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A Study of Quantitative Precipitation Forecasting in the TVA Basin

By

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A STUDY OF QUANTITATIVE PRECIPITATION FORECASTING IN THE TVA BASIN

Introduction

In recent years there has been an increased demand for quantitative forecasts of precipitation for certain areas for periods ranging up to several days in advance. It is generally recognized that the problem of estimating future rainfall amounts is more difficult than predicting rainfall occurrence, and very little progress has been made to date in developing quantitative precipitation forecasting methods. Techniques for estimating the probable magnitude of rainfall were outlined by Showalter[1], but the principles and formulas he presented are suggested methods or guides rather than rigid techniques or specific forecasting procedures.

In response to the demand that further research in quantitative precipitation forecasting be conducted, a pilot project was initiated in 1945, having the following objectives:

a. To develop adequate methods of summarizing rainfall and other meteorological data for use in further development of quantitative forecasting methods.

b. To assemble and organize methods of treatment of these data, insofar as such methods had already been developed by research in various places.

c. To make use of the results of previous research and to carry out new research in developing specific objective methods and criteria for forecasting quantitative precipitation for particular drainage basins.

d. To verify forecasts made by such techniques and to develop verification methods which would provide adequate check on current forecasts and indicate further research needs.

This report on the progress of the project outlines a method of attack and describes some statistical techniques that might be useful to others approaching similar problems. A description of an objective forecasting technique is given along with actual examples of forecasts made by use of it.

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[1]A. K. Showalter, "An Approach to Quantitative Forecasting of Precipitation", Bulletin of the American Meteorological Society. April-September 1944.

The Problem Selected

The area selected for this study was the east-central section of the TVA drainage basin, chosen because (1) 24- and 36-hour quantitative rainfall forecasts had been made for it for several years and (2) precipitation records and data for the area were most nearly adequate for the purpose. Figure 1 shows the location of the east-central section, about 12,000 square miles, which is primarily a valley opening to the southwest of the basin, bounded by two ranges of mountains which gradually converge to the northeast. The object of the investigation was to study the relationship between the amount of precipitation occurring in this area during a 24-hour period beginning at 0730 EST and the meteorological conditions immediately preceding that time. The winter months of December, January, and February were chosen for the first part of the study.

Precipitation data

A network of 60 stations in the area was selected from those listed in the following issues of "Precipitation in Tennessee River Basin"[1]:

January	1940-1944
February	1940-1944
December	1939-1943

In order to get a rough idea of the sampling reliability of this and smaller networks, a sample of the data was taken, and the 60 stations were divided into two groups of 30 stations each, as shown in Figure 2. Average 24-hour precipitation amounts were then computed separately for each group by adding the amounts recorded for each station and dividing the total by 30, as shown in Table 1. This was done for a 4-month period, with the results indicated in Table 2. Figure 3 shows the values for the stations of Group 1 plotted against the values for the stations of Group 2. On the basis of the high correlation indicated by this diagram, it was decided to work up the remaining precipitation data on the sample of only 30 stations (Group 1). A more accurate estimate of the 24-hour amount falling over the area would be obtained by using 60 stations and giving different weights to each, but it was believed such additional expenditure of effort was not justified at this time. Table 3 presents the average precipitation values for stations of Group 1 for the whole period of record studied. A plus sign (+) means that a measurable amount was observed at one or more stations but that the average for the area was less than 0.006 inch. If the average was as high as 0.006 inch, the value was rounded to 0.01 inch.

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[1] Published by the Tennessee Valley Authority Hydraulic Data Division

Figure 4 is a frequency distribution of the values listed in Table 3. It should be noted that average amounts of 0.01 inch or more occurred on about 50 percent of the days; amounts greater than 1.25 inches were rare, occurring less than 2 percent of the time.

The Meteorological Variables

Precipitation amounts for 24-hour periods were related to a number of independent meteorological variables, selected on the basis of previous research and forecasting experience[1]. For a particular 24-hour period, no data taken from observations later than 0730 EST on the forecast day were used as independent variables. Data from the last available 10,000-ft. chart, 2300 EST, were used as well as data from the 1930 EST surface map.

In this part of the study a total of 270 cases was used, from the winters of 1941-42, 1942-43, and 1943-44. Maps representing these 270 cases were then stratified into two classes, C_1 or C_2, by the following procedure:

Making use of the 2300 EST 10,000-ft. map, the isobar passing through Knoxville was traced on the following 0730 EST surface weather map. This isobar was followed upstream no farther than 100° W. long. If it intersected an area of precipitation on the 0730 surface map where amounts greater than 0.01 inch had occurred in the previous 6 hours, the map was classified as C_2. A map was also classified as C_2 if precipitation was occurring at 0730 EST at any one of the three "key stations" of Vicksburg, Miss., Meridian, Miss., or Montgomery, Ala. In cases where the 10,000-ft. isobar did not cross a precipitation area as defined above and no precipitation was falling at any one of the three "key stations", the map was classified as C_1. Figures 5 and 6 illustrate the method of classification by giving examples of both C_1 and C_2 maps.

In a few cases this classification could not be made readily because Knoxville was near the center of a closed low at 10,000 feet. These cases were treated separately and grouped in a third class, C_3.

The effectiveness of this stratification is indicated by the frequency distributions shown in Figure 7. Of the 182 maps that were classified as C_1, 70 percent showed no precipitation or less than 0.01 inch, and only 7 percent of the amounts were greater than 0.25 inch. Of the 83 cases in the C_2 group, only 17 percent showed less than 0.01 inch, and 43 percent of the amounts were greater than 0.25 inch.

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[1] A. K Showalter, former head of the Hydrometeorological Section of the U. S. Weather Bureau, and T W. Kleinsasser, forecaster at the Weather Bureau Station at Knoxville, Tenn., gave valuable assistance on this phase of the project.

For each class of maps, 13 independent variables were used in relating precipitation amounts to the previous meteorological conditions. These variables were labeled and defined as follows:

X_1 = Memphis sea level pressure at 1930 EST, 12 hours before the beginning of the 24-hour period.

X_2 = Memphis sea level pressure at 0730 EST, the beginning of the 24-hour period.

X_3 = Chattanooga sea level pressure minus the Memphis sea level pressure at 0730 EST.

X_4 = Tallahassee sea level pressure minus the New Orleans sea level pressure at 0730 EST.

X_5 = Shreveport dew point at 0730 EST.

X_6 = St. Louis dew point at 0730 EST.

Y_4 = Size of the precipitation zone on the 0730 EST map in the area bounded by the 83d and 95th meridians and the 31st and 37th parallels. This area was divided into 18 squares, as shown in Figure 8, and the variable Y_4 then took values ranging from 0 to 18. On Figure 8, the value of Y_4 was estimated as 1.

Y_5 = Direction of representative 0730 EST surface winds in the east-central area, as determined from the Knoxville and Chattanooga observations and the surface isobars. In cases where the winds over the area were light and/or variable under the influence of a nearby high or low pressure center, the observations were classified into group H (for high) and group L (for low).

Y_6 = Direction of the 10,000-ft. wind at Knoxville as determined from the 2300 EST map.

Y_7 = Minimum latitude reached by following the 10,000-ft.[1] isobar upwind through Knoxville no farther than 100° W. long. In cases where this isobar did not go south of Knoxville between Knoxville and 100° W. long., Y_7 is defined as the latitude where the isobar crosses 100° W. long. In Figure 8, the value of Y_7 used was 35.

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[1]The contour lines on the 700-mb. constant pressure map may be used in place of the isobars on the 10,000-ft. map. Also, a height difference of 100 feet on the 700-mb. constant pressure map may be considered as approximately equivalent to a pressure difference of 2 mb. on the 10,000-ft. map.

Y_8 = Longitude of the first 10,000-ft. trough to the west of Knoxville, the trough being defined as the point of lowest pressure along the parallel running through Knoxville. In Figure 8 the value of Y_8 was determined as 89.

U_3 = Chattanooga pressure minus Little Rock pressure from the 10,000-ft. chart of 2300 EST.

$U_4 = \frac{D_1 + D_2}{2}$, where D_1 is the Memphis dew point and D_2 is the Montgomery dew point at 0730 EST.

These independent variables and the subsequent precipitation amounts were listed for each day of period as shown in Table 4. For a particular date, the values of X_2, X_3, X_4, X_5, X_6, Y_4, Y_5, and U_4 are from the 0730 EST surface map. The values of Y_6, Y_7, Y_8, and U_3 are from the previous 2300 EST 10,000-ft. map, and the value X_1 is from the previous 1930 EST surface map. The precipitation amount in the last column is for the 24-hour period beginning at 0730 EST for the date indicated.

Figure 9 is an outline of the method used in combining the 13 independent variables into one parameter, W. The general procedure was to work with the variables in pairs and to determine functions Y_1, Y_2, etc. by graphical methods. For example, as shown in Figure 10, the dependence of precipitation on variables X_1 and X_2 was investigated by plotting the observed precipitation amounts on a graph with X_1 values as the abscissae and X_2 values as ordinates. This graph was then divided into cells containing about 10 observations each, and the fraction p/n was plotted in each cell, where p was the number of observations of 0.01 inch precipitation or more and n was the total number of cases in the group. A "probability" surface was then fitted to these data by drawing lines of equal percent, keeping these lines as smooth as possible. Figure 11 shows the scatter diagram for X_3 and X_4, and Figures 13 and 14 show the probability lines that were drawn for these two charts.

A function, $Y_1 = f_1 (X_1 , X_2)$ is thus given by the lines shown in Figure 13. For example, if the value of X_1 = 1,020 mb. and X_2 = 1,014 mb., the value of Y_1 is approximately 68. Likewise, if X_3 = 9 mb. and X_4 = 1 mb., the value of Y_2 is 40, as shown in Figure 14.

The function, $Z_1 = f_4 (Y_1, Y_2)$ was determined by plotting Y_1 against Y_2, as shown in Figure 12, and using the same graphical technique. Figure 15 shows the percentage contour lines that were determined

from the data. Figures 16 to 24 show the charts that resulted by following the outline shown in Figure 9. Table 5 shows a sample of the numerical values of Y_1, Y_2, etc.

After the values of W were obtained, the data were summarized in Table 6, which shows how the precipitation amounts are related to W. In general, low values of W are associated with zero or small precipitation amounts, and high values of W are associated with the larger precipitation amounts. Table 7 presents the data from the previous table in terms of cumulative frequencies and percents. For example, in the 26 cases where 9/26 (35 percent) of the cases had precipitation amounts of zero or less than 0.01 inch, 20/26 (77 percent) had precipitation amounts of 0.09 inch or less. These precentage figures were then plotted to show how the probability of obtaining a specified precipitation amount, or less, varied as a function of W. Smooth curves were drawn through the plotted points, as shown in Figure 25.

Table 8 was constructed by reading the values from the curves shown in Figure 25. This table shows the probability that a precipitation amount will fall within a specified range when a particular value of W has been observed. For example, when W = 35, the curves in Figure 25 indicate that the relative frequency of occurrence of no measurable precipitation is 71 percent. The relative frequency of occurrence of less than 0.09 inch is 92 percent, so the difference (92 - 71 = 21 percent) is the relative frequency of occurrence for amounts ranging from 0.01 to 0.09 inch, inclusive.

Charts and tables similar to those worked up for the C_1 group were worked up for the C_2 and C_3 groups and are presented in Figures 26 to 39 and Tables 9 to 11. The "probability" contours on these charts were based on the percent of occurrence of amounts greater than 0.25 inch. These charts and tables were then tested by using them to make experimental forecasts for the winter of 1945-46.

Experimental Forecasts

The method of making the experimental forecasts of 24-hour precipitation over the east-central section is illustrated by taking as an example the forecast for December 13, 1945. The following data were selected from the weather maps:

X_1 = 1,019 millibars, the sea level pressure at Memphis at 1930 EST, December 12.

X_2 = 1,012 millibars, the sea level pressure at Memphis at 0730 EST, December 13.

