A STUDY OF THE OBSERVED AREAL DISTRIBUTION OF RAINFALL AS A FUNCTION OF THE DENSITY OF RAIN GAGES

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A STUDY OF THE OBSERVED AREAL DISTRIBUTION OF RAINFALL AS A FUNCTION OF THE DENSITY OF RAIN GAGES

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ABSTRACT

A Study of the Observed Areal Distribution of Rainfall As a
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A study was made of reported rainfall as a function of the density of gages for several geographical areas including Texas, Colombia, Guyana, Panama, Venezuela, and Ecuador--each having different terrain effects. Consideration was given to the data required to determine daily or long-term monthly means. The accuracies of different methods of computing the areal rainfall were checked, along with the variation of random sampling.

The results indicate that, for daily data to be accurate, the gage-spacing must be smaller than the diameter of the individual storms. In Texas, this diameter is about 17 mi; it is smaller in the mountainous and tropical areas. Fewer gages are needed for monthly totals and still fewer for long-term monthly means. The different methods of computing the amount of rainfall did not show large differences or systematic errors.

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to Professor W. K. Henry under whose direction this research was performed and for his guidance, stimulation and assistance during my graduate program. My thanks are extended to Dr. Robert A. Clark, Dr. Edward A. Hiler, and Dr. Vance E. Moyer for their encouragement and help in the final preparation of the manuscript.

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CHAPTER I

INTRODUCTION

Those who work with rainfall data know all of the difficulties involved in obtaining a basic collection of data. They know also that most of the problems for proper analysis of rainfall come from the inappropriate number of gages located in an area and the extreme variability of rainfall, even for such short distances as 20 mi. The above problems and the errors which the analyst may make in the analysis of the areal distribution of rainfall call attention to the importance of the network of rainfall gages for a proper analysis.

Because planning, design, and operational problems are based on the network of rain gages, it is obvious that more attention must be focused in this field, not only for the improvement of the analysis but in the saving of money and of time.

Whenever organizations start to improve networks of gages, they should be able to follow certain technical rules which are based on the physical processes of the atmosphere, such as, movement of the storms, types of storms, and the effects of terrain. The source of moisture is another element which causes variation in the amount of water catchment for a particular location. Thus, more study is needed of all the influences which are connected with rainfall

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The citations on the following pages follow the style of the Journal of Applied Meteorology.

catchment before the network is established. Most operational rainfall networks today reflect the location of population. Some areas have too few gages while other areas may have too many. Some areas have numerically enough gages, but the arrangement of the rain gages is unsatisfactory. Because funds for supporting the collection of basic data are difficult to obtain, the first step in establishing a proper rain-gage network would be to study thoroughly the existing network to determine the degree of accuracy that can be obtained. In order to do this, 11 rain-gage networks were selected. They are: Navasota River, East Yegua Creek, Burton Creek, and the Blacklands Experimental Watershed in Texas; the United Fruit Company area close to Puerto Armuelles, Panama; Falcon State in Venezuela; San Carlos Sugar Plantation in Ecuador; Georgetown and New Amsterdam in Guyana; and Medellin and Bogota in Colombia. The rain-gage density ranges from one gage per 0.20 mi^2 (Burton Creek) to one gage per 325 mi^2 (Navasota).

OBJECTIVES:

The objectives of this study are to determine the variation of observed rainfall over an area as related to the density of rain gages, and also, to find the minimum density of rain gages that is required for accurate reporting of rainfall.

LITERATURE REVIEW:

A search of literature reveals little information concerning the variation of reported rainfall amount as a function of rain-gage density. Collenge and Jamieson (1968) state that the spatial distribution of rainfall has received little attention to date. They also point out that current investigations have been essentially qualitative in nature. Collenge and Jamieson (op.cit.) in a study of the spatial distribution of storm rainfall, point out that the sparsity of gages is a severe handicap to proper rainfall analysis.

Nicks (1963), in a study of rain-gage networks, states that relocation of rain gages on a uniform basis usually will allow a reduction in the number of gages by one order of magnitude, yet will still yield desirable daily-areal results. This reduction in the number of gages, however, will lower the accuracy of daily rainfall assessment for tributaries. Sharp (1961) found relatively small differences between storm rainfall amount based on a network of 39 gages and those determined from ten to 15 gages for an area of 160 km^2. A reduction to fewer than five gages for the same area resulted in significant differences.

Osborn and Keppel (1966), in a study of a rainfall network in a semi-arid region, found that the characteristics of convective thunderstorms which are typical of the southwestern United States are described best by data from large, dense, rain-gage networks.

Court (1961) lists many area-depth equations (where average rainfall is a function of the network area) that have been proposed by different investigators. He states further that, at the present time, no expression encompassing all important aspects of this problem is available.

Eagleson (1967) proposes that little advantage is gained by utilizing more than two properly located stations for the determination of long-term areal-mean rainfall. The area under study was 1250 mi^2.

Thom(1940) postulates that linear correlation of storm rainfall amounts between two stations results from two factors: average storm depth and direction of storm travel.

Henry (1966, 1968) has demonstrated the extreme variations, in an areal sense, of daily rainfall. He made, in areas with dense rain-gage networks, numerous analyses of daily rainfall. He showed that two stations located about 20 mi apart had only a random relationship related to the amount of daily rainfall. Also, the relationships of monthly totals of rainfall for stations located that distance apart, on occasion, had negative correlations.

Barnard (1965), Guest (1965), and Morris (1967) all showed spatial variations of the rainfall patterns in relation to local terrain. Most of the work cited above was for tropical areas. However, Bell (1966) and Huff (1967) have showed that the variations of precipitation for short distances are extreme even in winter storms within the United States.

Watts (1956) in a study of the horizontal distribution of rainfall in tropical areas found that if a single gage near the center of the area (170 mi^2) is taken as representative of the whole area, 47% of the days in the period September-December are rain days; when two well-spaced gages are selected, the percentage of rain days increases no more than 1%. By increasing the gages to a total of 21, the rain days increase to 58%.

Kohler (1958), in a study of the design of hydrological networks, points out that one of the difficulties in acquisition of funds for supporting the collection of adequate basic data is that requirements are of a continuing and endless nature.

CHAPTER II

GENERAL CHARACTERISTICS OF THE ELEVEN SELECTED AREAS UNDER STUDY

The 11 selected rain-gage regions were divided into the following groups based on some similarities such as location and topography:

First Group: Navasota River, East Yegua Creek, Burton Creek, and Blacklands Experimental Watershed in Texas.

Second Group: Georgetown and New Amsterdam in Guyana.

Third Group: Medellin and Bogota in Colombia.

Fourth Group: Ecuador, Panama, and Falcon State in Venezuela.

The general location of all these areas may be seen in figure 1.

FIRST GROUP:

THE NAVASOTA RIVER

This stream is located in East Texas and flows southward into the Brazos River. It drains an area of approximately 2500 mi^2, with a terrain of low, rolling hills. This area has a generally mild climate; in summer the days are hot and the nights warm. The mean annual temperature is about 67°F, and the mean annual precipitation is about 40 inches.

The Navasota River has eight rainfall gages inside the basin, but for the purpose of this study, the area was extended to include rainfall gages with a non-uniform distribution over 11,360 mi^2. The number of gages represents a density of one gage per 325 mi^2.

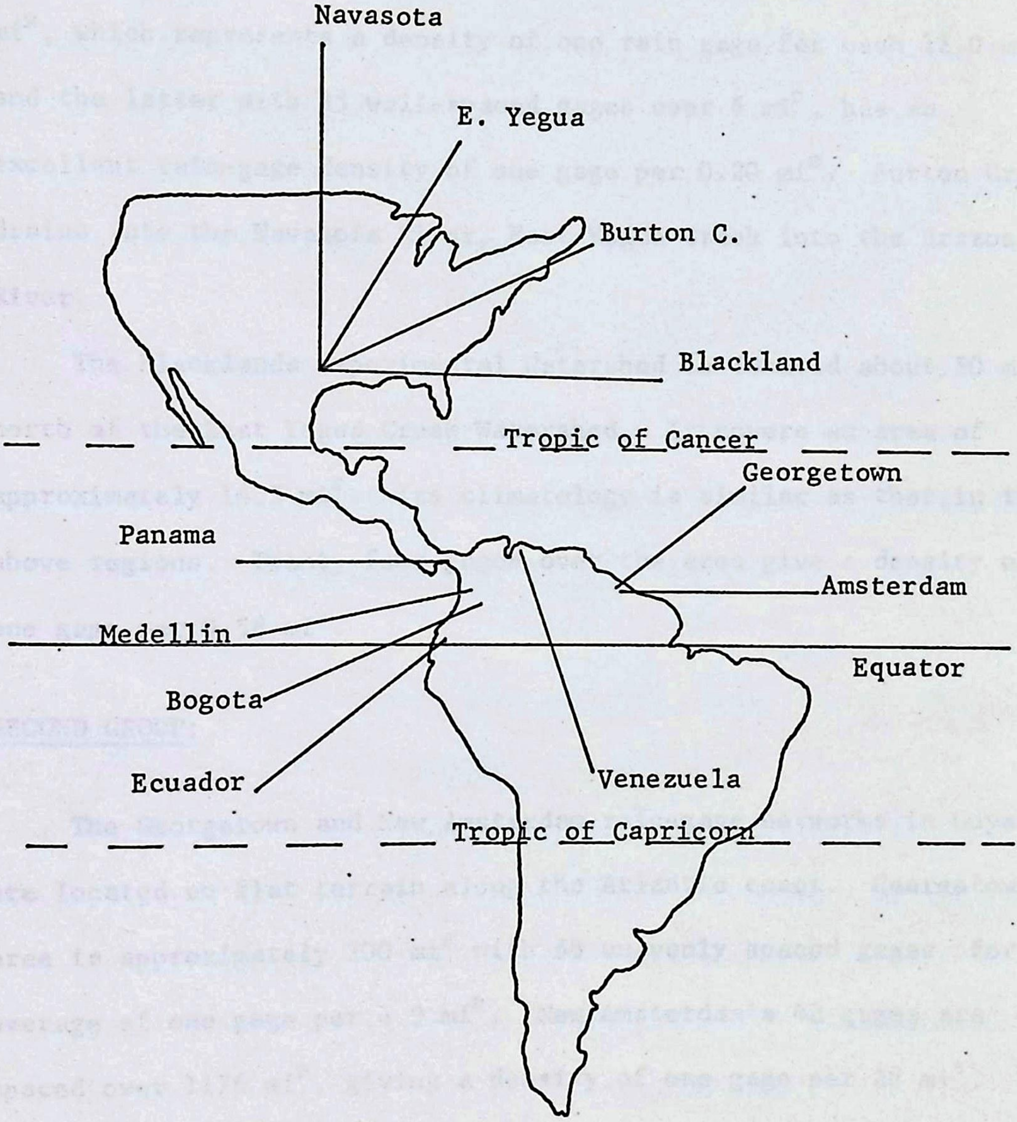

Figure 1. Map showing the general location of the areas used in this study.

The East Yegua Basin near Dime Box, Texas, and the Burton Creek Watershed located in Bryan, Texas, have a climate similar to the Navasota basin. The former contains 25 well-spaced gages over 274 mi^2, which represents a density of one rain gage for each 11.0 mi^2, and the latter with 25 well-spaced gages over 6 mi^2, has an excellent rain-gage density of one gage per 0.20 mi^2. Burton Creek drains into the Navasota River, East Yegua Creek into the Brazos River.

The Blacklands Experimental Watershed is located about 50 mi north of the East Yegua Creek Watershed. It covers an area of approximately 14.5 mi^2. Its climatology is similar as that in the above regions. Twenty-four gages over the area give a density of one gage per 0.58 mi^2.

