
Dd	-.3872	.5637	.7163	.3415	-.3683	.7401	.5980	1.0000		
F_1	-.3934	.5302	.7278	.3349	-.3533	.7306	.5817	.9844	1.0000	
Qmax	.8320	.3788	.2790	.6328	.6676	.3052	.2643	-.2911	-.3343	1.0000

TABLE 9 (APPENDIX I)

CORRELATION MATRIX OF LOGARITHMS OF MORPHOMETRIC PARAMETERS -- NORTH-CENTRAL UTAH

	A	S	M	R	BL	HD	Rr	Dd	1 F	Q.5	Q.1	Q.0.	Qmax
A	1.0000												
S	.7867	1.0000											
M	.9890	.8008	1.0000										
R	-.1770	.1218	-.1125	1.0000									
BL	.9516	.6654	.9209	-.1499	1.0000								
HD	.1402	.4776	.2310	.8771	.0909	1.0000							
Rr	-.9079	-.5522	-.8599	.4757	-.9405	.2177	1.0000						
Dd	.4955	.7184	.5905	.4404	.3781	.8141	-.1897	1.0000					
1 F	.4470	.4893	.5746	.2992	.3031	.6205	-.1761	.8283	1.0000				
Q.5	.7326	.7830	.7308	-.0053	.5732	.2693	-.5103	.5036	.3655	1.0000			
Q.1	.6971	.7795	.6960	-.0207	.5312	.2462	-.4794	.4772	.3515	.9924	1.0000		
Q.01	.6136	.7531	.6142	-.0302	.4384	.2166	-.4017	.4283	.3183	.9579	.9856	1.0000	
Qmax	.8182	.8780	.8207	.0379	.6792	.3330	-.5921	.5792	.4354	.9562	.9608	.9366	1.0000

TABLE 10 (APPENDIX I)

CORRELATION MATRIX OF LOGARITHMS OF MORPHOMETRIC PARAMETERS -- SOUTHERN CALIFORNIA

	A	S	M	R	BL	HD	Rr	Dd	1 F	Q.5	Q.1	Q.01	Qmax
A	1.0000												
S	.6998	1.0000											
M	.9406	.8809	1.0000										
R	.9397	.6046	.8471	1.0000									
BL	.9968	.6633	.9211	.9440	1.0000								
HD	.8799	.8684	.9309	.8829	.8657	1.0000							
Rr	-.8634	-.5870	-.8236	-.6519	-.8653	-.6408	1.0000						
Dd	-.0768	.5825	.2186	-.1933	-.1153	.2899	-.0099	1.0000					
1 F	-.5491	.1639	-.2327	-.6064	-.5878	-.2287	.4458	.7583	1.0000				
Q.5	.8929	.5607	.8125	.8425	.8816	.7156	-.7497	-.2220	-.5575	1.0000			
Q.1	.9516	.6843	.9308	.8507	.9369	.7925	-.8625	-.0780	-.4345	.9049	1.0000		
Q.01	.7947	.7832	.8920	.6651	.7798	.8082	.7779	3327	-.0805	.5681	.8358	1.0000	
Qmax	.9128	.5814	.8615	.8554	.9010	.7616	-.7765	-.1522	-.4943	.8845	.9559	.7659	1.0000

TABLE 11 (APPENDIX I)