X_3 = 10, Chattanooga minus Memphis sea level pressure at 0730 EST, December 13.

X_4 = 5, Tallahassee minus New Orleans sea level pressure at 0730 EST, December 13.

X_5 = 43, Shreveport dew point at 0730 EST, December 13.

X_6 = 27, St. Louis dew point at 0730 EST, December 13.

Y_4 = 15, size of precipitation area on the 0730 EST map, December 13.

Y_5 = 2, direction of surface wind at 0730 EST, December 13.

Y_6 = 12, direction of 10,000-ft. wind at Knoxville, 2300 EST, December 13.

Y_7 = 33, lowest latitude reached by 10,000-ft. isobar passing through Knoxville at 2300 EST, December 13.

Y_8 = 112, longitude of lowest pressure at 10,000 feet west of Knoxville at 2300 EST, December 13.

U_3 = 0, Chattanooga pressure minus Little Rock pressure at 10,000 feet at 2300 EST, December 13.

U_4 = 36, average of Montgomery and Memphis dew points at 0730 EST, December 13.

Since the map was classified in Group C_2, the following values of the functions of the independent variables were determined from Figures 26 to 37:

Y_1 = 70 from Figure 26	Z_3 = 50 from Figure 32
Y_2 = 80 from Figure 27	Z_4 = 30 from Figure 33
Z_1 = 72 from Figure 28	U_2 = 40 from Figure 34
Y_3 = 35 from Figure 29	V = 75 from Figure 35
Z_2 = 76 from Figure 30	R = 56 from Figure 36
U_1 = 87 from Figure 31	W = 50 from Figure 37

Reference to Table 11 or Figure 38 indicated the following statements would be appropriate for the 24-hour period beginning at 0730 EST, December 13:

1. The chance of no rain occurring is quite negligible.

2. There are about 22 chances out of 100 that the observed amount will be in the class interval of 0.01-0.09 inch, and similar chances that it will be in the class interval of 0.10-0.24 inch.

3. The most likely class interval for the precipitation amount is from 0.25 to 0.74 inch, inclusive, the chances being slightly less than 1 in 3.

4. There is a reasonably good chance, 23 in 100, that the precipitation amount will be greater than 0.75 inch but less than 1.25 inches.

5. There is very little chance that the precipitation amount will equal or exceed 1.25 inches.

The observed amount in this case proved to be 0.38 inch. Forecasts made in a similar manner for each day of the period from December 1, 1945, to February 28, 1946, are shown in Table 12. A contingency table summarizing the verification is presented in Table 13. The correlation between the forecast and observed amount was 0.69, a highly significant value, since there is less than one chance in a thousand that a coefficient that large or larger would be obtained as a result of random sampling from a population with zero correlation. Two-thirds of the forecast amounts were within ± 0.10 inch of the observed amounts and one half were within ± 0.05 inch of observed amount.

Discussion

It should be noted that frequency distributions of precipitation amounts are usually skew, so that the mean of the distribution will not in general correspond to the mode. This consideration as well as others raises the question as to whether it makes much sense to forecast precipitation amounts by only stating a single figure such as a mean or expected value. Furthermore, there does not seem to be much justification (in practical forecasting) in attempting to predict rainfall amounts to the nearest hundredth of an inch, since neither the accuracy of the forecasts nor of the precipitation observations justifies such refinement. The alternative suggested here is to make quantitative precipitation forecasts by estimating the probability that the precipitation amount will fall within a specified range or ranges.

It is planned that this project will be continued with primary emphasis placed on determining additional factors or parameters which can be used to improve the accuracy of the forecasts. This phase will be closely coordinated with the project which makes daily precipitation forecasts for the TVA basin, and copies of the preliminary charts shown here have been given to the forecasters to use. It is

expected that it will be possible for them to suggest modifications and additional factors that should be considered. Among some of the additional variables that give indications of improving the correlations are those based upon the following:

1. Position and direction of movement of the surface low pressure center.

2. Curvature of the surface and 10,000-ft. isobars over southeastern United States.

3. Distribution of moisture at the 5,000- and 10,000-ft. levels.

4. Upper air stability indices and measurements.

Some difficulty is expected in studying the factors based upon upper air humidity measurements, since there is no large supply of such data located in the important region immediately to the south and west of the TVA basin. For this reason the study of the effect of the upper air moisture distribution will be confined chiefly to the past two or three winters.

Table 1.--Example of computation of average 24-hour precipitation amount over the east-central section -- December 19, 1944

	Group 1			Group 2		
No.		Station	Amount		Station	Amount
1.....	208	Catlettsburg	0.98	391	Chattanooga	0.28
2.....	434	Eastland	.55	92	Morgan Springs	.13
3.....	156	Breedenton	.20	157	Roddy	.50
4.....	209	Gatlinburg	.16	205	Alcoa	.64
5.....	170	Loudon	.55	158	Kingston	.38
6.....	207	Knoxville	.26	160	Pilot Mountain	
7.....	167	Petros	.42	164	Clockrange	
8.....	159	Helbetsburg		163	Crossville	.17
9.....	166	Concord	.35	169	TVA Nursery	.75
10.....	321	Norris	.50	323	Norris Dam	.43
11.....	325	Lafoletter	.15	333	Arthur	.39
12.....	340	Pennington Gap	.25	338	Rose Hill	.45
13.....	331	Big Barren	.45	339	Jonesville	.33
14.....	335	Tazewell	.49	341	Olinger	.31
15.....	337	Sneedville	.50	327	White Hollow	.28
16.....	348	Clinchport	.35	336	Big Sycamore	.58
17.....	290	Morristown	.37	289	Joppa	.83
18.....	346	Flat Gap		292	Stoney Point	.34
19.....	291	Rogersville	.46	93	Big Spring	.30
20.....	347	Little War Gap	.35	99	Parksville	.25
21.....	94	Georgetown	.43	119	Servilla	.42
22.....	97	Riceville	.31	171	McGhee	.51
23.....	116	Columbus	.30	173	Kittie	.33
24.....	174	Tellico Plains	.83	177	Cade's Cove	.62
25.....	175	Mint	.47	211	Dandridge	
26.....	176	Calderwood	.69	213	Bull's Gap	.57
27.....	212	White Pine	.40	214	Lick Creek	.31
28.....	215	Jearoldstown	.38	218	Camp Creek Bald	.43
29.....	216	Little Chucky	.65	219	Limestone	.40
30.....	220	Embreeville	.50	242	Cosby	.66
		Total	12.30		Total	11.59

$$\text{Average} = \frac{12.30}{30} = .41 \qquad \text{Average} = \frac{11.59}{30} = .39$$

Table 2.--Comparison of 24-hour average precipitation amounts for two groups of stations

Day	February 1940		December 1940		February 1942		December 1944	
	Grp. 1	Grp. 2	Grp. 1	Grp. 2	Grp. 1	Grp. 2	Grp. 1	Grp. 2
1.....	+	+	.32	.40	.01	.01	+	.01
2.....	+	+	.02	.01	+	.01		
3.....				+	+	+		
4.....		.01						
5.....	.06	.10	.01	.02	.34	.35		
6.....	.23	.26	+	+	.36	.40		
7.....	.05	.08	.05	.04	.57	.64	.16	.13
8.....	+	+	.13	.11	.04	.03	.51	.61
9.....	+	+	+	.02			.02	.02
10....	.72	.82	+	+	.03	.03		
11....	.09	.10			.02	.03	.19	.15
12....			+	+	+	+	.24	.25
13....	+	+	.43	.44		+	.02	.01
14....	.71	.76	.33	.29			.04	.01
15....	+	.05	.08	.10		+		+
16....			.07	.09	.09	.09		
17....	.05	.05	.02	.03	1.26	1.35		+
18....	.62	.71			.01	+	.04	.05
19....	.25	.31	+	+	.01	+	.41	.39
20....	.22	.17	+	+				+
21....	.02	.02	.01	+				
22....	.04	.02					.18	.19
23....	.02	.04					+	+
24....		+	+	+	.49	.35	.01	.02
25....	.20	.24	.04	.05	.31	.37	.16	.09
26....		+	.08	.01		+	.30	.40
27....	+	.01	.03	.06	.05	.07	.10	.08
28....	.97	.92	.22	.29	.02	.03	.53	.56
29....	.05	.07	.89	.76			.70	.69
30....			.13	.14			.41	.49
31....			+	+			.17	.12

Table 3.--Average 24-hour precipitation amounts for the east-central section based on Group 1 stations

Day	Dec. 1939	Jan. 1940	Feb. 1940	Dec. 1940	Jan. 1941	Feb. 1941	Dec. 1941	Jan. 1942	Feb. 1942	Dec. 1942	Jan. 1943	Feb. 1943	Dec. 1943	Jan. 1944	Dec. 1944
1....	.11	.07	+	.32			+	.55	.01	.24		.04		.01	.02
2....	.24	.01	+	.02	.44	.01	.01	.40	+	1.28			.01	.13	
3....	.03	+			.09	.02	.24		+	+		.01	.05	1.14	.05
4....	+				.13		.38	.32		.44	+	1.10	.12	.08	.02
5....		.02	.06	.01			.31	+	.33	+	+	.78	+		
6....			.23	+			+	+	.36	1.01	.01	.58	.08	.04	.48
7....		.03	.05	.05		+			.53	.04		.02	.26		.01
8....		.16	+	.13		.02		.12	.04	.24	.17		.03	.01	.03
9....		.02	+	+						.03	.02		.09	.14	1.31
10...			.72	+				+	.03	+			.08	+	.08
11...	.08	.04	.09		+			+	.02	+	.05	.78	.48		.30
12...		.23		+					+	.02	+	+			.06
13...	.35	.02	+	.43			.76			.02		.12			+
14...	.05	.56	.71	.33		.48	.06					.02	.03		.23
15...		.12	+	.08	.04	.04					.09	+	+	.45	.40
16...	+			.07	.40	+			.07	.42	+	+		.19	
17...	.01		.05	.02	.04	.01			1.22	.01	+				.91
18...			.62						.01		.40				1.44
19...		.07	.25	+	+		.01	.75	.01		.07				+
20...	.63	+	.22	+				.02		.04				+	.23
21...			.02	.01						.06		.29		+	.14
22...			.04					+		.01		.14			.23
23...	.04	.11	.02		.23		.48	+		.52	+			+	.54
24...	.89	.60		+	.14	+	.56		.48		.02				+
25...	.02		.20	.04	.54	.04	.01		.30	.04	+		.18		.03
26...	.01			.08	.06	.02	.10			.08	.88		.92		1.19
27...	.53		+	.03	.21	.16			.05	.02	.76	.01	.07	+	.68
28...	.03		.97	.22		.12		.91	.02	1.14	.24		.04	.10	.13
29...	.02		.05	.89				.03		1.68	.02		.35	.02	.84
30...	+	.05		.13						1.39	.01		+		
31...		.01		+	.04		.01	.46		.04	+				

Table 4.--Tabulation of independent variables and precipitation amount

Date		Map Type	X_1	X_2	X_3	X_4	X_5	X_6	Y_4	Y_5	Y_6	Y_7	Y_8	U_3	U_4	$\bar{A}$
1941	12-1...	C_1	21	20	3	2	50	45	0	H	12	32	95	1	55	.01
	2...	C_2	18	18	3	0	57	44	2	L	10	33	92	1	57	.24
	3...	C_2	19	20	1	0	54	47	0	16	10	30	90	1	53	.38
	4...	C_2	18	14	0	-1	50	51	6	3	9	25	94	5	56	.31
	5...	C_1	10	11	4	0	59	43	0	11	12	33	100	0	51	+
	6...	C_1	21	29	-7	-7	35	22	0	15	11	36	88	-1	35	0
	7...	C_1	30	28	-2	-1	30	21	0	1	16	42	105	-5	24	0
	.															
	.															
	.															
1944	2-25...	C_2	14	10	7	2	62	50	4	10	13	14	113	1	62	1.19
	26...	C_1	7	8	3	5	64	45	3	9	11	30	100	5	62	.68
	27...	C_1	11	18	-1	2	57	30	1	12	10	26	117	3	57	13
	28...	C_2	17	11	4	5	65	32	6	1	11	29	120	1	54	.84
	29...	C_2	10	24	-9	-6	39	22	1	14	11	36	90	0	36	0

Table 5.--Sample listing of values of functions Y_1, Y_2 .....W.