SECOND GROUP:

The Georgetown and New Amsterdam rain-gage networks in Guyana are located on flat terrain along the Atlantic coast. Georgetown's area is approximately 200 mi^2 with 58 unevenly spaced gages, for an average of one gage per 4.9 mi^2. New Amsterdam's 42 gages are spaced over 1176 mi^2, giving a density of one gage per 28 mi^2. Both regions are tropical and have similar climates.

THIRD GROUP:

Medellin and Bogota in Colombia are tropical mountain areas on the South American Continent. The Medellin rain-gage network has

53 gages well spaced over an area of approximately 2100 mi^2, making a density of one gage per 40 mi^2. In the Bogota area of 936 mi^2, the 61 gages give a density of one gage per 15 mi^2. The elevation of Bogota is about 8000 ft, so that the temperature is always cool. The terrain which the network covers is very rough with high mountains. The climate of Medellin is milder than that of Bogota, but the terrain is rough and mountainous.

FOURTH GROUP:

San Carlos Sugar location, Ecuador, on the South American Continent, is located close to the Equator; it is a flat, coastal area with 13 rainfall gages over 85 mi^2, which gives a density of one gage per 6.5 mi^2.

The region in Panama is located in the coastal plain between the Pacific Ocean and the mountains to the north. The area has a flat terrain and is at sea level. This area has a typically tropical climate, i.e., both a rainy and a dry season. It is warm or hot during the year; cold weather is infrequent. In general, the precipitation is a result of convective activity. This area has 35 rain gages over 114 mi^2, representing a density of one gage per 3.25 mi^2. Falcon State in Venezuela is another tropical region. It has a topography varying between 2800 and 15 ft above mean sea level. The mean annual precipitation over the area is about 45 in. It has a mean annual evaporation of 118 in. and a mean annual temperature of 21°C. The 22 non-uniformly distributed gages cover

561 mi^2, representing a density of one gage per 25.5 mi^2. In this same area another network was selected which had 12 gages over 220 mi^2.

CHAPTER III

PROCEDURE OF ANALYSIS

The data used in this study were supplied by several sources. They are:

a. Texas A&M Research Foundation Project 645, "Research in Tropical Rainfall Patterns and Associated Meso Scale Systems."

b. Texas A&M Water Resources Institute Project 5013.

c. Instituto Nacional de Obras Sanitarias, Caracas, Venezuela.

d. Weather Bureau, U.S. Department of Commerce, Washington, D.C.

e. Blacklands Experimental Watershed, Riesel, Texas.

The rainfall data used were daily values, monthly totals, and long-term mean monthly totals. Only selected days were processed. No specific criteria were used in selecting the data except to select days when some of the gages recorded some rain, since a day with all zeros would be meaningless. In general, only days with rather large rainfall amounts were included.

Table 1 presents a summary of the number of gages utilized in each area. The stations are grouped by regions having somewhat similar climates.

The first investigation was to determine what variations in rainfall occur due to a random selection of stations. The location of the gages in Panama was the most uniform of any, and since the effects of terrain were small, this region was selected for the

TABLE 1.

The grouping of networks and number of gages utilized for daily, monthly, and mean-monthly studies.

Group	Region	Area-mi^2	Number of gages used Daily	Monthly	Mean-monthly
I	Navasota	11,360	35	28	X
	East Yegua	274	25	20	X
	Burton C.	5.76	25	19	X
	Blacklands	14.5	24	X	X
II	Amsterdam	1,176	42	36	41
	Georgetown	200	41	43	58
III	Bogota	936	32	45	61
	Medellin	2,100	52	52	59
IV	Panama	114	36	26	29
	Ecuador	85	13	X	X
	Venezuela	561	22	12*	X

*area reduced to 220 mi^2

random test. Five stations were selected by lot. The average rainfall of each of the five was computed by using the arithmetic means. The process was repeated several times.

One standard method of determining the rainfall in a prescribed area is to determine the arithmetic mean using all gages available. Another is to plot the data on a map and make an isohyetal analysis. By use of a planimeter, a calculation of the amount of rain may be made. Both methods were employed using the same data so that the two methods could be compared. Also, for a given area the computations were made using 5, 10, 15, etc., stations until all available data were used, so as to have different rain-gage densities. The first five stations were selected to give the "best" coverage of the area. The next five were added again to give "best" coverage. Random selection of the stations was discarded because in practice networks of rain gages are established by building upon the existing network instead of making a new and random placement of the gages. This plan of selecting stations was used throughout the rest of the study. Next, the maximum and minimum daily rainfall reported at any gage for a selected day was identified. Then, it was noted where this station appeared in the sequence of the increments of five stations. This was to demonstrate that the extreme values easily could be missed with only a few gages.

The objective of this study is to determine the accuracy of the reported rain as a function of the gage density. To do this the gages in a region were counted and the area of the region was determined. Since the actual size of the region would be important, the region was circumscribed at about the distance between gages by making a smooth border with as large a radius of curvature as possible. By inspection of the area, five stations were selected to give the "best" areal coverage. Then five more were added, and the selection continued with increments of five gages until all were included. Then the average rainfall was computed using all stations, the first five, first ten, etc. The differences between the value of the rain for the selected stations were compared with the total for all stations and the difference was defined as error and converted into percent of the total.

The area-depth rainfall amounts based on standard techniques were computed for different gage densities, to determine the differences which might produce variations in estimated runoff through use of different rain-gage densities.

CHAPTER IV

PRESENTATION OF RESULTS

A. Random station analysis:

Five stations were selected by drawing lots. The process was repeated several times. The data from Panama were used because of the density and the uniform spacing of the rain gages. The results are shown in Table 2. The area included in the network was 114 mi^2, which is a rather small area.

TABLE 2.

Mean daily rainfall (inches) of area using a random selection of five stations, and using all 36 stations for several selected days.

Day	First Five	2nd Five	3rd Five	4th Five	All 36
1	0.92	1.02	0.64	0.48	0.78
2	0.81	1.51	1.60	1.51	1.17
3	1.41	2.10	1.20	1.12	1.40
4	0.24	0.27	0.47	0.39	0.35
5	0.54	0.53	0.47	0.50	0.56
6	0.72	0.93	0.65	0.72	0.70
7	0.52	0.62	0.57	0.59	0.60
8	0.25	0.30	0.26	0.53	0.34
9	0.77	0.77	0.44	0.65	0.51
10	2.25	2.73	2.80	1.93	2.34

In some cases, the values obtained from a different selection of stations are the same, or nearly so. In other cases, the values deviate considerably from the average given for the 36 stations. Use of such data could cause erroneous estimates of runoff, irrigation requirements, or for other hydrologic use. Thus, it is demonstrated that the reported rainfall may yield different average values, depending upon the location and number of the gages. Table 2 represents only a few of the results of this test. Many more storms were tested, but all produced similar results. Also, the errors appeared random: just as many were below the average of the 36 stations as were larger.

B. Isohyetal analysis:

The daily rainfall data were plotted on maps so that isohyets could be drawn. The isohyets were drawn using proportional spacing and also subjective inputs of the analyst, drawn from his knowledge of the nature of the storms. The maps were analyzed utilizing the 5 "best" stations, 10, 15, etc., until all stations were included.

Examples of the variation of the analysis are shown in Figures 2a, 2b, and 2c. The difference between the analyses utilizing data from 5, 15, and 25 rain gages is easy to notice. This series does not represent an exceptional case, but illustrates the variation observed for all such analyses. Analyses were made for the Burton Creek, Panama, Navasota, Yegua, and Venezuelan areas. They are different in size; however, each showed the same

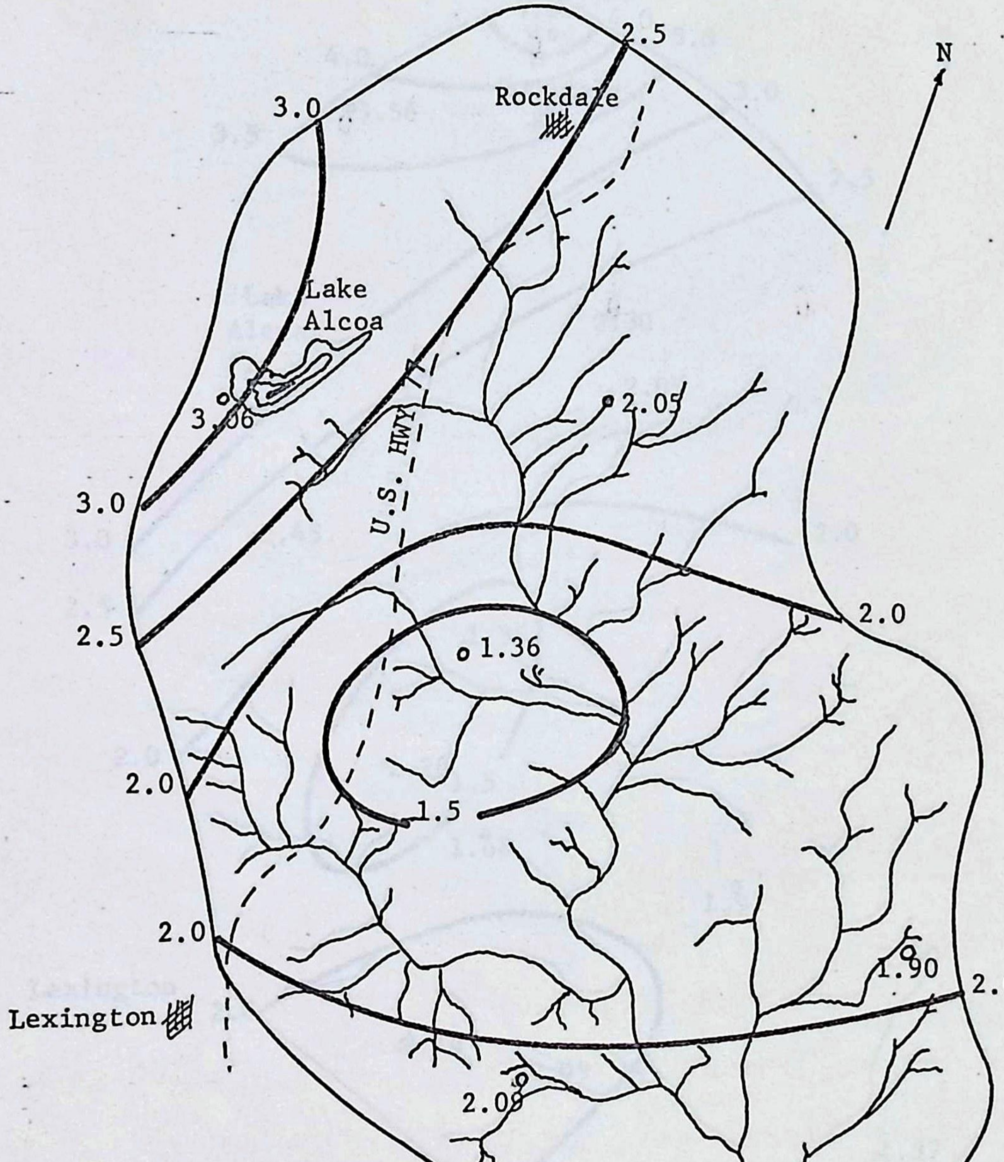

Figure 2a. Isohyetal map (inches) of one-day rainfall using five gages over East Yegua Creek.