CORRELATION MATRIX OF LOGARITHMS OF MORPHOMETRIC PARAMETERS -- INDIANA

	A	S	M	R	BL	HD	Rr	Dd	1 F	Q.5	Q.1	Q.01	Qmax
A	1.0000												
S	.7632	1.0000											
M	.8396	.6957	1.0000										
R	.0007	-.0199	.2809	1.0000									
BL	.9794	.7170	.8102	.0024	1.0000								
HD	-.2167	-.1105	.2149	.9235	-.2138	1.0000							
Rr	-.7322	-.5484	-.4224	.6619	-.7477	.7702	1.0000						
Dd	-.4643	-.2041	.0644	.5714	-.4599	.8425	.7176	1.0000					
1 F	-.4714	-.2709	.0832	.4548	-.4814	.7465	.6574	.9564	1.0000				
Q.5	.3731	.4148	.6695	.6413	.3537	.6409	.1530	.4710	.4025	1.0000			
Q.1	.2740	.3240	.6296	.6499	.2476	.6940	.2387	.5717	.5195	.9855	1.0000		
Q.01	.1881	.2485	.5848	.6407	.1554	.7206	.3023	.6411	.6044	.9530	.9906	1.0000	
Qmax	.1784	.1795	.5405	.6648	.1601	.7112	.3137	.5867	.5503	.9611	.9865	.9854	1.0000

TABLE 12 (APPENDIX I)

CORRELATION MATRIX OF LOGARITHMS OF MORPHOMETRIC PARAMETERS -- APPALACHIAN PLATEAU

	A	S	M	R	BL	HD	Rr	Dd	1 F	Q.5	Q.1	Q.01	Qmax
A	1.0000												
S	.8889	1.0000											
M	.9711	.9241	1.0000										
R	.6553	.3589	.5281	1.0000									
BL	.9308	.8797	.8782	.6038	1.0000								
HD	.6320	.4663	.5454	.9187	.5736	1.0000							
Rr	-.8114	-.8598	-.7972	-.2369	-.8875	-.2450	1.0000						
Dd	-.2469	.1279	-.1210	-.4629	-.2462	-.0752	.0580	1.0000					
1 F	-.7820	-.5416	-.6112	-.7855	-.7968	-.6591	.6194	.5095	1.0000				
Q.5	.9742	.9024	.9570	.6007	.9401	.6135	-.8773	-.1492	-.7345	1.0000			
Q.1	.9742	.8971	.9603	.5967	.9324	.6094	-.8705	-.1488	-.7260	.9979	1.0000		
Q.01	.9703	.8863	.9567	.5891	.9255	.5981	-.8676	-.1550	-.7226	.9927	.9983	1.0000	
Qmax	.9497	.8259	.9474	.6254	.8446	.6148	-.7474	-.2082	-.6811	.9418	.9574	.9664	1.0000

TABLE 13 (APPENDIX I)
REGIONAL FLOOD MAGNITUDE RELATIONSHIPS

Region	Equation	F Ratio	R^2	Prob.	Std. error of Estimate
Central Texas	$Qmax = 17369\ M^{.43}\ HD^{.54}\ F^{-.96}$	(3,9) = 16.41	.85	p=.001	.1000
	$Qmax = 36650\ M^{.64}\ Rr^{.54}\ Dd^{-1.68}$	(3,9) = 8.59	.74	p=.01	.1295
Southern Calififornia	$Qmax = 155\ M^{1.04}\ HD^{-.83}\ F_1^{-.73}$	(3,8) = 14.87	.85	p=.001	.2746
	$Qmax = 380\ M^{.89}\ Dd^{-1.87}$	(2,9) = 28.56	.86	p=.0001	.2450
North Central Utah	$Qmax = 23M^{.90}\ HD^{1.19}\ F_1^{-1.58}$	(3,7) = 9.13	.72	p=.005	.2923
	$Qmax = 38618\ M^{2.20} Rr^{2.51}\ F_1^{-3.73}$	(3,7) = 11.50	.83	p=.005	.2286
Indiana	$Qmax = 424\ M^{.46}\ HD^{.73}\ F_1^{.21}$	(3,6) = 4.05	.67	p=.01	.4200
	$Qmax = 424\ M^{.82}\ Rr^{.67}\ Dd^{.56}$	(3,6) = 3.90	.66	p=.05	.4251
Appalachian Plateau	$Qmax = 100\ M^{.79}\ HD^{.19}\ F_1^{-.29}$	(3,7) = 26.14	.92	p=.0001	.2153
	$Qmax = 38\ M^{.89}\ Dd^{-.50}$	(2,8) = 38.79	.91	p=.0001	.2151
Indiana	$Q.5 = 115\ M^{.53}\ HD^{.62}$	(2,7) = 8.46	.71	p=.025	.3372
Appalachian Plateau	$Q.5 = 5M^{.47}\ HD^{.61}\ Rr^{-.73}$	(3,7) =220.94	.99	p=.0001	.0818