Date		Y_1	Y_2	Y_3	Z_1	Z_2	Z_3	Z_4	U_1	U_2	V	R	W	$\bar{A}$
1941	12-1.....	46	50	55	46	50	25	60	55	35	51	78	52	.01
	2.....	32	50	62	32	62	70	30	53	50	55	79	62	.24
	3.....	26	33	62	26	50	40	40	40	30	32	75	47	.38
	4.....	53	23	63	54	76	55	70	76	60	78	86	80	.31
	5.....	68	37	60	50	55	45	60	60	53	61	71	61	+
	6.....	14	10	30	12	20	25	20	8	15	8	43	8	0
	7.....	20	35	24	27	14	15	30	13	15	10	34	10	0
1944	2-25....	68	72	68	70	76	30	60	89	30	73	84	75	1.19
	26....	75	63	63	69	89	65	70	90	80	93	91	95	.68
	27....	40	52	54	46	60	50	66	61	65	68	83	75	.13
	28....	70	50	60	70	74	42	20	88	20	67	76	64	.84
	29	5	5	27	2	13	10	5	3	4	2	56	5	0

Table 6.--Frequency table of precipitation amounts as a function of W for Group C_1

W	Precipitation Class 0	1	2	3	4	5	Total Cases	$\bar{A}$
0- 5	24	1					25	
6-10	26	2					28	
11-25	25	2	3				30	
26-40	19	7		1			27	.02
41-50	19	9					28	.01
51-65	9	11	1	5			26	.09
66-80	4	4	2	1	3		14	.23
86-95		1	1	2			4	.33

Class	Amount
0	Less than .01"
1	.01" to .09"
2	.10" to .24"
3	.25" to .74"
4	.75" to 1.24"
5	1.25" and more

$$\bar{A} = \frac{\text{Total precipitation}}{\text{No. of cases}}$$

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Table 7.--Cumulative frequency table for Group C_1

W	0	1 or less	2 or less	3 or less	4 or less	5 or less
0- 5.....	24 96%	25 100%	25	25	25	25
6-10.....	26 93%	28 100%	28	28	28	28
11-25.....	25 83%	27 90%	30 100%	30	30	30
26-40.....	19 70%	26 96%	27 100%	27	27	27
41-50.....	19 68%	28 100%	28	28	28	28
51-65.....	9 35%	20 77%	21 81%	26 100%	26	26
66-80.....	4 29%	8 57%	10 71%	11 79%	14 100%	14
86-95.....	0	1 25%	2 50%	4 100%	4	4

Table 8.--Relation between W and the probability that the precipitation amount will fall within a specified range -- Group C_1

W	<.01	.01-.09	.10-.24	.25-.74	.75-1.24	≥1.25	$\bar{A}$
0	97	3					
1	97	3					
2	96	4					
3	96	4					
4	96	4					
5	95	4	1				
6	95	4	1				
7	94	5	1				
8	93	6	1				
9	93	6	1				
10	92	7	1				1
11	91	7	2				1
12	90	8	2				1
13	90	8	2				1
14	89	9	2				1
15	88	10	2				1
16	87	10	3				1
17	86	11	3				1
18	86	11	3				1
19	85	12	2	1			1
20	84	13	2	1			1
21	83	13	3	1			1
22	82	14	3	1			1
23	82	14	3	1			1
24	81	15	3	1			1
25	80	15	4	1			1
26	79	16	3	2			1
27	78	17	3	2			1
28	77	17	4	2			1
29	76	18	4	2			1
30	76	18	4	2			1
31	75	18	4	3			1
32	74	19	4	3			1
33	73	20	4	3			1
34	72	20	5	3			1
35	71	21	5	3			1
36	70	22	5	3			1
37	69	22	5	4			1
38	68	23	5	3	1		1
39	67	23	5	4	1		1
40	66	24	5	4	1		1
41	65	25	5	4	1		1
42	63	26	5	5	1		2
43	62	27	5	4	2		2
44	61	27	5	5	2		2
45	60	27	6	5	2		2
46	59	28	5	6	2		2
47	57	29	6	6	2		2
48	56	29	6	6	3		2
49	55	30	6	6	3		3
50	53	31	6	7	3		3
51	52	31	7	7	3		4
52	51	31	7	7	4		5
53	49	32	7	8	4		6
54	48	32	8	7	5		7
55	46	33	8	8	5		7
56	45	33	8	8	6		8
57	43	34	8	9	6		9
58	42	34	8	10	6		9
59	40	34	9	10	7		10
60	39	34	9	10	8		11
61	38	34	9	11	8		12
62	36	34	10	12	8		12
63	35	34	11	11	9		13
64	34	34	11	12	9		14
65	32	34	11	13	10		14
66	31	34	11	14	10		15
67	30	34	11	14	11		16
68	28	34	12	14	12		16
69	27	34	12	15	12		17
70	26	34	12	16	12		18
71	24	34	13	16	13		18
72	23	34	12	17	14		19
73	22	33	13	18	14		20
74	20	34	13	18	15		21
75	19	34	13	18	16		21
76	18	33	13	20	16		22
77	17	33	13	20	17		23
78	15	34	13	20	18		24
79	14	33	14	20	19		25
80	13	33	14	21	19		26
81	12	33	14	21	20		26
82	11	33	14	21	21		27
83	10	32	15	21	22		28
84	9	32	15	21	23		29
85	8	32	15	21	24		30
86	6	32	15	22	25		31
87	5	32	16	21	26		32
88	4	31	16	23	26		33
89	3	31	16	23	27		34
90	2	31	17	22	28		35
91	2	30	17	21	30		36
92	1	30	17	21	31		37
93	1	29	17	21	32		39
94		29	18	20	33		40
95		28	18	21	33		41
96		28	17	21	34		42
97		27	17	21	35		44
98		27	17	21	35		45
99		26	17	21	36		46
100		26	17	21	36		48

Table 9.--Frequency table of precipitation amounts as a function of W for Group C_2

W	Precipitation Class 0	1	2	3	4	5	Total Cases	$\bar{A}$
0- 6	6	2					8	
7-15	2	7	2				11	.04
16-30	3	5	3	4	1		16	.21
31-50		5	6	2	2		15	.25
51-70	1	3	1	8	5	1	19	.55
71-85		1		4	1	6	12	.91
90-96				1	1		2	.85

Table 10.--Cumulative frequency table for Group C_2

W	0	1 or less	2 or less	3 or less	4 or less	5 or less
0- 6.....	6 75%	8 100%	8	8	8	8
7-15.....	2 18%	9 82%	11 100%	11	11	11
16-30.....	3 19%	8 50%	11 69%	15 93%	16 100%	16
31-50.....	0	5 33%	11 73%	13 87%	15 100%	15
51-70.....	1 5%	4 21%	5 26%	13 68%	18 95%	19 100%
71-85.....	0	1 8%	1 8%	5 42%	6 50%	12 100%
90-96.....	0	0	0	1 50%	2 100%	2

Table 11.--Relation between W and the probability that the precipitation amount will fall within a specified range --Groups C_2 and C_3

W	<.01	.01-.09	.10-.24	.25-.74	.75-1.24	≥1.25	$\bar{A}$	W	<.01	.01-.09	.10-.24	.25-.74	.75-1.24	≥1.25	$\bar{A}$
0	84	15	1												
1	83	16	1				0	51	2	21	21	31	24	1	42
2	81	17	2				0	52	2	21	20	31	25	1	43
3	79	19	2				0	53	2	20	19	32	25	2	44
4	76	21	3				1	54	2	20	18	32	26	2	46
5	72	24	4				2	55	2	19	18	31	28	2	47
6	68	26	6				2	56	2	19	17	31	28	3	49
7	62	30	7	1			3	57	2	18	16	32	29	3	50
8	56	34	8	2			3	58	2	18	14	33	29	4	52
9	50	38	10	2			4	59	2	17	14	33	30	4	53
10	44	41	12	3			5	60	2	17	13	33	29	6	55
11	38	44	14	3	1		6	61	2	16	12	34	28	8	57
12	34	46	15	4	1		6	62	2	16	10	34	28	10	59
13	30	46	18	5	1		7	63	2	16	9	34	27	12	61
14	26	47	19	6	2		8	64	2	15	9	34	26	14	63
15	23	47	21	7	2		9	65	2	14	9	34	24	17	65
16	20	46	24	8	2		9	66	1	15	8	34	22	20	67
17	19	45	25	9	2		10	67	1	14	7	35	21	22	69
18	17	45	26	9	3		11	68	1	14	6	35	20	24	70
19	16	43	28	10	3		12	69	1	13	6	35	18	27	72
20	15	41	30	10	4		12	70	1	13	6	34	16	30	74
21	14	40	30	12	4		13	71	1	12	6	34	15	32	76
22	13	39	31	13	4		14	72	1	12	5	34	14	34	77
23	12	39	31	13	5		15	73	1	11	5	34	13	36	78
24	12	37	32	14	5		16	74	1	11	4	34	12	38	80
25	11	37	32	14	6		17	75	1	10	4	34	11	40	81
26	11	35	32	16	6		18	76	1	10	3	34	11	41	82
27	10	35	32	17	6		19	77	1	9	3	34	11	42	83
28	10	33	33	17	7		20	78	1	9	2	34	11	43	84
29	9	33	32	19	7		20	79	1	8	3	33	10	45	85
30	8	33	32	19	8		21	80	1	8	2	33	10	46	86
31	8	32	32	20	8		22	81	1	7	2	33	10	47	87
32	7	32	31	21	9		23	82	1	7	2	32	11	47	88
33	7	31	31	21	10		24	83	1	6	2	33	10	48	89
34	6	30	32	22	10		25	84	1	6	2	32	10	49	89
35	6	29	31	23	11		26	85	1	5	2	32	10	50	90
36	6	28	31	23	12		27	86	1	4	3	31	10	51	91
37	5	28	31	24	12		28	87	1	4	2	32	10	51	91
38	5	27	30	25	13		29	88	1	3	3	31	10	52	92
39	5	27	29	25	14		30	89	1	3	2	32	9	53	93
40	4	27	29	26	14		31	90	1	2	2	32	10	53	93
41	4	26	28	27	15		31	91		3	2	31	10	54	94
42	4	25	28	27	16		32	92		3	2	30	10	55	95
43	4	24	28	27	17		33	93		2	2	31	10	55	94
44	3	25	26	28	18		34	94		2	2	31	9	56	96
45	3	24	25	29	19		35	95		2	2	30	9	57	96
46	3	23	25	29	20		36	96		2	1	31	9	57	96
47	3	23	24	29	21		37	97		1	2	31	8	58	97
48	3	22	23	30	22		38	98		1	2	30	8	59	97
49	2	22	23	30	23	1	39	99		1	1	31	8	59	97
50	2	22	22	30	23	1	40	100		1	1	31	7	69	98

Table 12.--Objective forecasts of 24-hour precipitation amounts for the TVA east-central section --Winter 1945-46