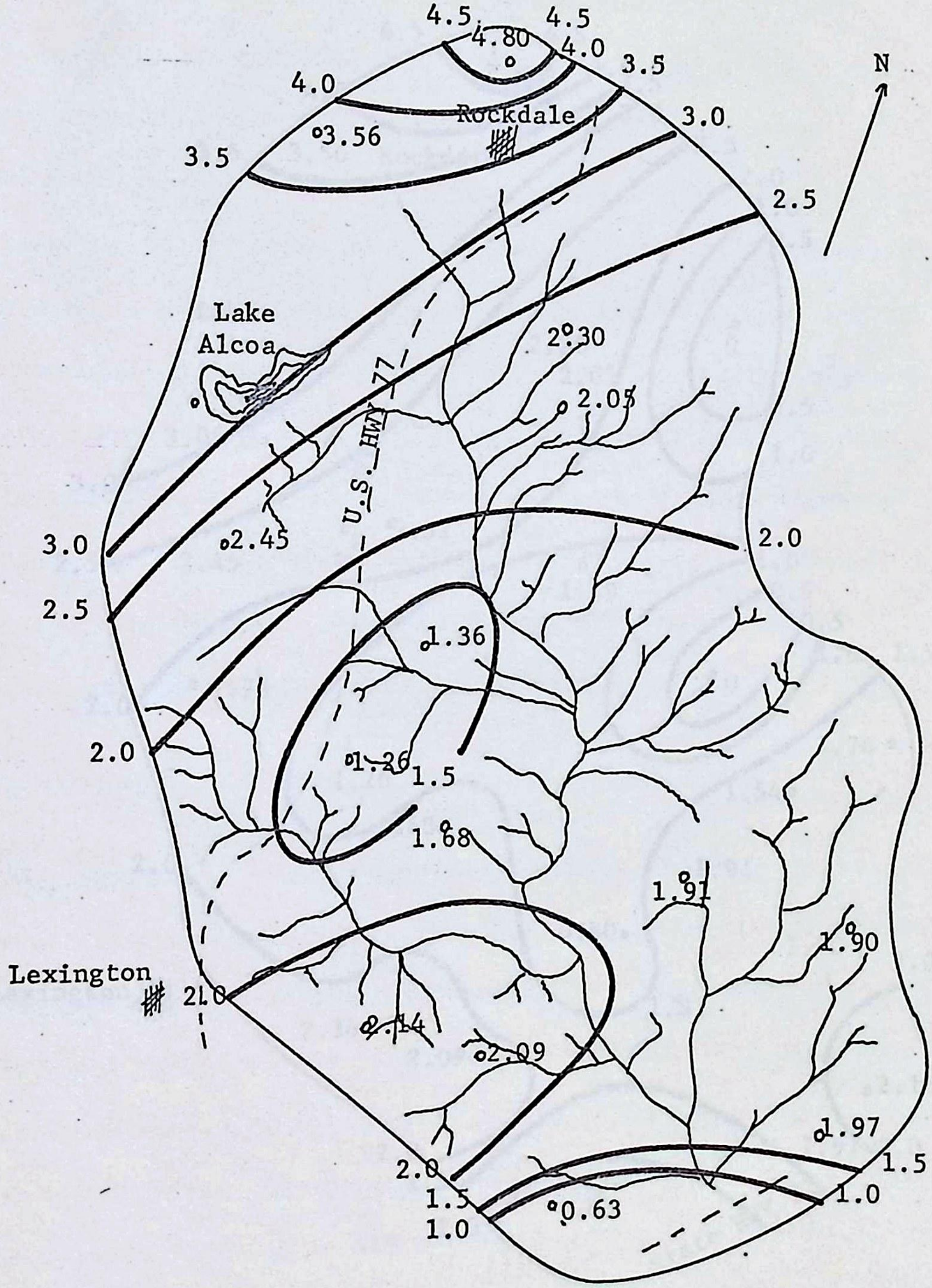

Figure 2b. Isohyetal map (inches) of one-day rainfall using 15 ga gages over East Yegua Creek.

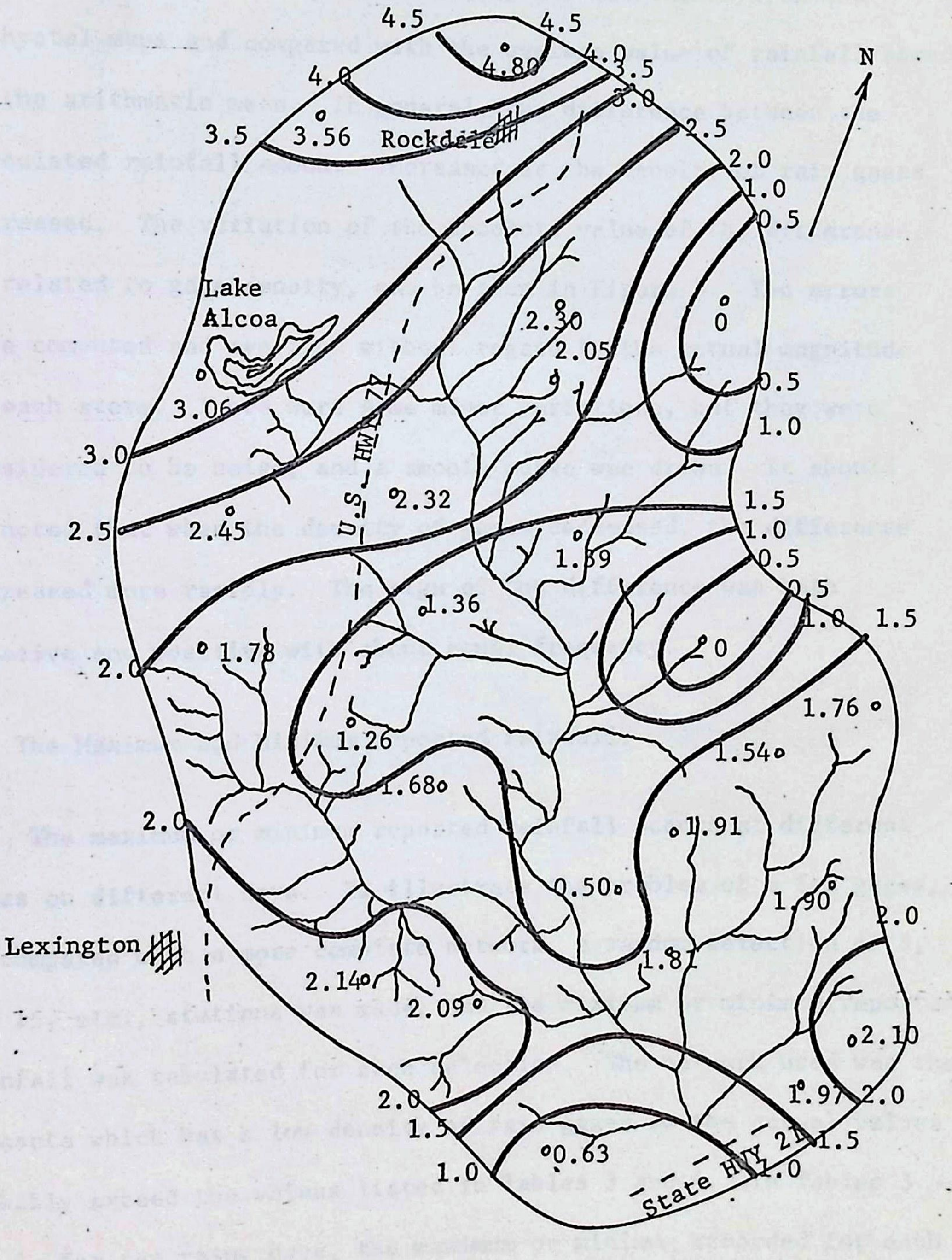

Figure 2c. Isohyetal map (inches) of one-day rainfall using 25 gages over East Yegua Creek.

general variability as more data were added.

The average rainfall for each day was determined from the isohyetal maps and compared with the average value of rainfall based on the arithmetic mean. In general, the difference between the calculated rainfall amounts increased as the density of rain gages decreased. The variation of the absolute value of the difference, as related to gage density, can be seen in Figure 3. The errors were computed and averaged without regard to the actual magnitude of each storm. There were some minor variations, but they were considered to be noise, and a smooth curve was drawn. It should be noted that when the density of gages decreased, the difference increased more rapidly. The sign of the difference was both negative and positive with about equal frequency.

C. The Maximum and Minimum reported rainfall:

The maximum or minimum reported rainfall occurs at different gages on different days. To illustrate the problem of a few gages, as compared with a more complete network, a random selection of 5, 10, 15, etc., stations was made, and the maximum or minimum reported rainfall was tabulated for each selection. The network used was the Navasota which has a low density of rain gages so the actual values probably exceed the values listed in Tables 3 and 4. In Tables 3 and 4, for ten rainy days, the maximum or minimum recorded for each day and the number of stations required to find that maximum or minimum have been listed.

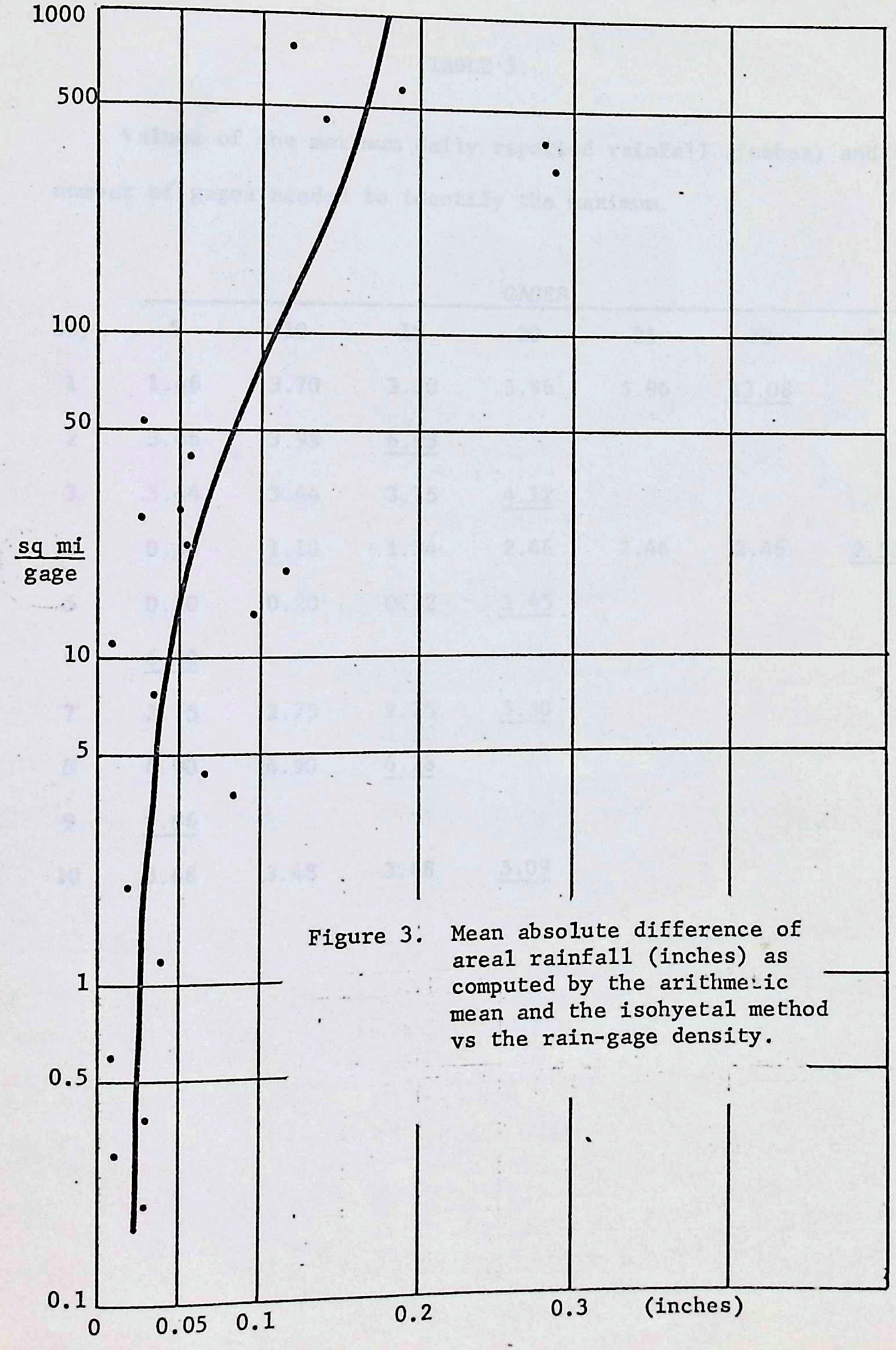

Figure 3. Mean absolute difference of areal rainfall (inches) as computed by the arithmetic mean and the isohyetal method vs the rain-gage density.