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APPENDIX II

APPLICATION OF DISCRIMINANT ANALYSIS

Background

Linear discriminant analysis is a multivariate analysis procedure used to classify observations into several distinct categories. As originally proposed by R. A. Fisher (1936), and modified by others (Anderson, 1958), the linear discriminant function derermines the linear combination of independent variables that provides the optimal dependent criterion for classifying observations into one of two or more distinct categories. For example, a botanist might want to classify a certain set of plants, known to belong to one or the other of two groups or species, into their proper groups through the use of several measurements taken on each plant. If the two groups of plants are fairly similar with respect to all of the measurements, correct classification based on any one set of measurements might prove difficult because of the overlap in the distributions of the observations. It might be possible to find a linear combination of these measurements that would yield distributions for the two species that would possess very little overlap. If so, this linear combination could be used to classify other plants known to belong to one or the other of the two groups or species. Similarly, drainage basins can be classified into two or more categories of flash-flood potential.

As an illustration of the technique, consider the following univariate, two-group case. Based on samples drawn from each of two distinct categories of the population of all possible values of the variate, probability density functions that best fit selected parameters of the samples of each category may be selected. (Figure 1 of this appendix). If f_1 (x) is the frequency density associated with any observations of the variate (parameter) as computed using the sample estimate of the frequency density function of category 1, and f_2 (x) is defined in a similar manner for category 2, then the value of the variate when f_1 (x) equals f_2 (x) defines the boundary between the categories. This boundary is, once again, based on sample estimates of the dispersions and means of known members of the two categories. Any observation, x, of the variate may be classified as being of category 1 if:

$$f_1 (x) \geq f_2 (x).$$

Since the boundary between the categories has been established, this classification can be accomplished by examining the relative magnitude of the variate of the observation to be classified and the value of the variate corresponding to the boundary between the categories.

In the multi-category multivariate case, the establishment of such boundaries is more difficult because of complications arising from the interactions of the means and the dispersions of each category. However, some assumptions concerning the frequency density function of each category can be used to compute sample estimates of the coefficients of linear functions of the variates that define these boundaries. Also, these sample estimates of the functions can be used to estimate likelihoods of category membership for any given observation vector. Assuming that the multivariate frequency density function of each category is normal, the frequency density $f_i (x)$ associated with an observation vector x and category i is:

$$f_i (x) = 2\pi^{-p/2} \; \Sigma_i^{-1/2} \; \exp [(x-\mu_i)' \; \Sigma_i^{-1} \cdot (x-\mu_i)], \; i=1,k$$

where p = the number of variables, Σ_i = within group dispersion matrix, μ_i = mean vector for category i, and k = number of categories. Taking the natural logarithm of the function and ommission of the factor $2\pi^{-p/2}$ which is common to the frequency distribution for each category gives the "equivalent discriminant score" defined by (Rao, 1965):

$$S_i = -1/2 \log \left| \Sigma_i \right| -1/2 \; (x-\mu_i)' \; \Sigma_i^{-1} \; (x-\mu_i) \, , \; i = 1,k$$

or,

$$S_i = (L_i) \; x - 1/2 \; L_i \mu_i$$

where x is the observation vector, L_i is the vector of discriminant coefficients for group i, and μ_i is the mean vector of group i. For three variates the discriminant coefficients, L, for group i are:

$$L_1 = \sigma^{11} m_1 + \sigma^{12} m_2 + \sigma^{13} m_3$$
$$L_2 = \sigma^{21} m_1 + \sigma^{22} m_2 + \sigma^{23} m_3$$
$$L_3 = \sigma^{31} m_3 + \sigma^{32} m_2 + \sigma^{33} m_3$$