Date	Probability that the 24-hour amount will be <.01	.01-.09	.10-.24	.25-.74	.75-1.24	≥1.25	Forecast Amount	Observed Amount
1945								
Dec. 1.....	.76	.18	.04	.02			.01	0
2.....	.39	.34	.09	.10	.08		.11	.03
3.....	.07	.32	.31	.21	.09		.23	1.01
4.....	.01	.09	.03	.34	.11	.42	.83	1.29
5.....	.30	.46	.18	.05	.01		.07	.01
6.....	.26	.47	.19	.06	.02		.08	+
7.....	.38	.34	.09	.11	.08		.12	0
8.....	.63	.26	.05	.05	.01		.02	.01
9.....	.32	.34	.11	.13	.10		.14	.75
10....	.23	.47	.21	.07	.02		.09	.03
11....	.96	.04					.00	+
12....	.74	.19	.04	.03			.01	.14
13....	.02	.22	.22	.30	.23	.01	.40	.38
14....	.48	.32	.08	.07	.05		.07	+
15....	.71	.21	.04	.04			.01	.03
16....	.95	.04	.01				0	0
17....	.96	.04					0	.04
18....	.03	.25	.26	.28	.18		.34	.27
19....	.56	.34	.08	.02			.03	.01
20....	.93	.06	.01				0	0
21....	.79	.19	.02				0	0
22....	.62	.27	.05	.04	.02		.02	.04
23....	.07	.32	.31	.21	.09		.23	.32
24....	.16	.09	.34	.27	.12		.61	.42
25....	.21	.20	.31	.25	.01		.43	.02
26....	.76	.18	.04	.02			.01	+
27....	.23	.47	.21	.07	.02		.09	.10
28....	.07	.31	.31	.21	.10		.24	.02
29....	.53	.31	.06	.07	.03		.03	.02
30....	.51	.31	.07	.07	.04		.05	.48
31....	.72	.24	.04				.02	.06
1946								
Jan. 1.....	.72	.24	.04				.02	+
2.....	.93	.06	.01				0	.02
3.....	.05	.27	.29	.25	.14		.30	.06
4.....	.34	.34	.11	.12	.09		.14	.05
5.....	.01	.03	.03	.31	.10	.52	.92	.58
6.....	.01	.03	.02	.32	.09	.53	.93	1.01
7.....	.01	.05	.02	.32	.10	.50	.90	2.65
8.....	.02	.31	.17	.22	.28		.35	.15
9.....	0	.28	.18	.21	.33		.41	.03
10....	.56	.29	.06	.06	.03		.02	.17
11....	.01	.14	.06	.35	.20	.24	.70	.96
12....	.49	.32	.07	.08	.04		.06	+
13....	.79	.16	.03	.02			.01	0

Table 12.--Cont.

Date	Probability that the 24-hour amount will be <.01	.01-.09	.10-.24	.25-.74	.75-1.24	≥1.25	Forecast Amount	Observed Amount
Jan. 14....	.82	.14	.03	.01			.01	.10
15....	.02	.22	.22	.30	.23	.01	.40	.07
16....	.23	.47	.21	.07	.02		.09	.22
17....	.72	.24	.02				.02	.01
18....	.95	.04	.01				0	0
19....	.30	.46	.18	.05	.01		.07	.01
20....	.22	.33	.13	.18	.14		.20	.18
21....	.44	.41	.12	.03			.05	.02
22....	.84	.13	.02	.01			.01	.01
23....	.77	.17	.04	.02			.01	.01
24....	.10	.33	.33	.17	.07		.20	.05
25....	.44	.41	.12	.03			.05	.01
26....	.20	.46	.24	.08	.02		.09	.11
27....	.96	.04					0	+
28....	.96	.04					0	.02
29....	.48	.32	.08	.07	.05		.07	.61
30....	.01	.11	.05	.34	.13	.36	.78	.75
31....	.17	.45	.26	.09	.03		.11	.02
Feb. 1.....	.96	.04					0	0
2.....	.94	.05	.01				0	0
3.....	.82	.14	.03	.01			.01	.07
4.....	.03	.25	.26	.28	.18		.34	.34
5.....	.01	.10	.03	.34	.11	.41	.82	.45
6.....	.04	.27	.29	.26	.14		.31	.29
7.....	.84	.13	.02	.01			.01	0
8.....	.32	.34	.11	.13	.10		.14	.52
9.....	.01	.11	.05	.34	.13	.36	.78	1.38
10....	.02	.22	.23	.30	.22	.01	.39	.35
11....	.95	.04	.01				0	+
12....	.51	.31	.07	.07	.04		.05	0
13....	.01	.07	.02	.33	.10	.47	.87	.38
14....	.63	.26	.05	.05	.01		.02	.02
15....	.96	.04					0	0
16....	.65	.25	.05	.04	.01		.01	0
17....	.48	.32	.08	.07	.05		.07	0
18....	.44	.41	.12	.03			.05	.23
19....	.01	.06	.02	.32	.10	.49	.89	.22
20....	.96	.04					0	0
21....	.95	.04	.01				0	0
22....	.48	.32	.08	.07	.05		.07	0
23....	.57	.29	.06	.06	.02		.02	.01
24....	.93	.06	.01				.02	.01
25....	.78	.17	.03	.02			.27	0
26....	.22	.33	.13	.18	.14		.20	.54
27....	.31	.34	.11	.14	.10		.15	.29
28....	.56	.34	.08	.02			.03	0

Table 13.--Verification of experimental forecasts for TVA east-central section -- Winter 1945-46

		Forecast Amount						
		<.01	.01-.09	.10-.24	.25-.74	.75-1.25	≥1.25	Total
Observed Amount	< .01	13	12	1	1			27
	.01-.09	3	17	5	4			29
	.10-.24		7	1	1	1		10
	.25-.74		2	4	6	3		15
	.75-1.24			2	1	2		5
	≥ 1.25					3		3
	Total	16	38	13	13	9		

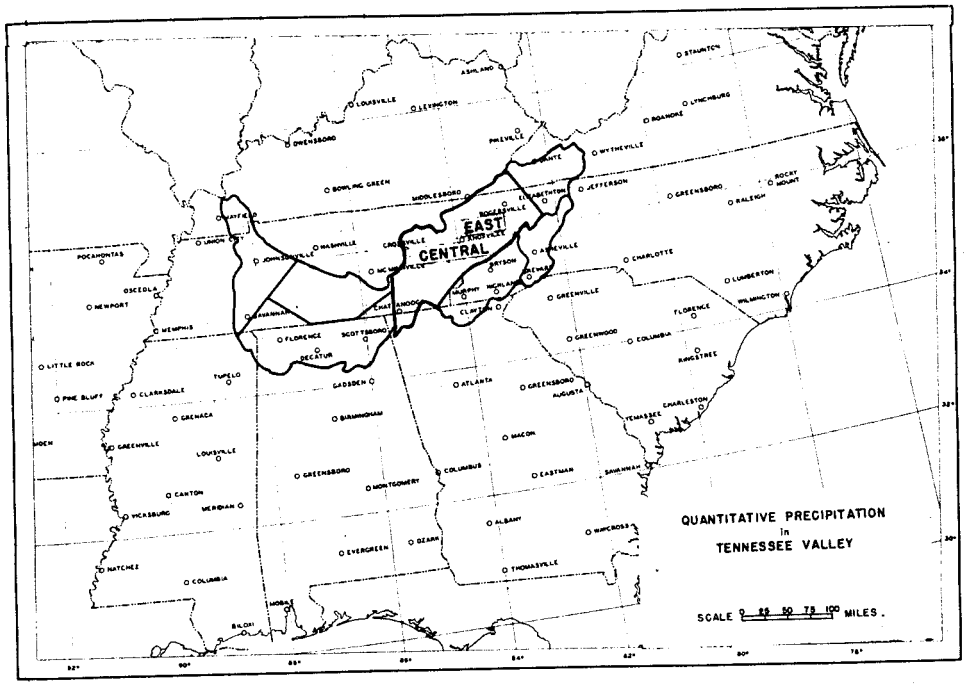


Figure 1

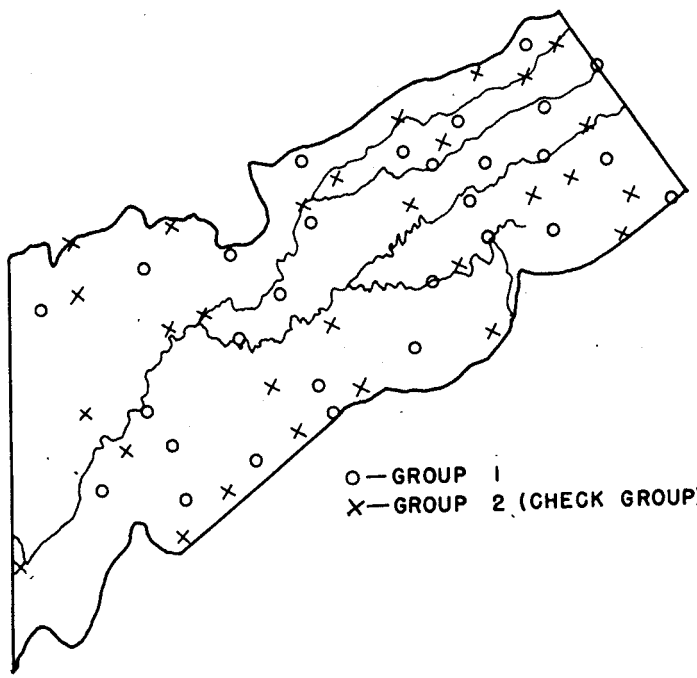
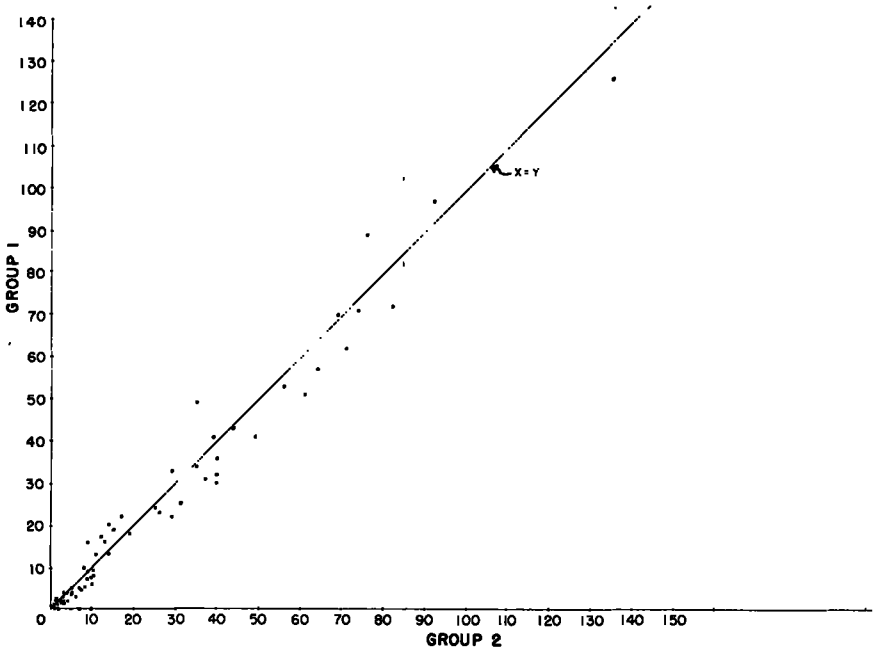


Figure 2



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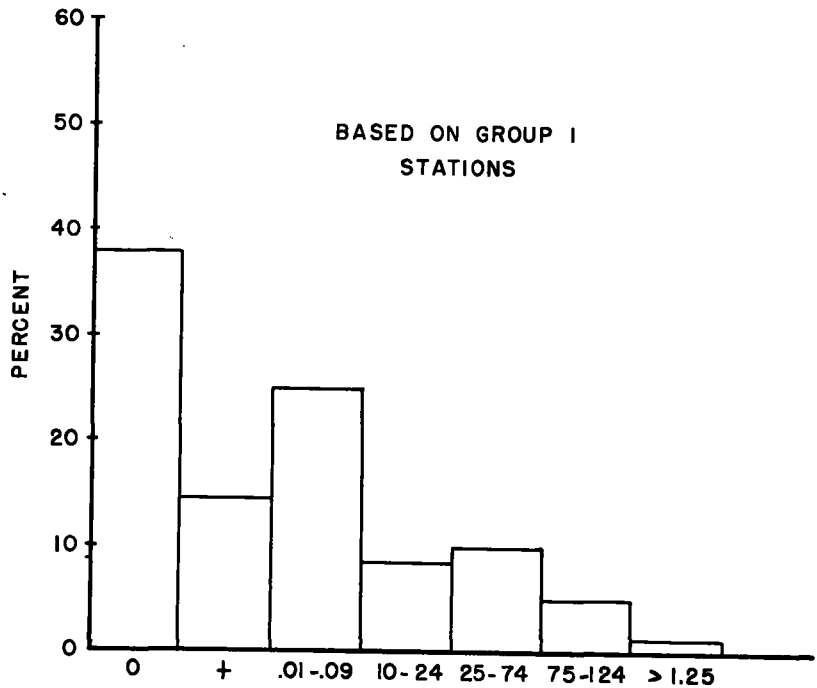