TABLE 3.

Values of the maximum daily reported rainfall (inches) and the number of gages needed to identify the maximum.

	GAGES						
Day	5	10	15	20	25	30	35
1	1.46	3.70	3.70	5.96	5.96	13.08	
2	3.46	3.95	6.93				
3	3.44	3.44	3.75	4.12			
4	0.58	1.10	1.34	2.46	2.46	2.46	2.53
5	0.20	0.20	0.72	1.45			
6	6.50						
7	2.75	2.75	2.75	3.30			
8	4.90	4.90	6.78				
9	9.96						
10	3.48	3.48	3.48	5.09			

TABLE 4.

Values of the minimum daily reported rainfall (inches) and the number of gages needed to identify the minimum.

	GAGES						
Day	5	10	15	20	25	30	35
1	0.72	0.52	0.36				
2	1.12	1.12	0.11	0.00			
3	0.59	0.59	0.59	0.34	0.34	0.34	0.09
4	0.20	0.00					
5	0.00						
6	1.12	1.12	1.12	1.02	0.64		
7	0.94	0.18	0.00				
8	0.00						
9	0.04	0.04	0.04	0.00			
10	0.09	0.00					

Since the data in Tables 3 and 4 are from selected days and randomly-selected gages, it is interesting to note not only that the maximum and the minimum vary considerably as more gages are employed, but also that a great range exists between the maximum and minimum values. In seven of the ten cases, the minimum was zero. If more gages were available, zero probably would have been reported on all ten days. The amount of 13.08 in. in one day is a very large rainfall; however, it was probably not the extreme amount which fell. All other days probably had larger amounts also.

D. Rain-gage spacing and reported daily rainfall:

After considering the two methods and the difference of the reported values of rainfall, it was decided to use only the arithmetic mean, because it was much easier to compute. Since the differences were small for most of the networks, and were both positive and negative, only one method needed to be utilized.

For all rain-gage networks, the five "best" stations were selected to make a uniform areal coverage. Then ten "best", then 15 "best", etc., until all stations were used. The average of all available gages in the network was used as the correct rainfall. Then the percentage error was computed and plotted versus the rain-gage density. Figure 4 is a plot of the four networks in Texas, with the percent error averaged from ten storms.

The Burton Creek network is the most dense network; the gage density is 0.20 mi^2/gage. The other three networks are all plotted

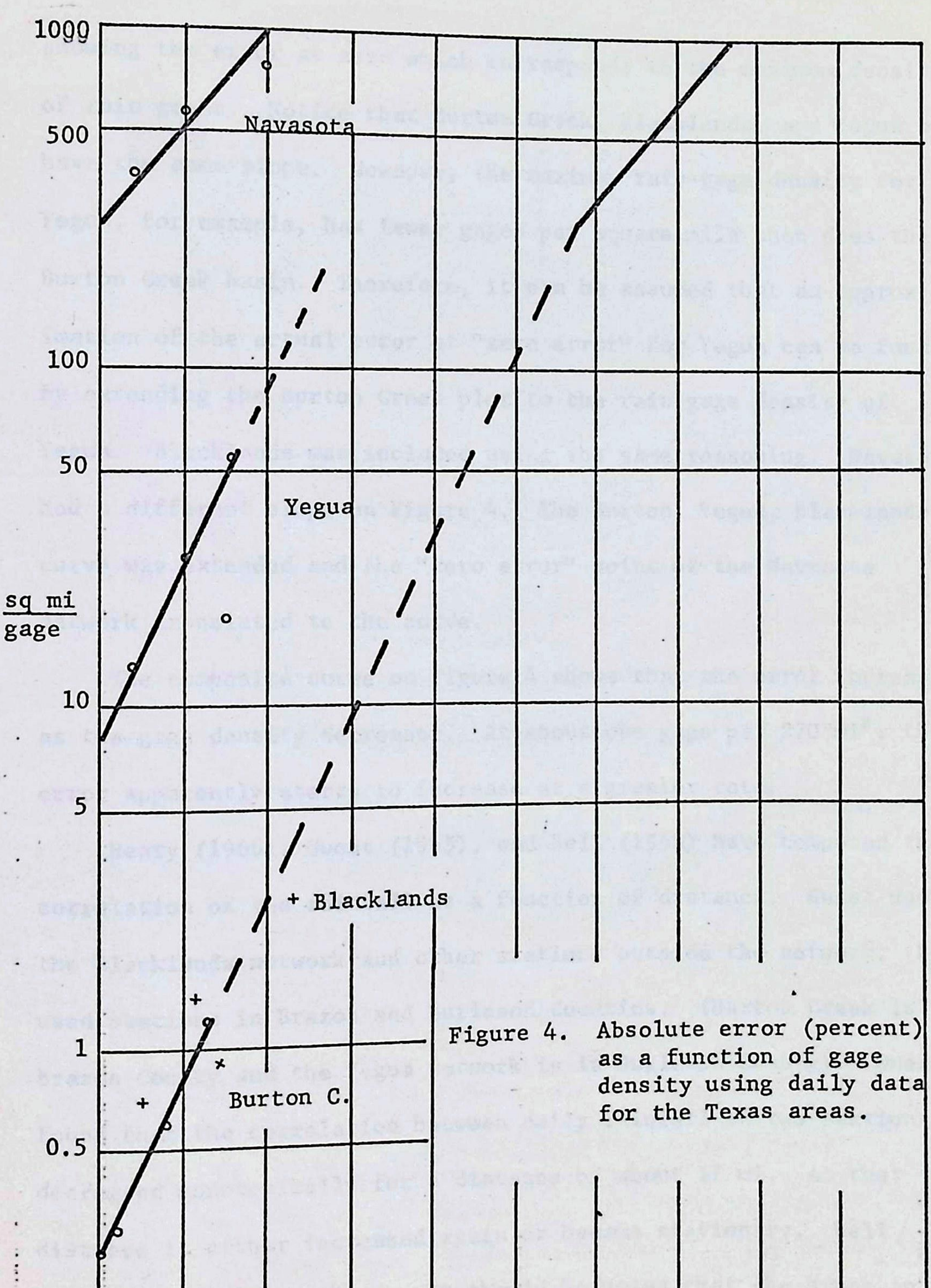

Figure 4. Absolute error (percent) as a function of gage density using daily data for the Texas areas.

showing the error at zero which corresponds to the maximum density of rain gages. Notice that Burton Creek, Blacklands, and Yegua all have the same slope. However, the maximum rain-gage density for Yegua, for example, has fewer gages per square mile than does the Burton Creek basin. Therefore, it can be assumed that an approximation of the actual error at "zero error" for Yegua can be found by extending the Burton Creek plot to the rain-gage density of Yegua. Blacklands was included using the same reasoning. Navasota had a different slope on Figure 4. The Burton, Yegua, Blacklands curve was extended and the "zero error" point of the Navasota network translated to the curve.

The composite curve on Figure 4 shows that the error increases as the gage density decreases. At about one gage per 270 mi^2, the error apparently starts to increase at a greater rate.

Henry (1966), Guest (1965), and Bell (1966) have computed the correlation of the rainfall as a function of distance. Guest used the Blacklands network and other stations outside the network. Bell used stations in Brazos and Burleson Counties. (Burton Creek is in Brazos County and the Yegua network is in Burleson County). Guest found that the correlation between daily rainfall at two stations decreased monotonically for a distance of about 17 mi. At that distance it either increased again or became stationary. Bell obtained a value of 16 mi. It should be noted that the break in the composite curve, Figure 4, occurs at 270 mi^2/gage. An estimate of the spacing is $\sqrt{270}$, which is about 16.5 mi--an excellent

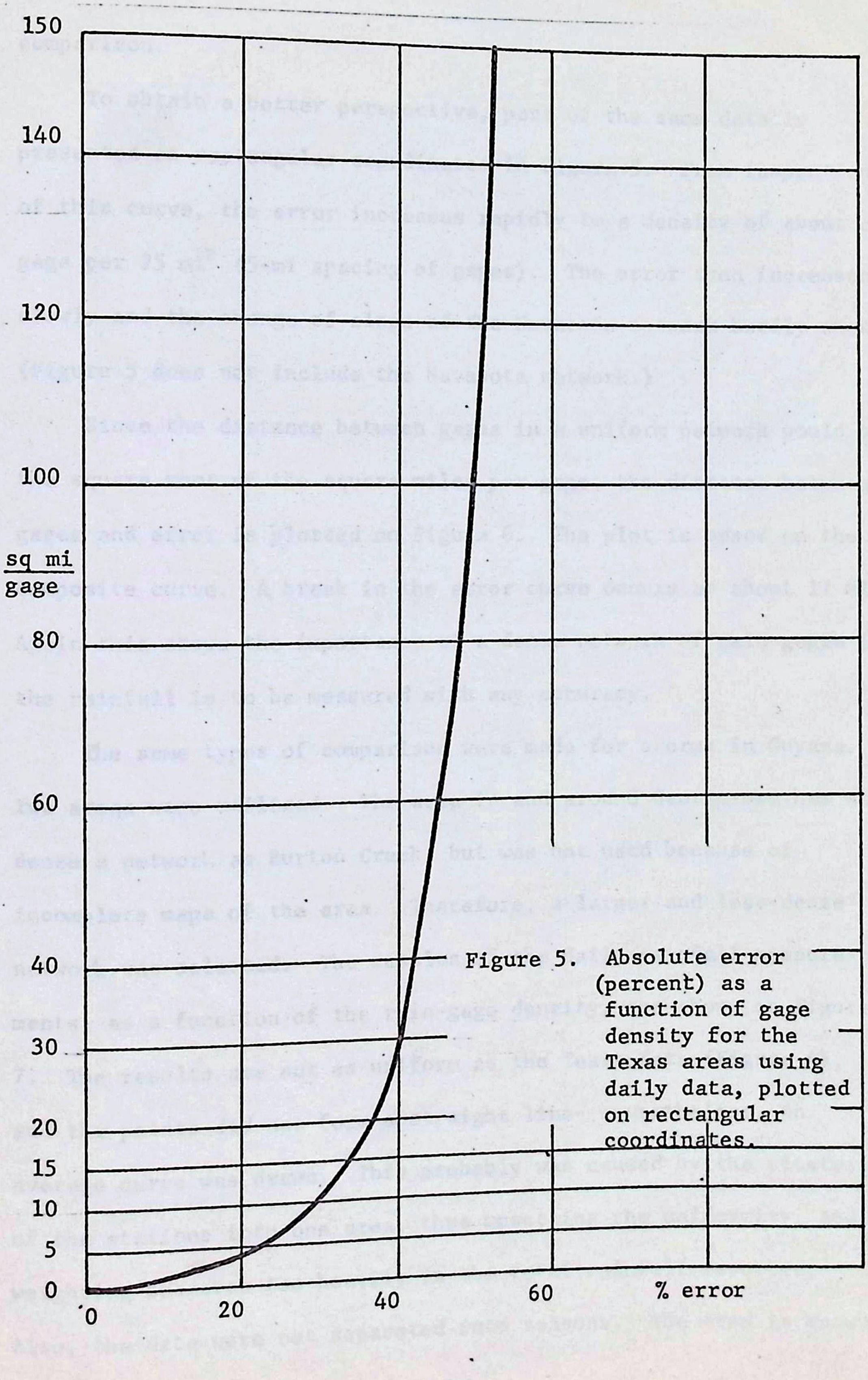

Figure 5. Absolute error (percent) as a function of gage density for the Texas areas using daily data, plotted on rectangular coordinates.

comparison.