where m is the sample estimate of the mean of a variable, and σ^{ik} is an element of the inverse of the dispersion matrix Σ. An observation of unknown category membership may be classified by computing the discriminant score of the observation for each category and assigning the observation to the category for which the score is the highest. This is, in effect, assigning the observation to the category with the largest likelihood of category membership defined by the maximum of:

$$f(x)_i = \frac{\exp(S_i)}{\sum \exp(S_k)}$$

Application of Discriminant Analysis to Verification Problem

Preliminary Categorization. Because no categories of locations characterized by varying degrees of flash-flood potential were available for direct analysis using the discriminant analysis technique, hierarchical cluster analyses were performed in order to discern any apparent groupings. The data used in the clustering procedures consisted of 160 unclassified observations for which the following drainage basin characteristics had been obtained from the U.S. Geological Survey and for which the proposed indices of flash-flood potential had been computed:

1. Drainage basin area in square miles
2. Main channel slope in feet per mile
3. Channel length in miles
4. Average annual precipitation in inches
5. Expected 6-hour 100-year rainfall (from NWS maps)

Although a detailed discussion of the mathematical techniques used in hierarchical cluster analysis cannot be presented here, a brief summary of the concepts of the technique is presented in the following paragraphs.

All hierarchical clustering methods begin computations with what is called a "similarity matrix" (Bullock, p.13). The elements of the similarity matrix define the measures of similarity for all pairwise groupings of clusters, or input data. Euclidean distance is frequently used as a similarity measure. At the beginning of the clustering procedure of m observations, there are m^2 possible pairwise combinations of the observations. Thus, the similarity matrix at the first step in the clustering procedure is m by m and, generally, the similarity matrix is symetric about an upper-left to lower-right diagonal. After the initial similarity matrix is formed, the two most similar clusters are combined into a single cluster unit. The similarity matrix is then recomputed to reflect the deletion of one clustering unit and change in characteristics demonstrated by the combined unit. This merging of the two most similar clusters is continued until all observations are in a single cluster. Thus, at the first step of the clustering all of the observed variance in the input variables is explained by mean vectors of the clusters, as there are as many clusters as there are observations. At the last setp of the procedure, none of the observed variance is explained by the mean vectors of the clusters, as only one cluster is formed.

Because of the similarity measure most frequently used in hierarchical cluster analyses, euclidean distance, it is often wise to use standardized variates instead of raw data, as variables of larger magnitude can sometimes control the clustering procedure in an undesirable manner. On the other hand, it is sometimes desirable to bias the clustering procedure to reflect the suspected importance of one or more of the analyzed variates. This may be accomplished by applying weighting factors to those standardized variates thought to be most significant. In other words, if in some application it is suspected that an increment in standard deviation of one variable is more significant than an increment in standard deviation of the other variables, then the standardized values of that variable should be weighted to reflect this importance. The magnitude of the weight must be subjectively determined by the analyst.

The clustering procedures described in the previous paragraphs were applied to the standardized logarithms of the data for the 160 unclassified locations described previously. The required computations were made using a series of computer routines developed at the University of Texas (Anderberg, 1973). Analysis of the results indicated that the drainage basin size and channel length were the primary cluster determining variables. Consequently, the weighting technique was used to shape the analysis so that the proposed indices of flash-flood potential were the primary cluster determining variables. The use of the weighting technique is valid in this application as the objective of the cluster-discriminant analysis is the examination of the ranking effectiveness of the indices. Application of a weighting factor of 3.0 to each of the observations of the 2 indices resulted in an analysis that was effectively controlled by the indices of flash-flood potential.