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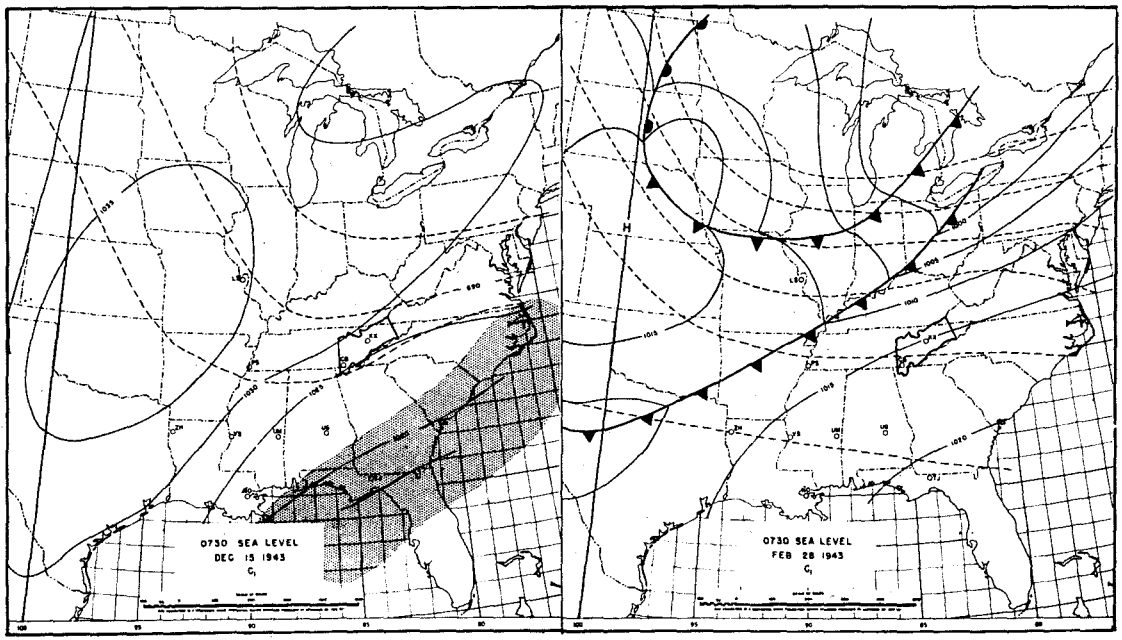

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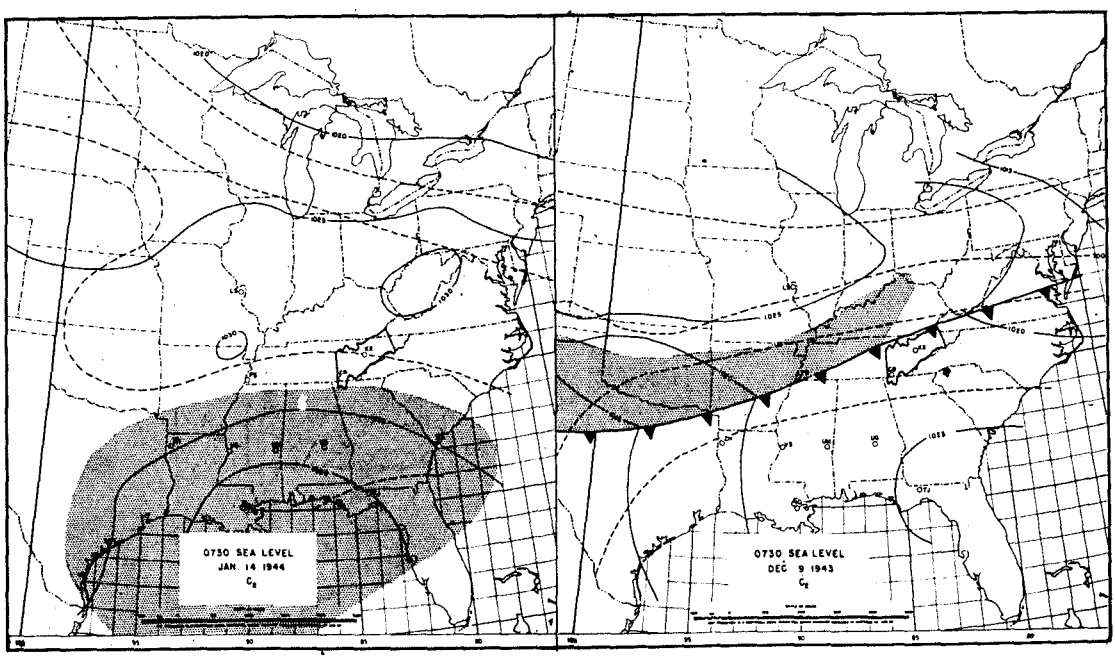

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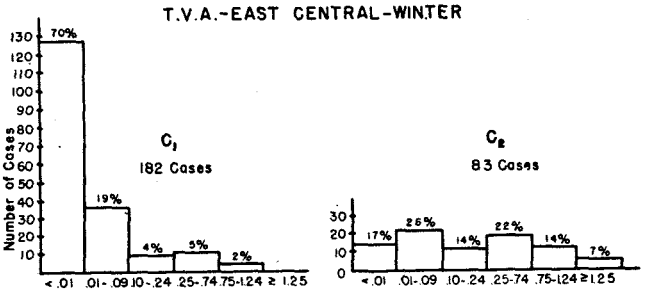

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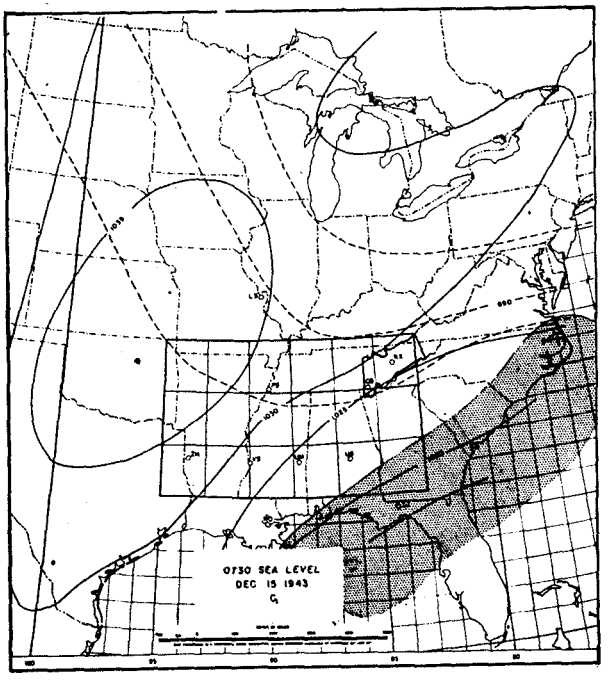

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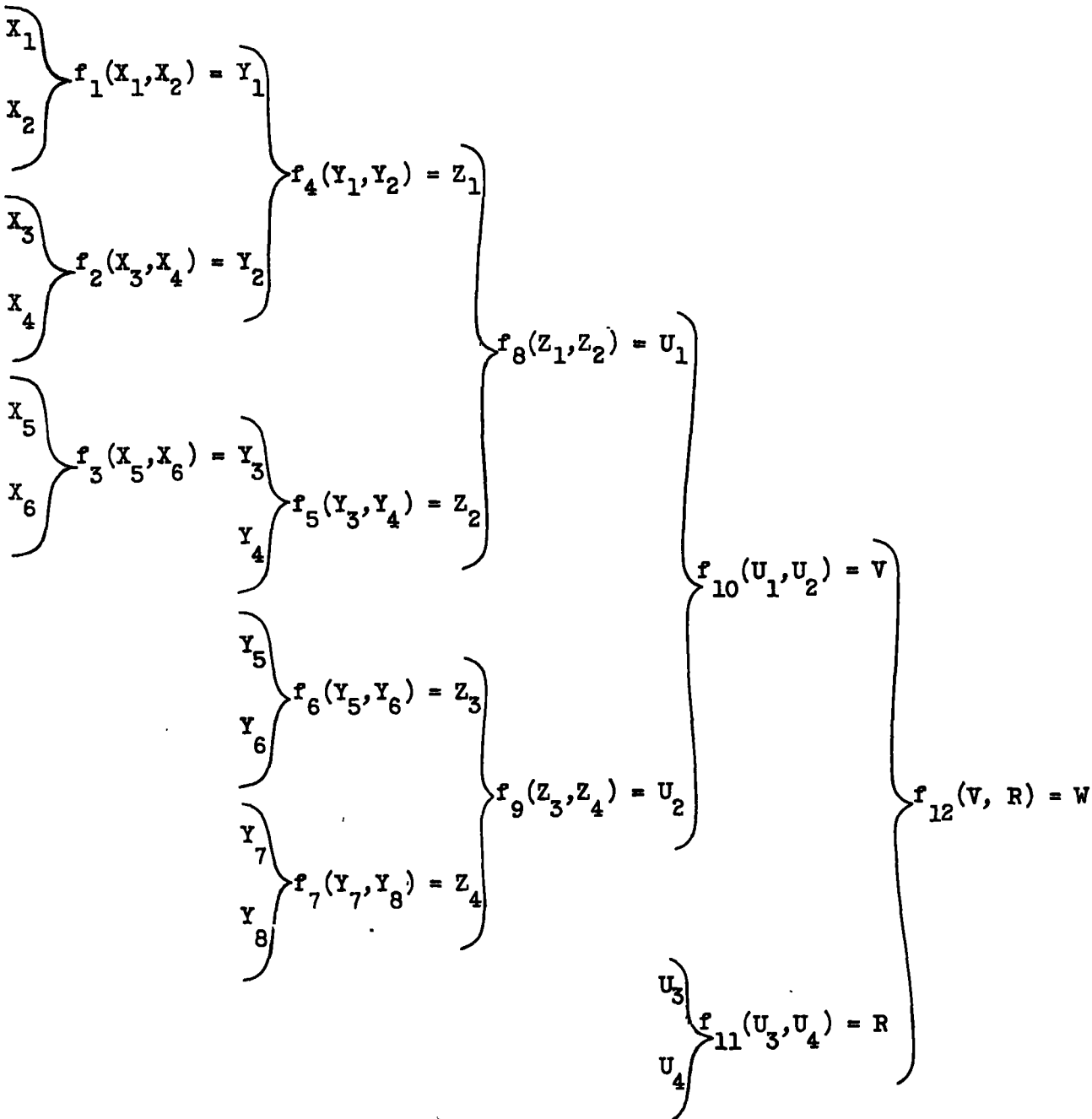

Thus, W is a function of the original variables X_1, X_2, X_3, X_4, X_5, X_6, Y_4, Y_5, Y_6, Y_7, Y_8, U_3 and U_4.

Figure 9.--Chart showing outline of method used to combine the 13 independent variables into one parameter, W.