To obtain a better perspective, part of the same data is presented on rectangular coordinates in Figure 5. From inspection of this curve, the error increases rapidly to a density of about one gage per 25 mi^2 (5-mi spacing of gages). The error then increases slowly and the change of slope of the Navasota network hardly shows. (Figure 5 does not include the Navasota network.)

Since the distance between gages in a uniform network would be the square root of the square miles per gage, the distance between gages and error is plotted on Figure 6. The plot is based on the composite curve. A break in the error curve occurs at about 17 mi. Again this shows the importance of a dense network of rain gages if the rainfall is to be measured with any accuracy.

The same types of comparison were made for storms in Guyana. Two areas were utilized. The area in and around Georgetown has as dense a network as Burton Creek, but was not used because of incomplete maps of the area. Therefore, a larger and less-dense network was selected. The results of the daily rainfall measurements, as a function of the rain-gage density, are shown on Figure 7. The results are not as uniform as the Texas data (Figure 4), and the points did not form a straight line--nevertheless, an average curve was drawn. This probably was caused by the clustering of the stations into one area, thus upsetting the uniformity, and weighting one area too heavily in the total rainfall reported. Also, the data were not separated into seasons. The area is known

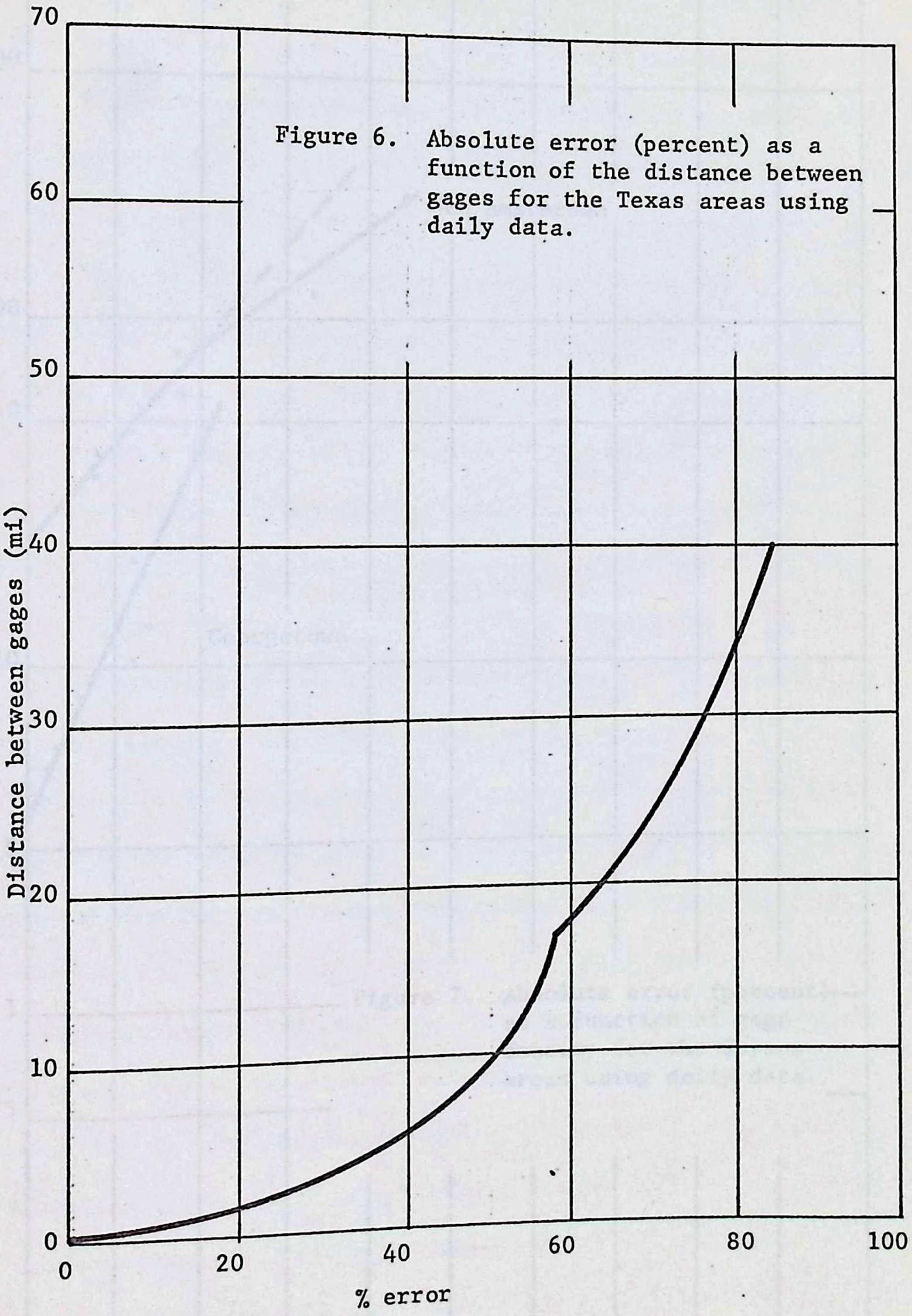

Figure 6. Absolute error (percent) as a function of the distance between gages for the Texas areas using daily data.

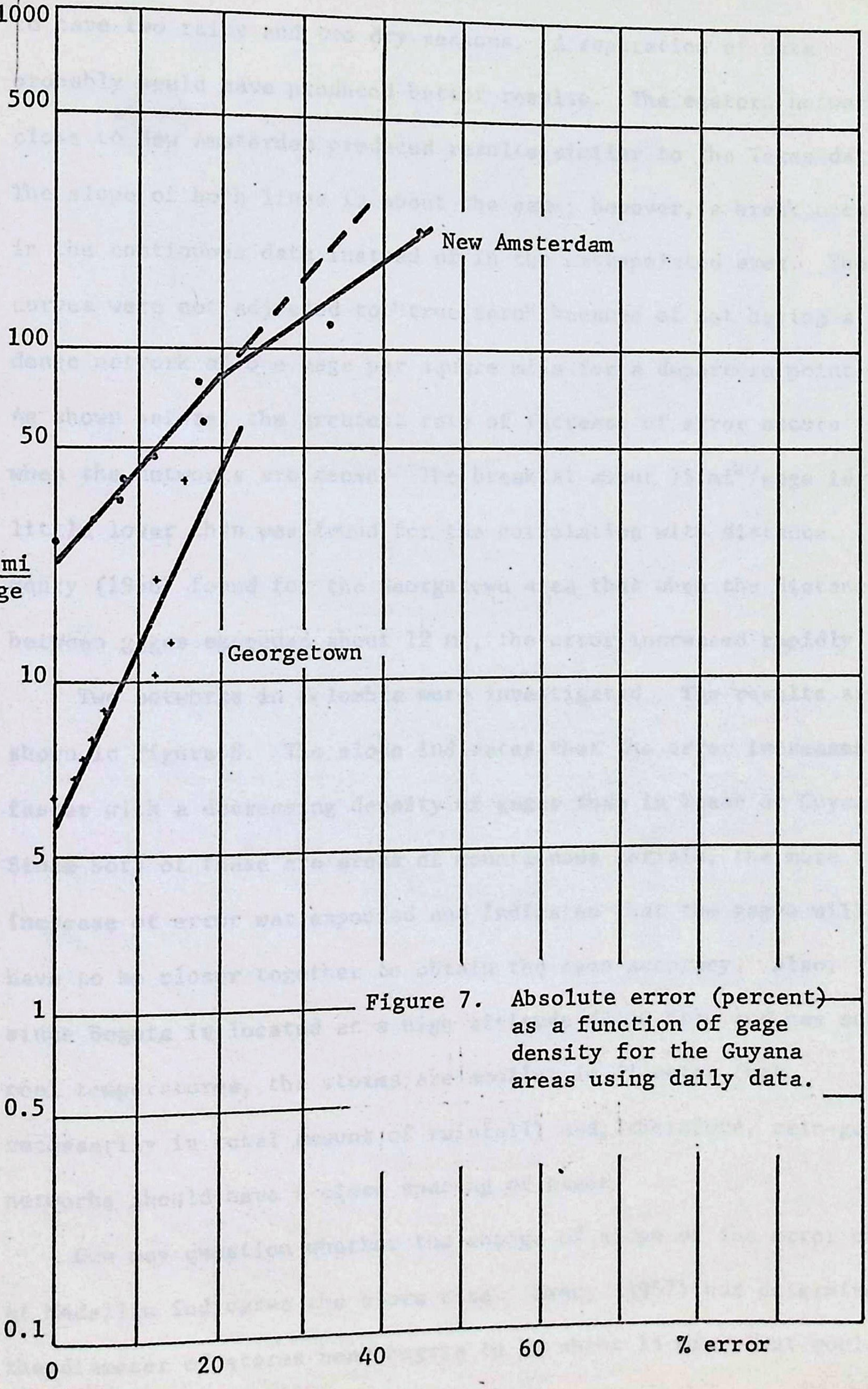

Figure 7. Absolute error (percent) as a function of gage density for the Guyana areas using daily data.

to have two rainy and two dry seasons. A separation of data probably would have produced better results. The eastern network close to New Amsterdam produced results similar to the Texas data. The slope of both lines is about the same; however, a break occurred in the continuous data instead of in the extrapolated area. The curves were not adjusted to "true zero" because of not having a dense network of one gage per square mile for a departure point. As shown before, the greatest rate of increase of error occurs when the networks are dense. The break at about 75 mi^2/gage is a little lower than was found for the correlation with distance. Henry (1968) found for the Georgetown area that when the distance between gages exceeded about 12 mi, the error increased rapidly.

Two networks in Colombia were investigated. The results are shown in Figure 8. The slope indicates that the error increases faster with a decreasing density of gages than in Texas or Guyana. Since both of these are areas of mountainous terrain, the more rapid increase of error was expected and indicates that the gages will have to be closer together to obtain the same accuracy. Also, since Bogota is located at a high altitude (8000 ft), and has such cool temperatures, the storms are smaller in diameter (not necessarily in total amount of rainfall) and, therefore, rain-gage networks should have a close spacing of gages.