The standard output of the routines used in the analyses consists of a printer plot of a tree diagram indicating the cluster formations (Figure 2 of this appendix). The 25 levels at the top of the tree diagram indicate the statistical dissimilarity between groups. For example, groups labelled 1 and 2 were combined at a significance level of 18. This indicates that groups 1 and 2 are about 18 times less similar than sub-clusters formed at level 1. Figure 2 indicates that the 160 locations may be divided into 4 main categories.

Discriminant Analysis of the Clusters. In order to provide an effective classification scheme so that the 42 test observations could be subsequently used to examine the effectiveness of the discriminating power of the proposed indices of flash-flood potential, the multi-group multivariate discriminant analysis procedure described previously was applied to the four groups obtained from the cluster analysis. The necessary computations were accomplished with the computer program, BMD07M, Stepwise Discriminant Analysis, developed at UCLA (Dixon, 1973). The data used in the analysis were the logarithms of the seven variables previously described. The results of the analysis indicate that the two proposed indices of flash-flood potential were the most important variables, as was anticipated since the clusters were formed primarily on observed differences in the two indices. As the other variables were of little significance, the final discriminant functions reflect only the influence of the logarithms of the proposed indices. The results of the discriminant analysis are shown as Table 1 of this appendix. The differences in mean logarithms indicated in Table 1 imply the following qualitative descriptions of the groupings:

Group 1 - Areas characterized by above average magnitude index and slightly below average warning time index

Group 2 - Areas characterized by above average magnitude index and above average warning time index

Group 3 - Areas characterized by below average magnitude index and above average warning time index

Group 4 - Areas characterized by below average magnitude index and below average warning time index.

Subsequent classification of the test observations indicated that group 2 is the category of most severe flash-flood potential and that group 3 is the category of the next most severe flash-flood potential.

In order to examine the geographic consistency of the discriminant analysis, the 160 observations used in the development of the discriminant functions, as well as the test group and other observations not used in the analysis because of the unavailability of drainage basin data, were classified and plotted on a map of the contiguous 48 states. The numbers shown on Figure 3 of this appendix indicate group membership of the observation and the circled numbers indicate that the location is a member of the test group. This map indicates some degree of geographic consistency and can be used to classify locations in a preliminary manner.

The relative magnitude of the hydrologic potential for flash flooding of a location may be evaluated by examining the similarities between the location and the most severe flash-flood potential category determined from the discriminant-cluster analysis. If the hydrologic properties pertinent to the determination flash-flood potential of the location can be represented by a point in a two-dimensional space of flash-flood magnitude index and flash-flood warning time index, then the distance between this point and the mean vector of the most severe category of flash-flood potential is a measure of the similarity between the location and the locations of severe flash-flood potential. A priority list can be determined by ranking locations on the basis of the relative magnitudes of the measures of similarity determined for each location.

TABLE I (APPENDIX II)

RESULTS OF DISCRIMINANT ANALYSIS

MEAN LOGARITHMS OF DATA BY CATEGORY

VARIABLE	TEST GROUP	GROUP 1	GROUP 2	GROUP 3	GROUP 4	TOTAL
AREA	2.06007	2.59742	2.22572	2.35224	2.41649	2.45368
SLOPE	1.62906	1.02218	1.49366	1.28669	1.42340	1.27782
LENGTH	1.36276	1.68038	1.47397	1.55114	1.56509	1.59462
MEAN PRCP	1.48526	1.51691	1.44525	1.62548	1.63205	1.57904
MAGNITUDE	-.46562	-.47376	-.34903	-.64384	-.73872	-.60927
INTENSITY	.76515	.24926	.81796	.56582	.24785	.33281
100 YR 6HR	.59125	.59978	.61735	.61654	.45706	.53729