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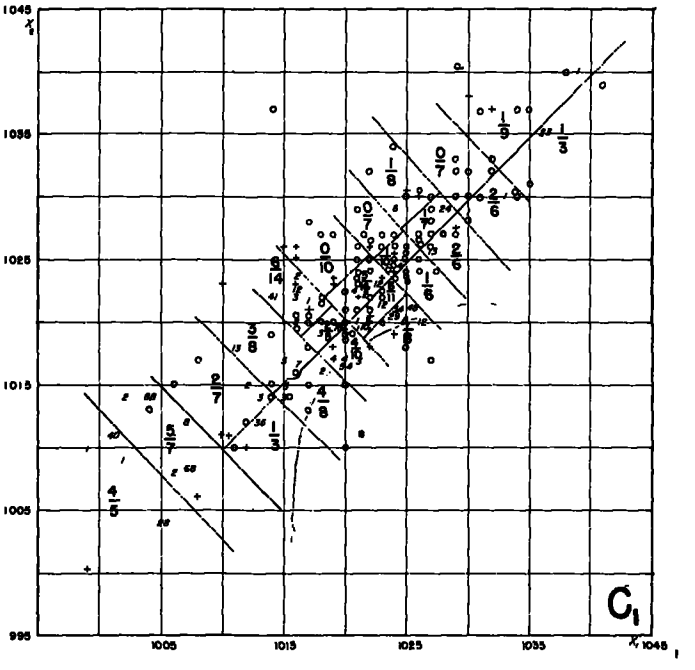

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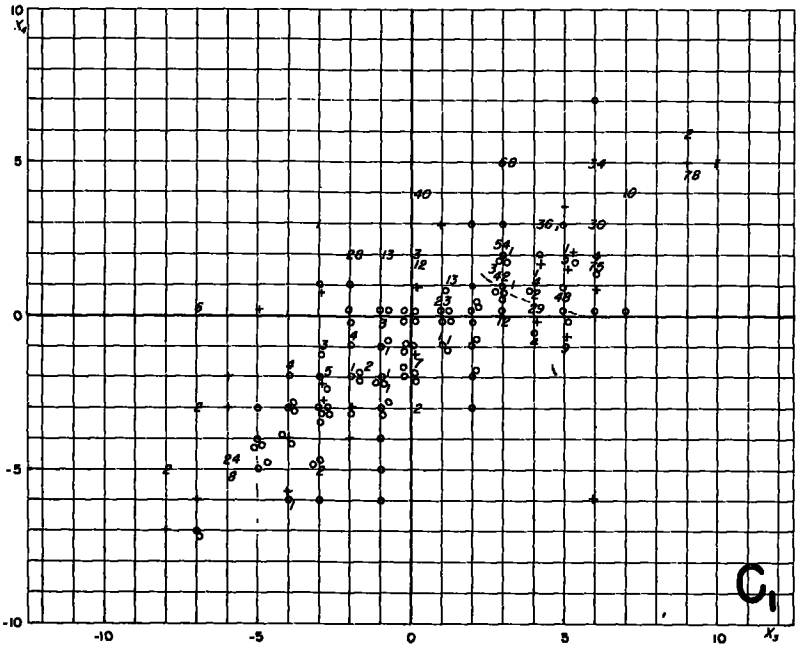

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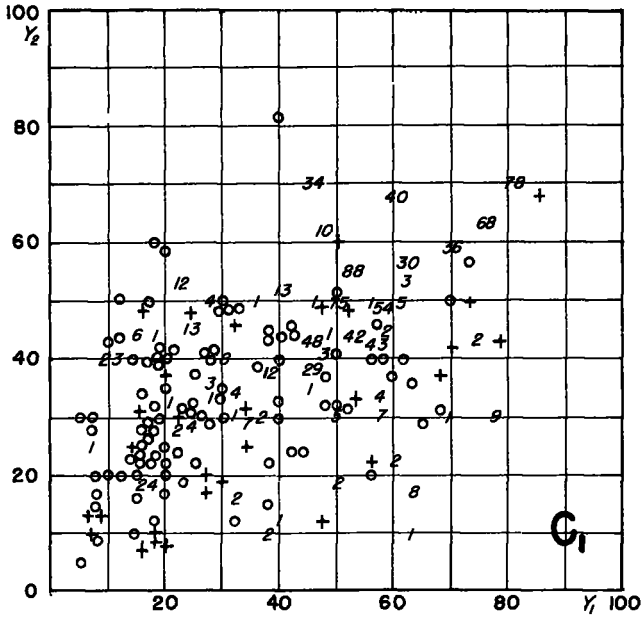

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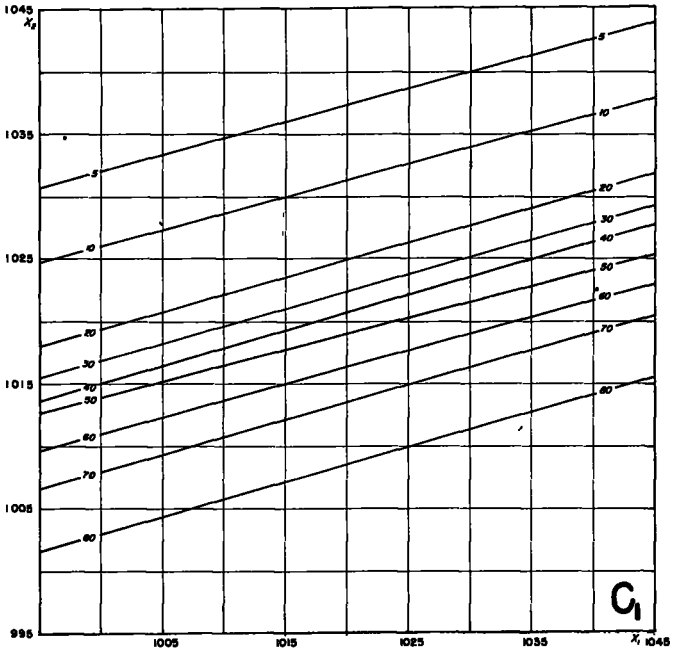

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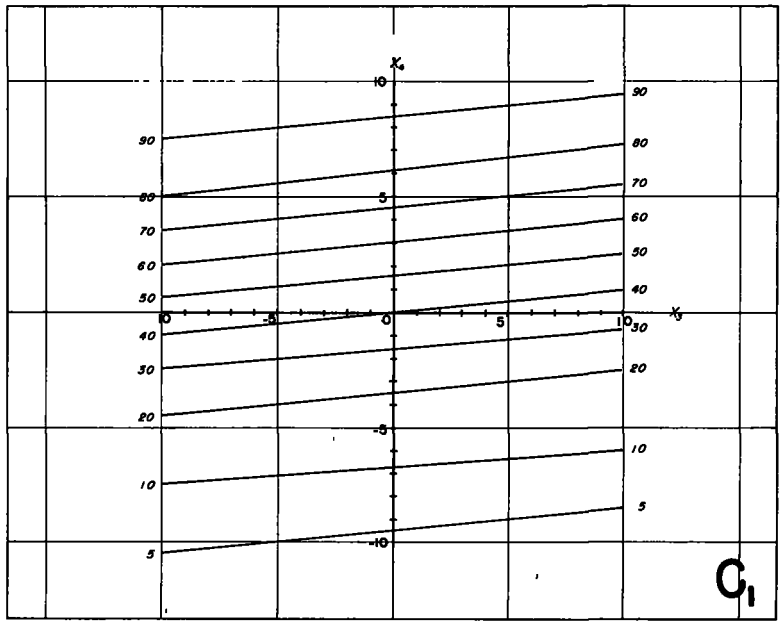

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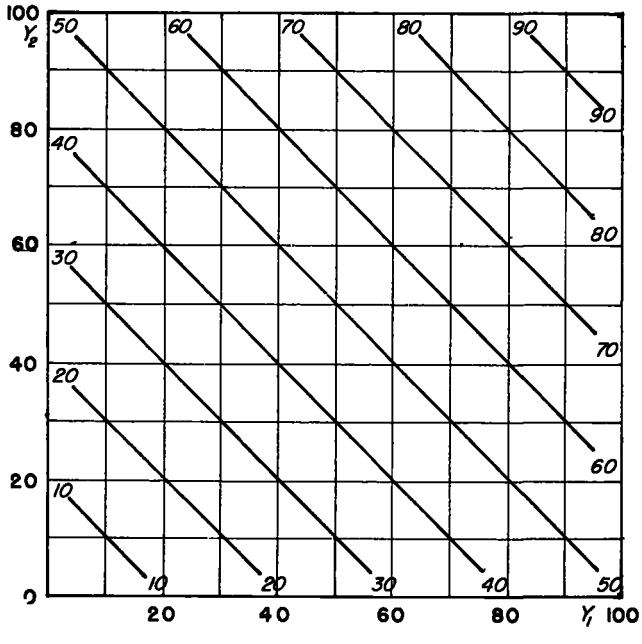

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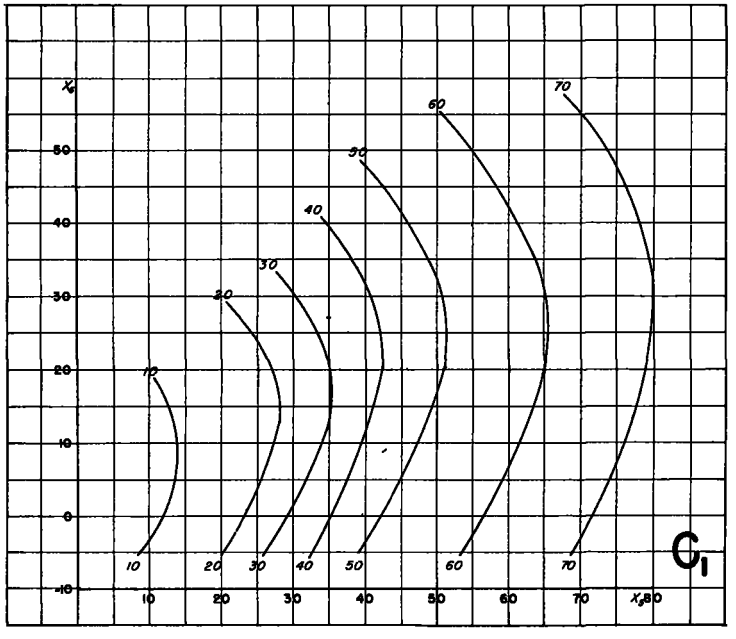

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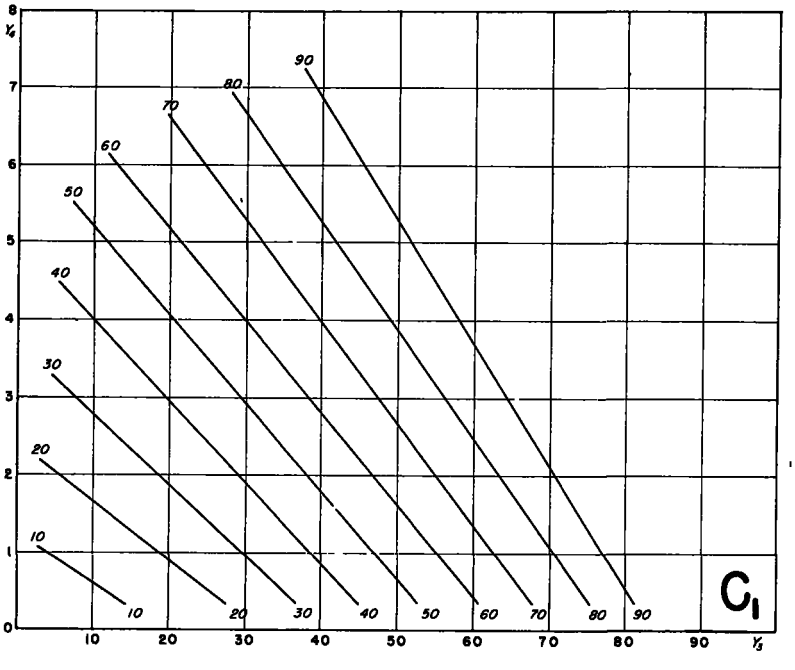