One may question whether the change of slope of the error curve at Medellin indicates the storm size. Henry (1967) has determined the diameter of storms near Bogota to be about 15 mi. That would

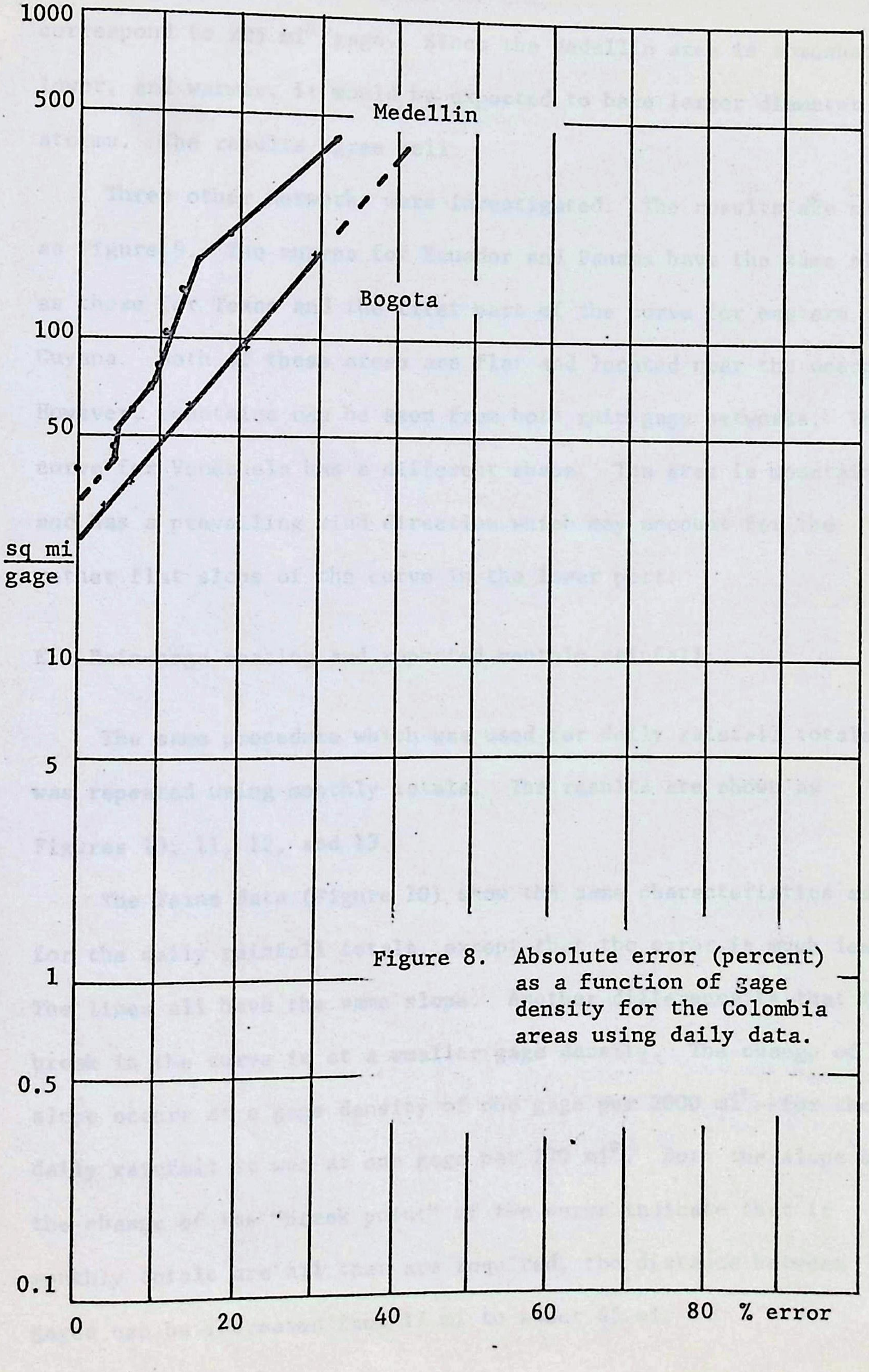

Figure 8. Absolute error (percent) as a function of gage density for the Colombia areas using daily data.

correspond to 225 mi^2/gage. Since the Medellin area is somewhat lower, and warmer, it would be expected to have larger diameter storms. The results agree well.

Three other networks were investigated. The results are shown as Figure 9. The curves for Ecuador and Panama have the same slope as those for Texas and the first part of the curve for eastern Guyana. Both of these areas are flat and located near the ocean. However, mountains can be seen from both rain-gage networks. The curve for Venezuela has a different shape. The area is mountainous and has a prevailing wind direction which may account for the rather flat slope of the curve in the lower part.

E. Rain-gage spacing and reported monthly rainfall:

The same procedure which was used for daily rainfall totals was repeated using monthly totals. The results are shown as Figures 10, 11, 12, and 13.

The Texas data (Figure 10) show the same characteristics as for the daily rainfall totals, except that the error is much less. The lines all have the same slope. Another difference is that the break in the curve is at a smaller gage density. The change of slope occurs at a gage density of one gage per 2000 mi^2--for the daily rainfall it was at one gage per 270 mi^2. Both the slope and the change of the "break point" of the curve indicate that if monthly totals are all that are required, the distance between gages can be increased from 17 mi to about 45 mi.

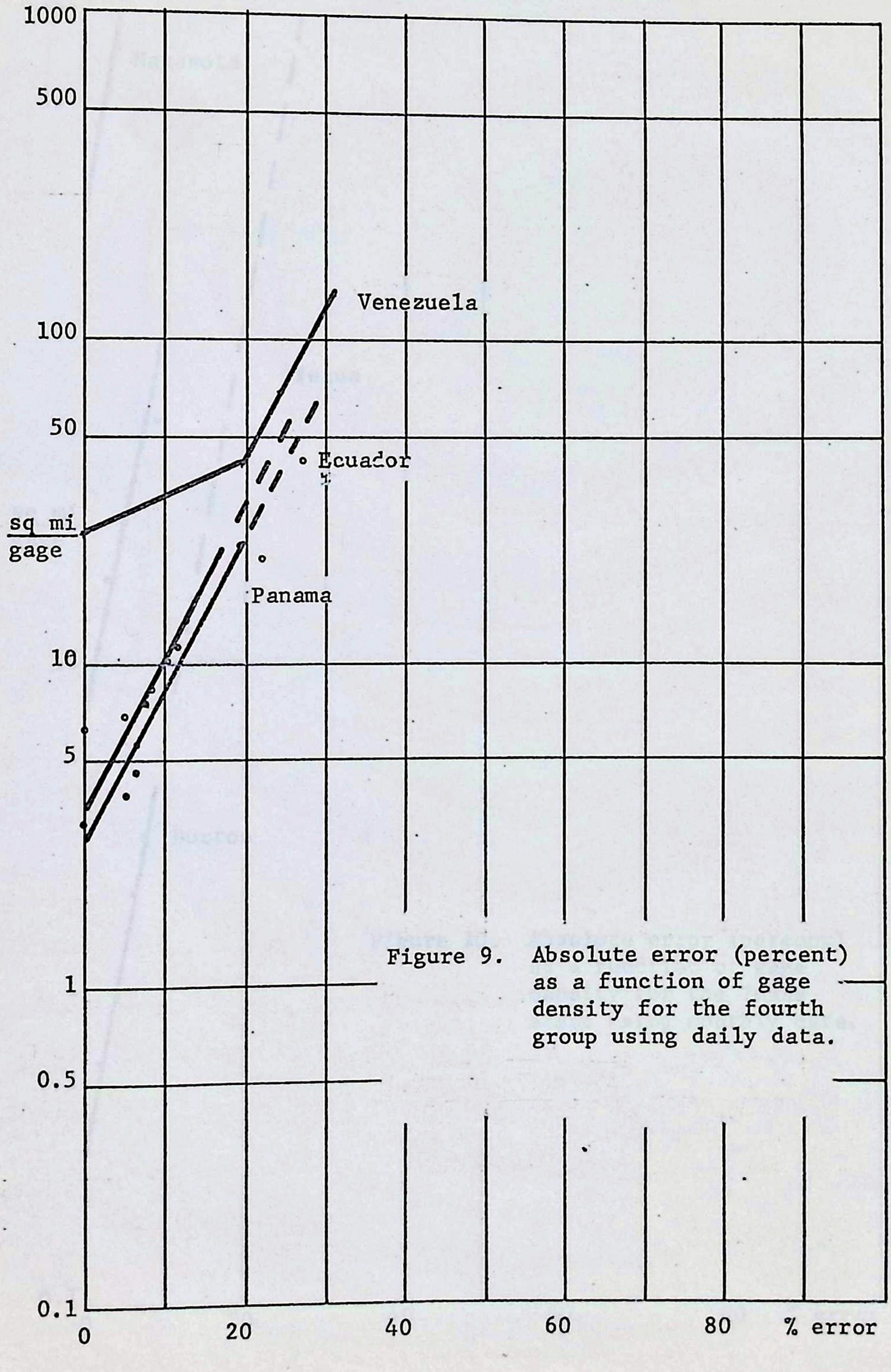

Figure 9. Absolute error (percent) as a function of gage density for the fourth group using daily data.

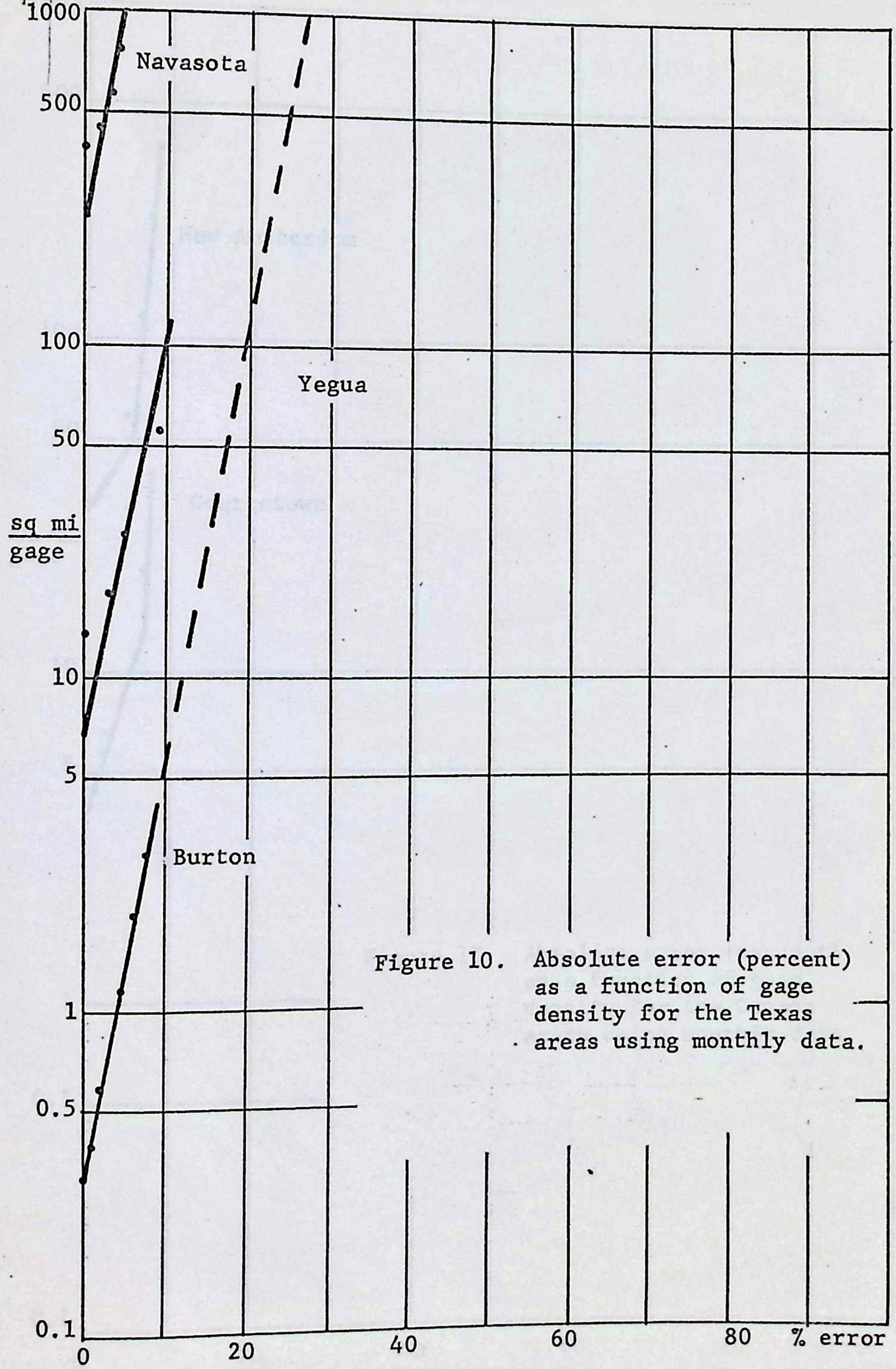

Figure 10. Absolute error (percent) as a function of gage density for the Texas areas using monthly data.