STANDARD DEVIATIONS OF LOGARITHMS OF DATA BY CATEGORY

VARIABLE	TEST GROUP	GROUP 1	GROUP 2	GROUP 3	GROUP 4
AREA	.60739	.32822	.79914	.40014	.36248
SLOPE	.55379	.62394	.55875	.47624	.60478
LENGTH	.32623	.24025	.44503	.21351	.24138
MEAN PRCP	.22643	.19528	.19166	.09023	.19147
MAGNITUDE	.19199	.09812	.16945	.08695	.09330
INTENSITY	.31314	.13053	.13517	.08142	.10647
100 YR 6HR	.13997	.18605	.19071	.08459	.15366

COEFFICIENTS OF DISCRIMINANT FUNCTIONS

VARIABLE	GROUP 1	GROUP 2	GROUP 3	GROUP 4
MAGNITUDE	-46.72	-35.91	-64.03	-72.52
INTENSITY	20.12	63.20	44.66	20.63
CONSTANT	-13.57	-32.11	-33.25	-29.34

FIGURE 1 (Appendix II)

Discriminant Analysis

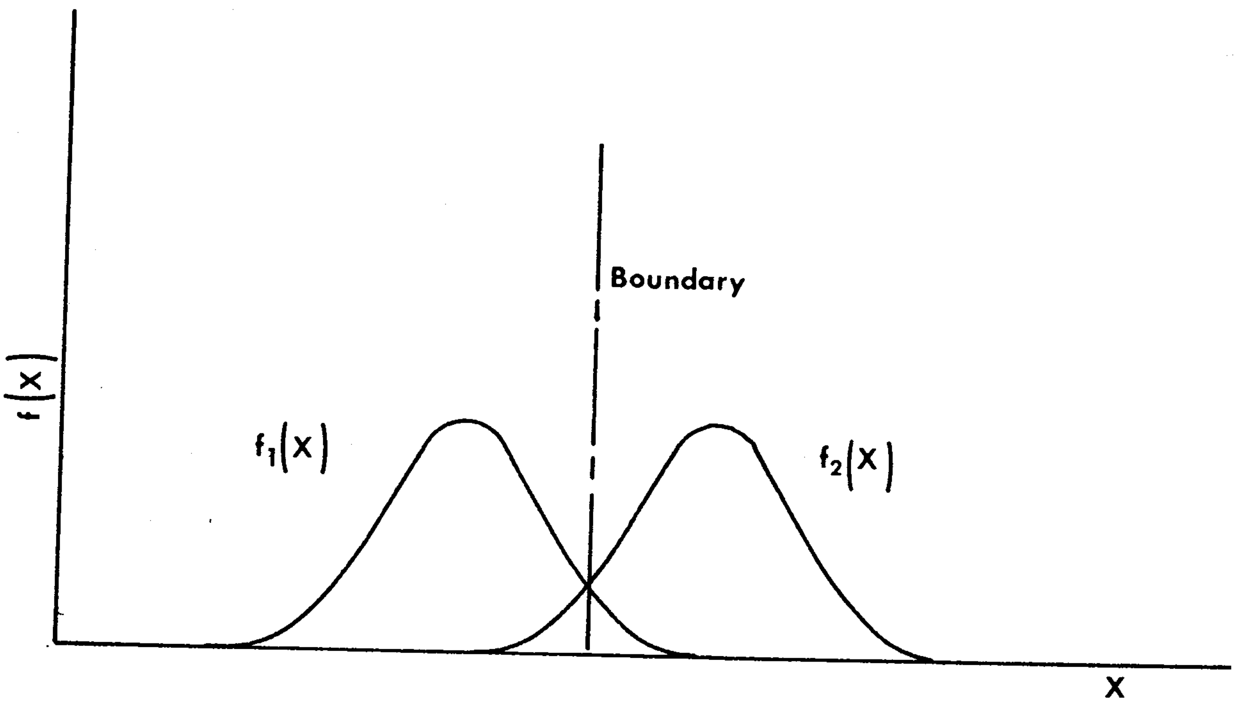


FIGURE 2 (Appendix II)