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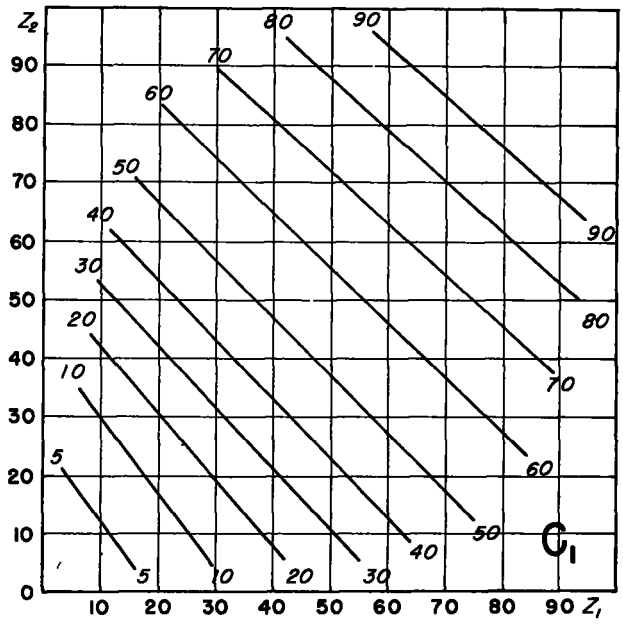

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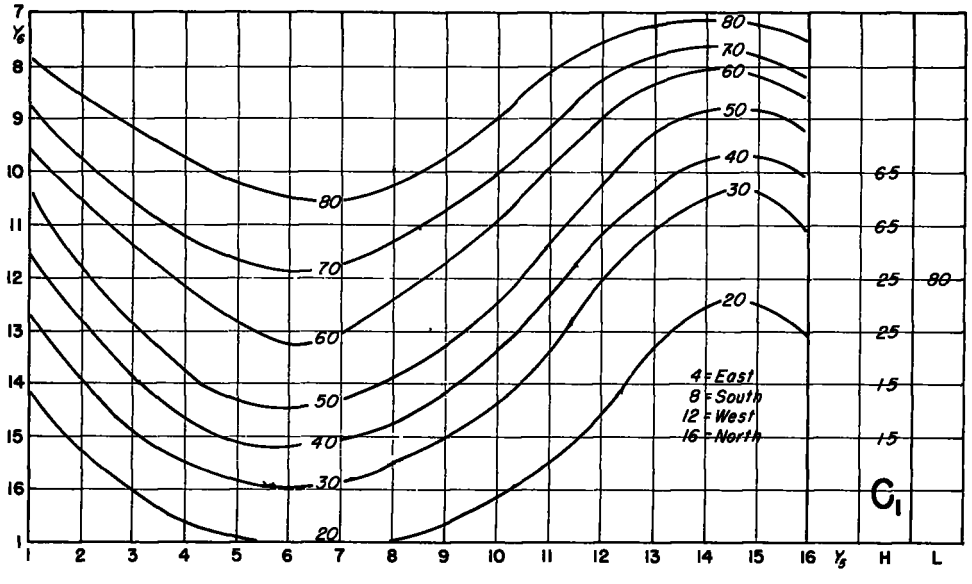

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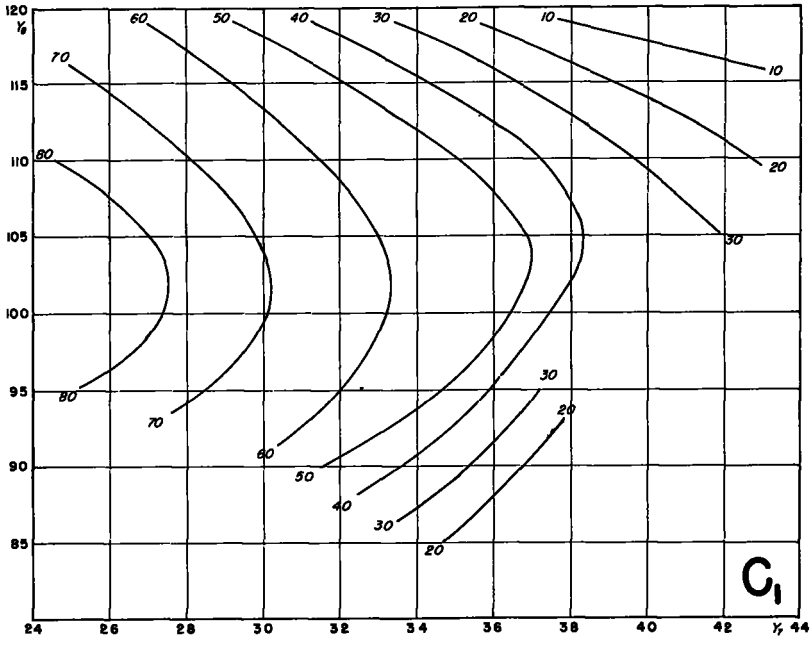

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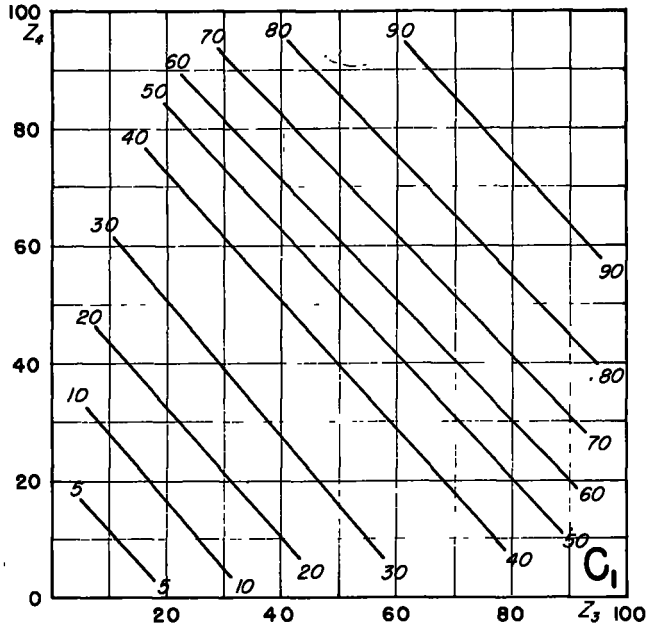

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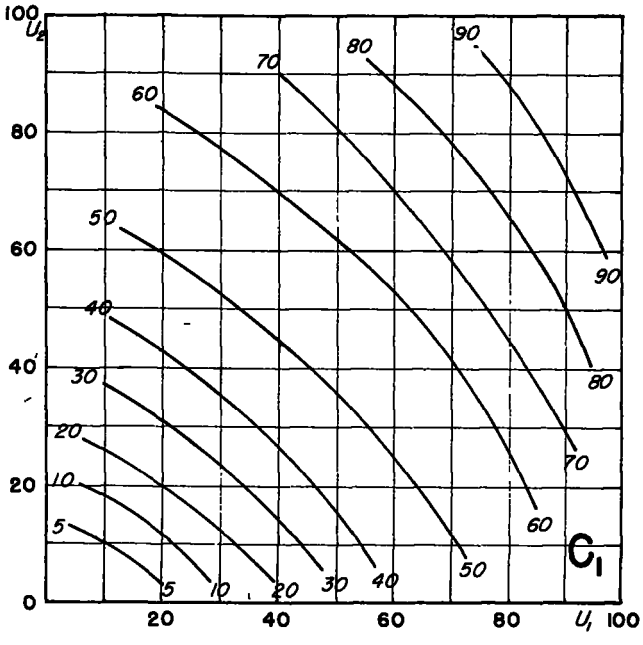

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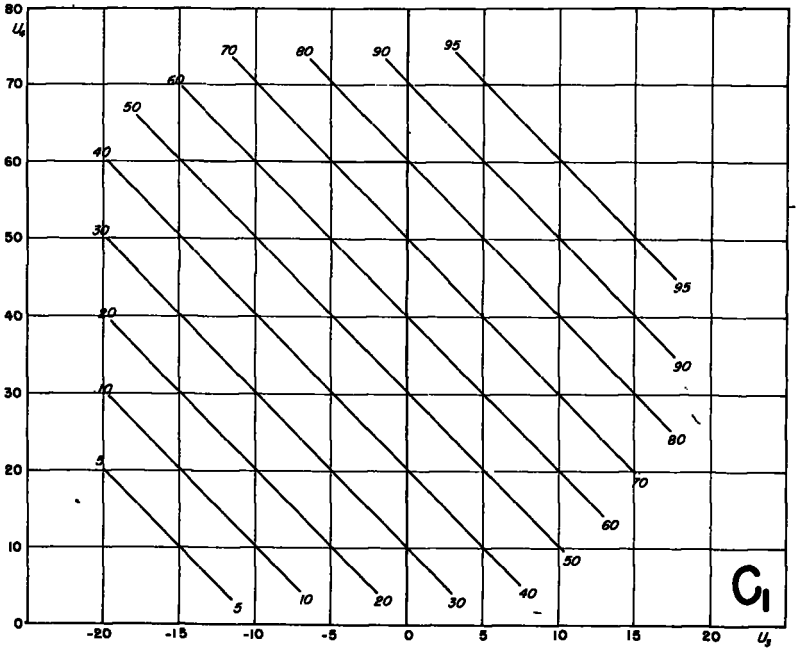

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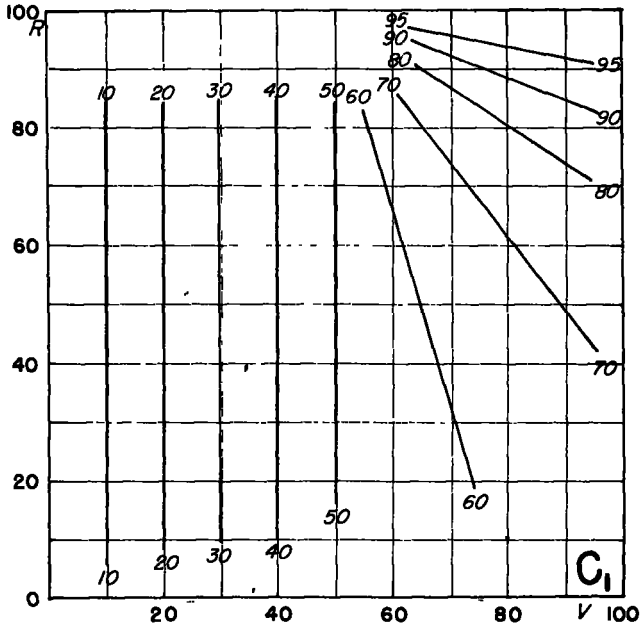

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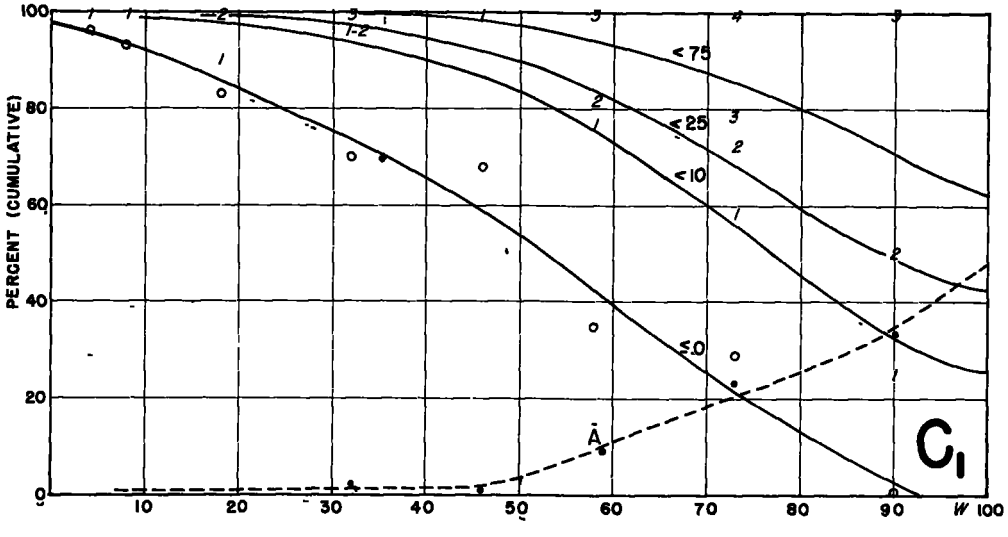