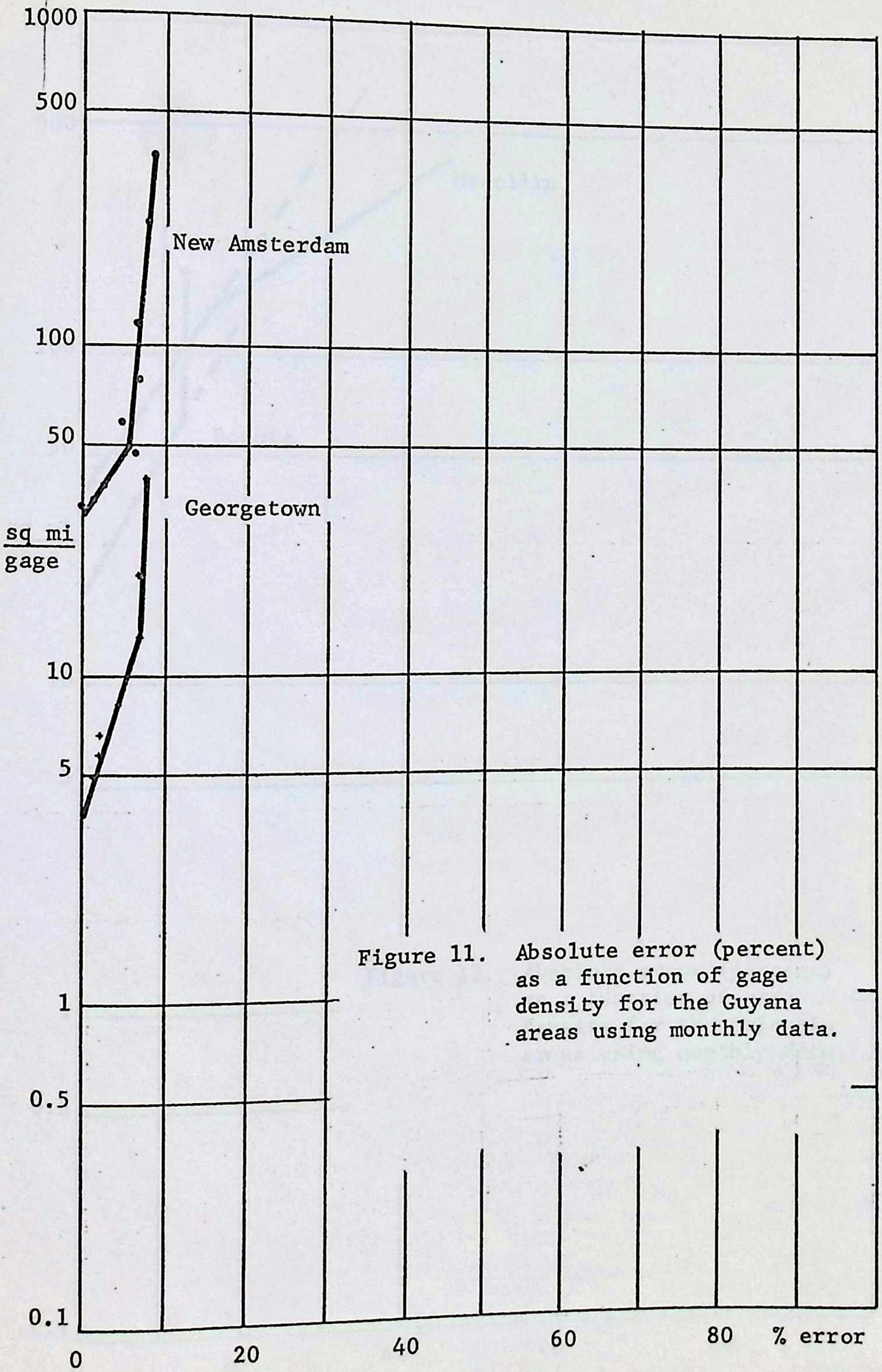

Figure 11. Absolute error (percent) as a function of gage density for the Guyana areas using monthly data.

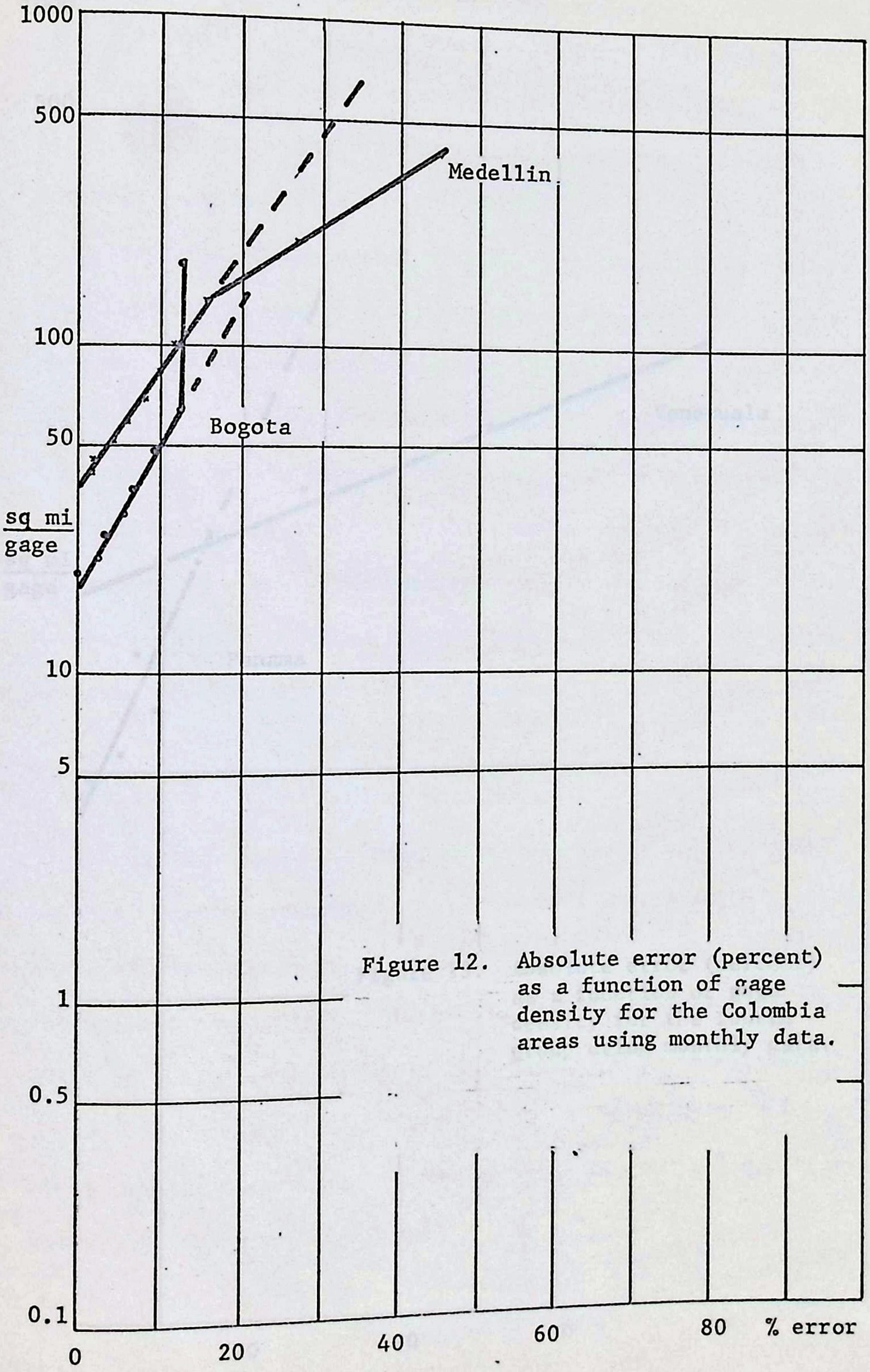

Figure 12. Absolute error (percent) as a function of gage density for the Colombia areas using monthly data.

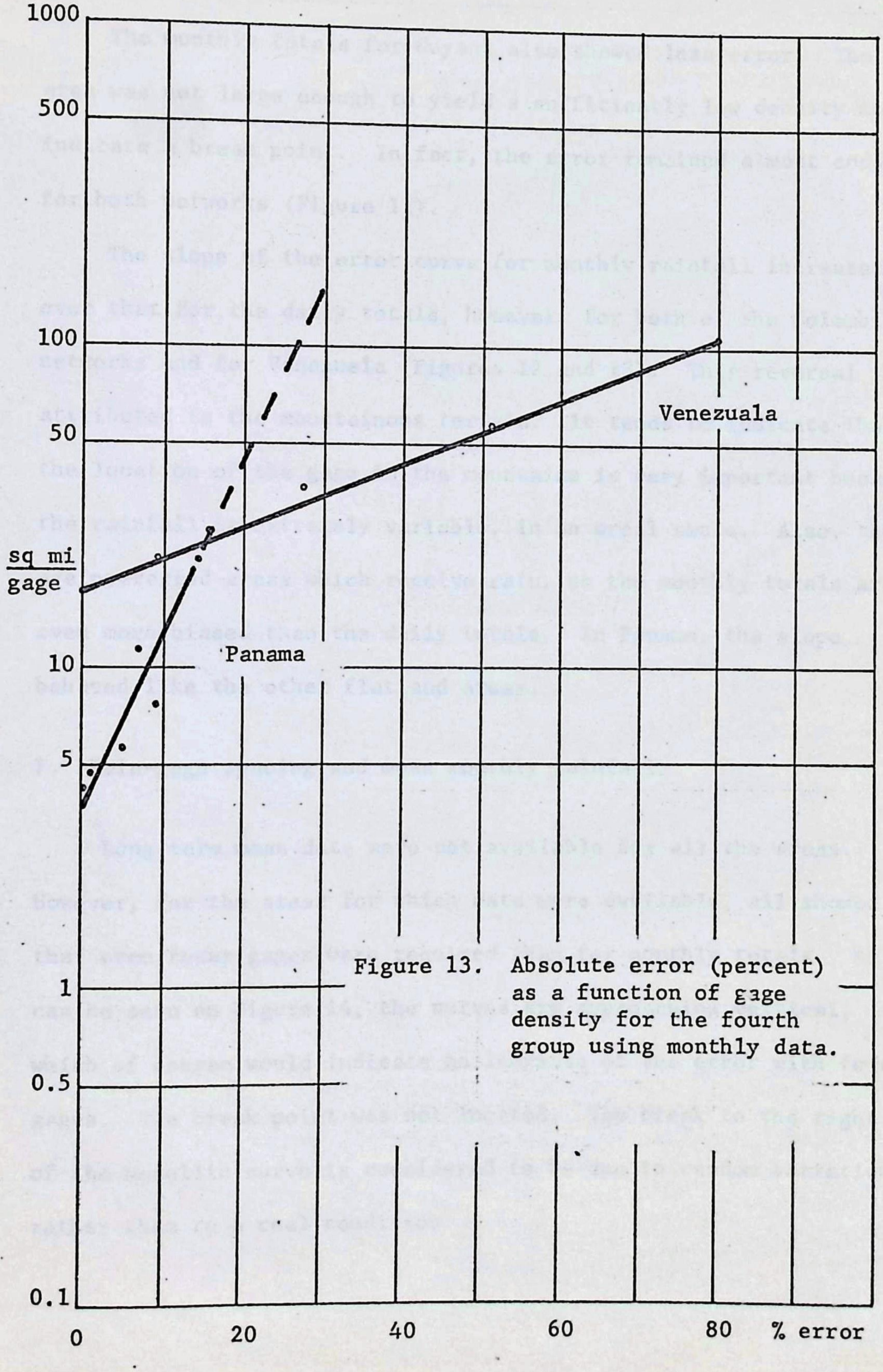

Figure 13. Absolute error (percent) as a function of gage density for the fourth group using monthly data.