Results of Cluster Analyses

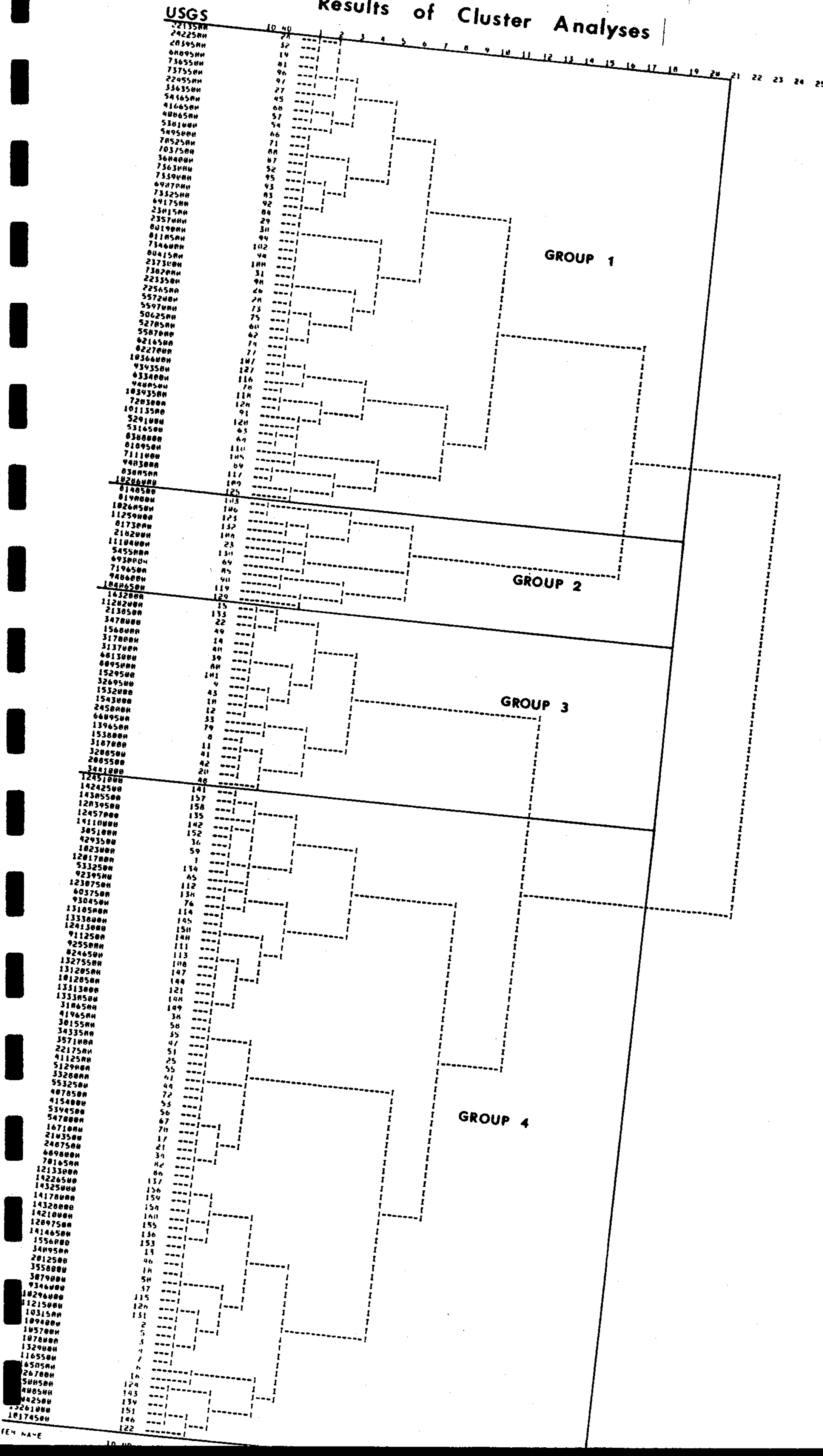
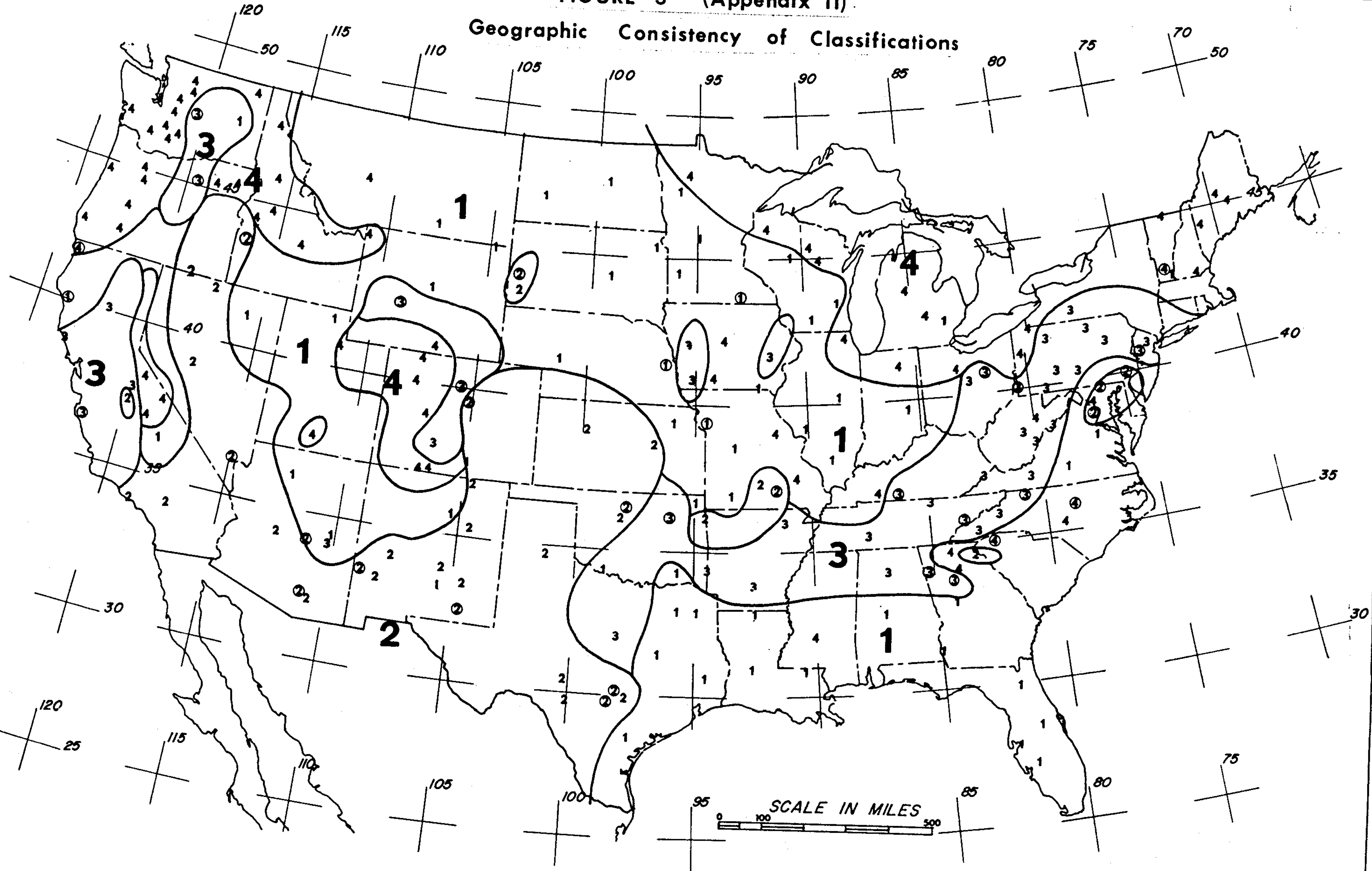


FIGURE 3 (Appendix II)

Geographic Consistency of Classifications



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