The monthly totals for Guyana also showed less error. The area was not large enough to yield a sufficiently low density to indicate a break point. In fact, the error remained almost constant for both networks (Figure 11).

The slope of the error curve for monthly rainfall increased over that for the daily totals, however, for both of the Colombian networks and for Venezuela (Figures 12 and 13). This reversal is attributed to the mountainous terrain. It tends to indicate that the location of the gage in the mountains is very important because the rainfall is extremely variable, in an areal sense. Also, there are preferred areas which receive rain, so the monthly totals are even more biased than the daily totals. In Panama, the slope behaved like the other flatland areas.

F. Rain-gage spacing and mean monthly rainfall:

Long-term mean data were not available for all the areas. However, for the areas for which data were available, all showed that even fewer gages were required than for monthly totals. As can be seen on Figure 14, the curves are approaching vertical, which of course would indicate no increase of the error with fewer gages. The break point was not located. The break to the right of the Medellin curve is considered to be due to random variation rather than to a real condition.

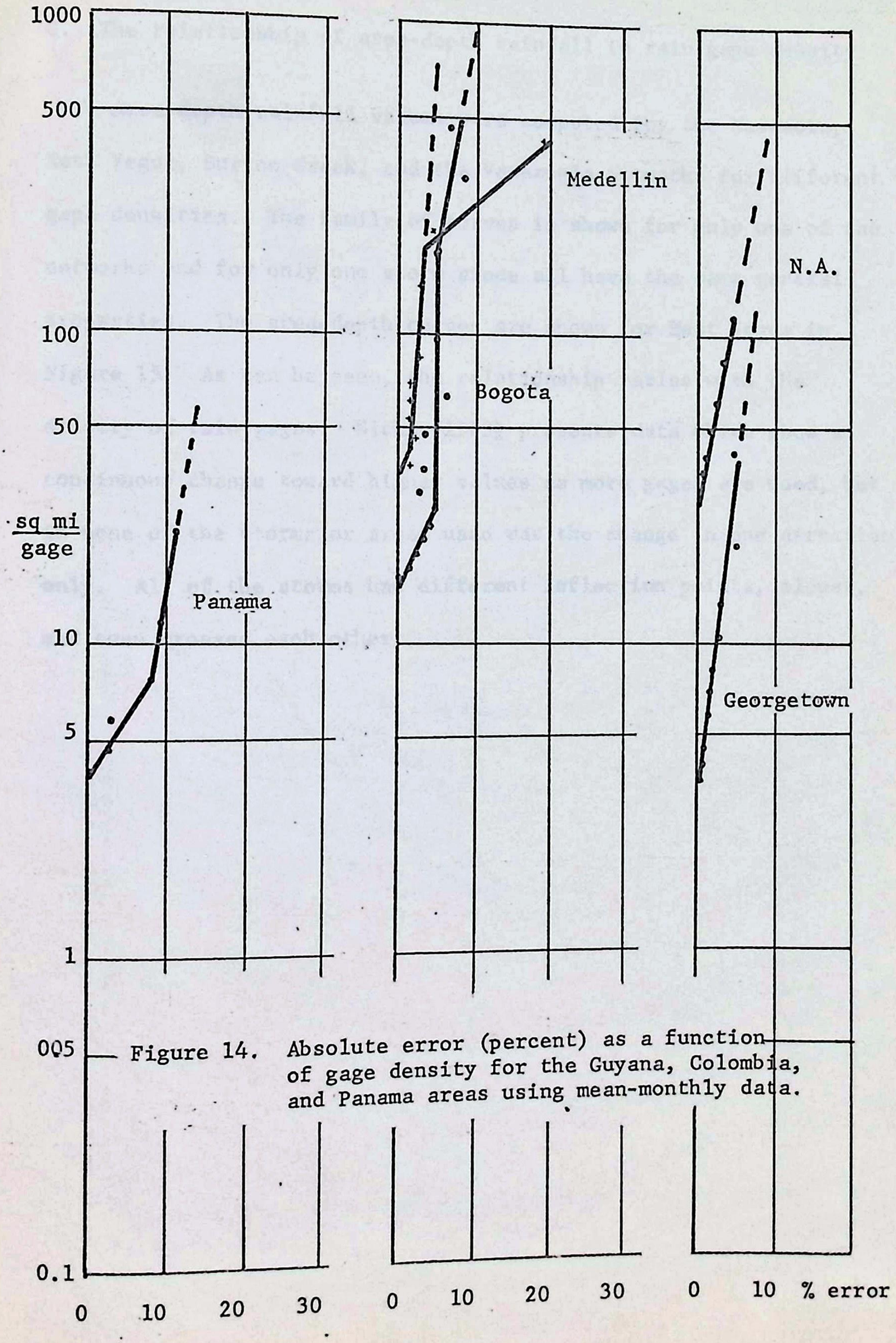

Figure 14. Absolute error (percent) as a function of gage density for the Guyana, Colombia, and Panama areas using mean-monthly data.

G. The relationship of area-depth rainfall to rain-gage density:

Area-depth rainfall values were computed for the Navasota, East Yegua, Burton Creek, and the Venezuela networks for different gage densities. The family of curves is shown for only one of the networks and for only one storm since all have the same general properties. The area-depth curves are shown for East Yegua in Figure 15. As can be seen, the relationship varies with the density of rain gages. Nicks (1963) presents data which show a continuous change toward higher values as more gages are used, but in none of the storms or areas used was the change in one direction only. All of the storms had different inflection points, slopes, and even crossed each other.

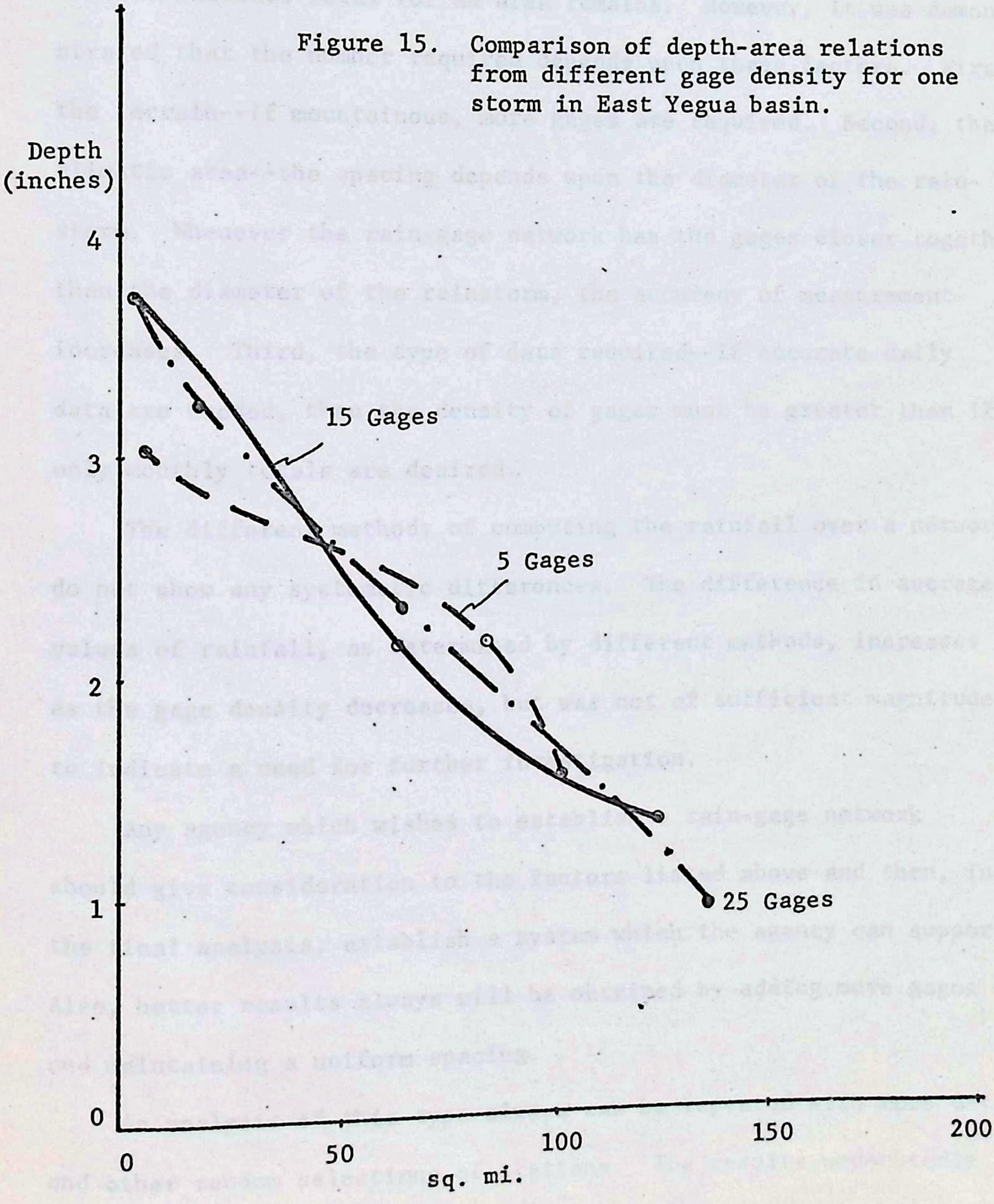

Figure 15. Comparison of depth-area relations from different gage density for one storm in East Yegua basin.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The problem of the number of rain gages needed to determine the correct rainfall total for an area remains. However, it was demonstrated that the number required depends upon three factors. First, the terrain--if mountainous, more gages are required. Second, the climatic area--the spacing depends upon the diameter of the rainstorm. Whenever the rain-gage network has the gages closer together than the diameter of the rainstorm, the accuracy of measurement increases. Third, the type of data required--if accurate daily data are needed, then the density of gages must be greater than if only monthly totals are desired.

The different methods of computing the rainfall over a network do not show any systematic differences. The difference in average values of rainfall, as determined by different methods, increases as the gage density decreases, but was not of sufficient magnitude to indicate a need for further investigation.

Any agency which wishes to establish a rain-gage network should give consideration to the factors listed above and then, in the final analysis, establish a system which the agency can support. Also, better results always will be obtained by adding more gages and maintaining a uniform spacing.

An analysis of this type always can be repeated with more data and other random selections of stations. The results undoubtedly will vary as the random sample shown here--however, it is believed that the basic conclusions will remain the same.

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VITA

Fernando Alvarez B. was born in San Juan de Colon, Tachira, Venezuela, on April 4, 1935, to Adelina and Nestor J. Alvarez. He attended private and public school in San Cristobal, Tachira, where he graduated bachelor from "Liceo Simon Bolivar" in July 1958. Senor Alvarez attended "Universidad Central de Venezuela", in Caracas, where he graduated "Hidrometeorologista" in August 1963. In 1963, he started to work as professor in meteorology at Universidad Central de Venezuela until May 1967. In February 1968, he attended Texas A&M University, where he received a M.S. degree in Meteorology in August 1969.

Fernando Alvarez married Elba Oberto of Falcon State, Venezuela on June 1, 1961. There are one daughter, Malena, and two sons, Ricardo and Fernando A. in their marriage.

This thesis was typed by Miss Lynda Sulik