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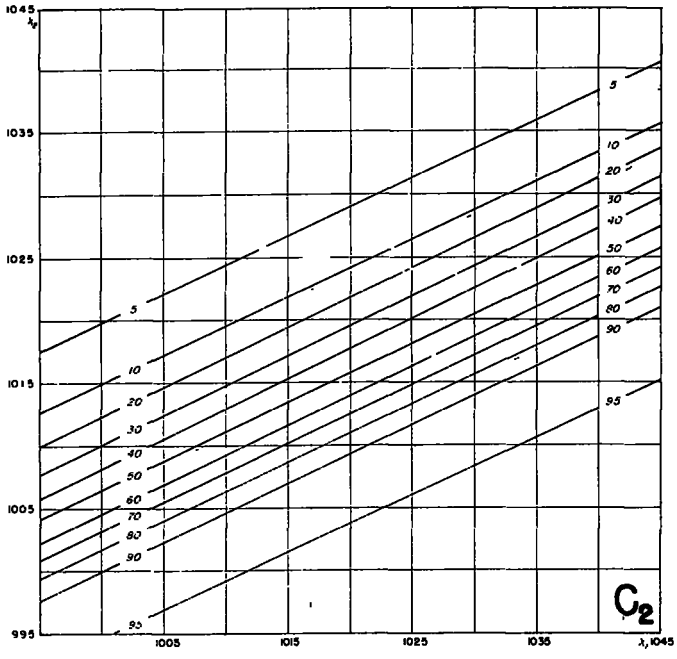

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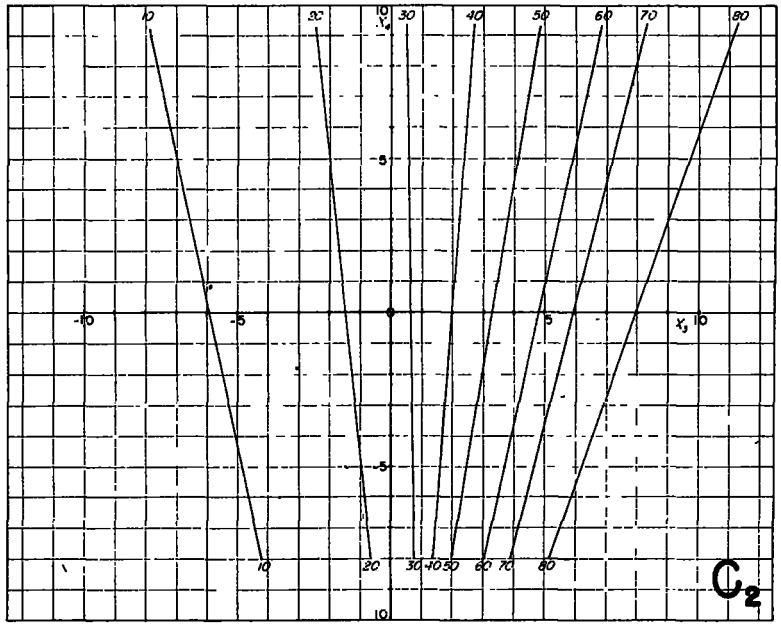

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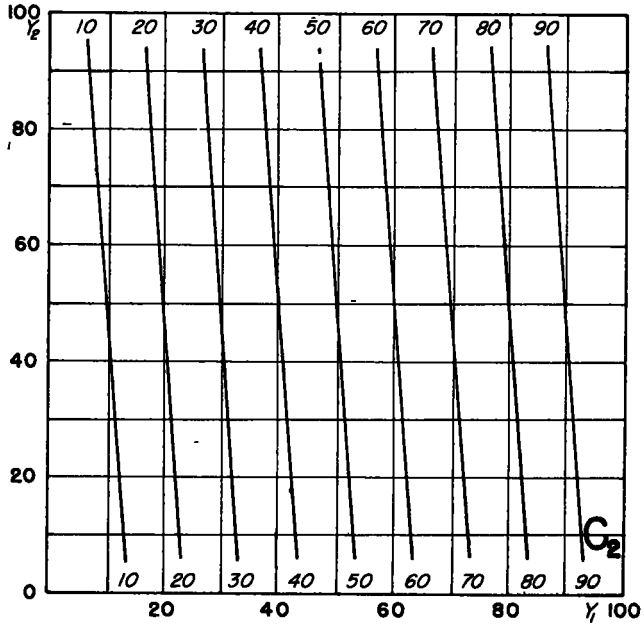

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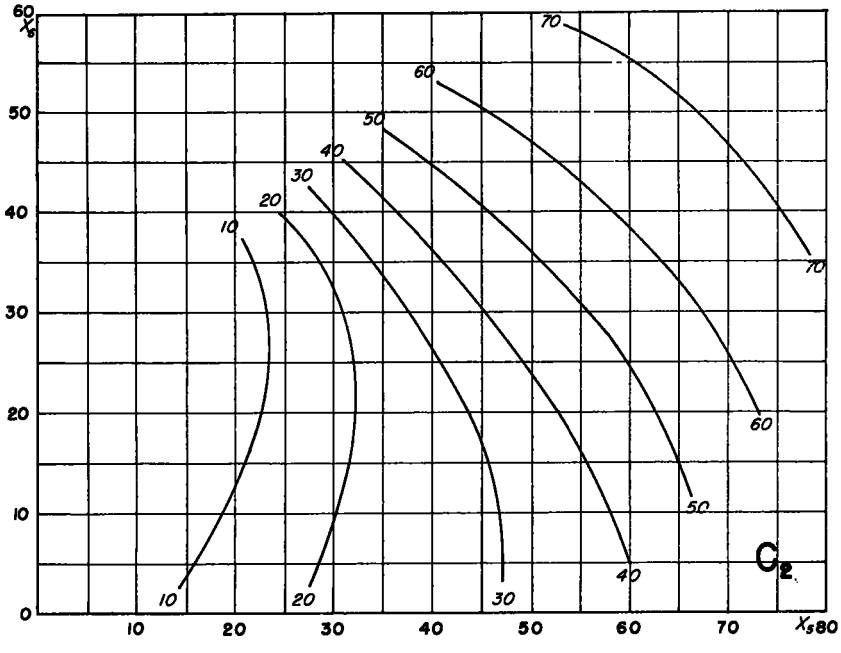

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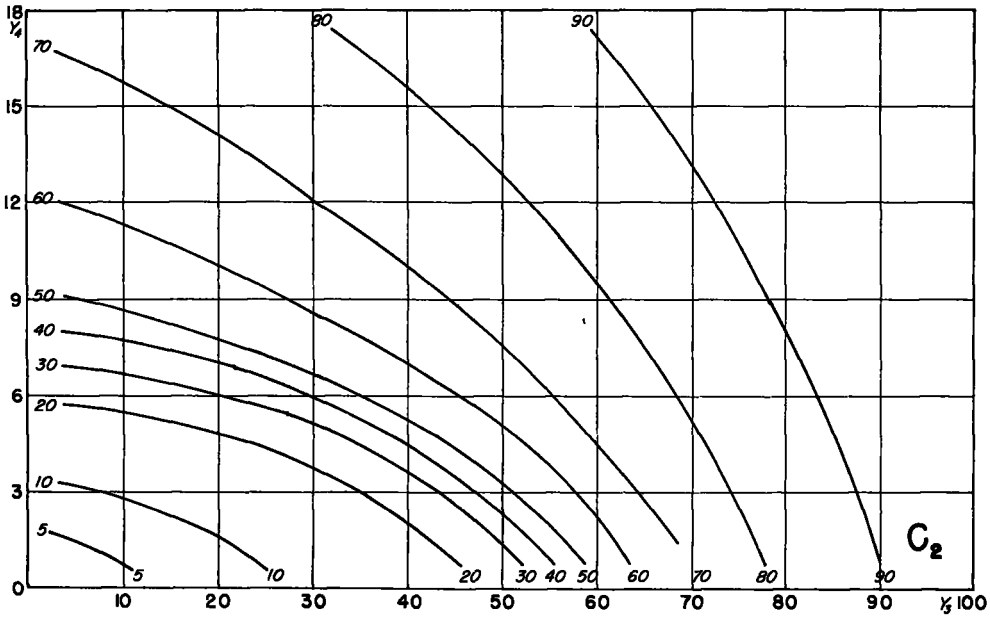

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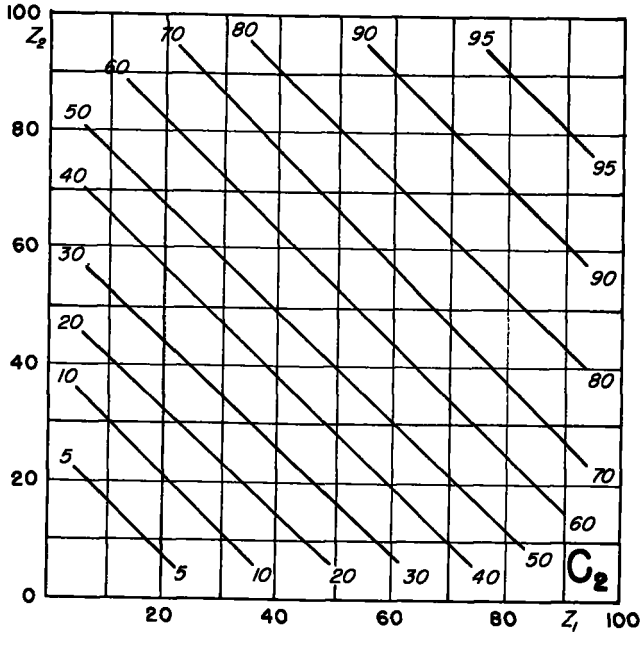

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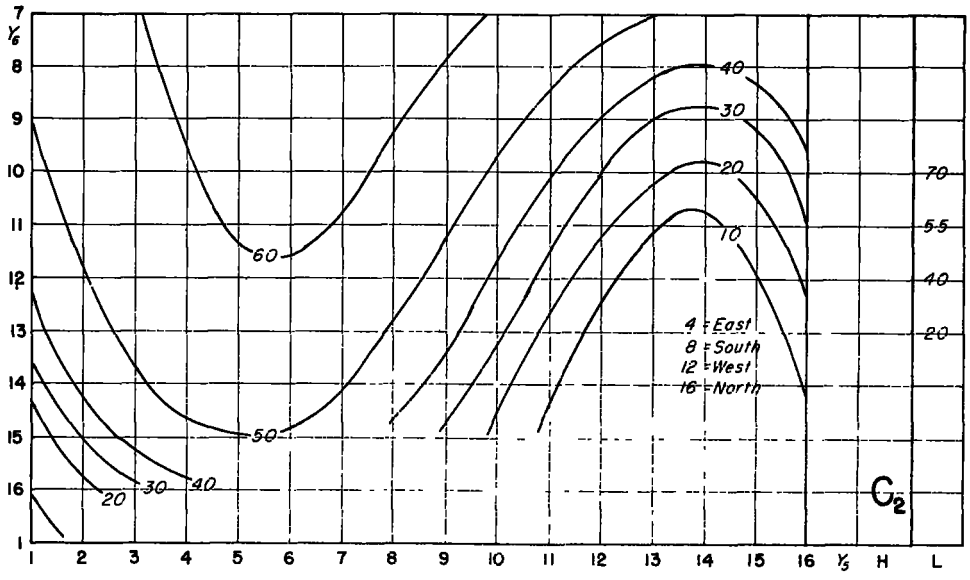

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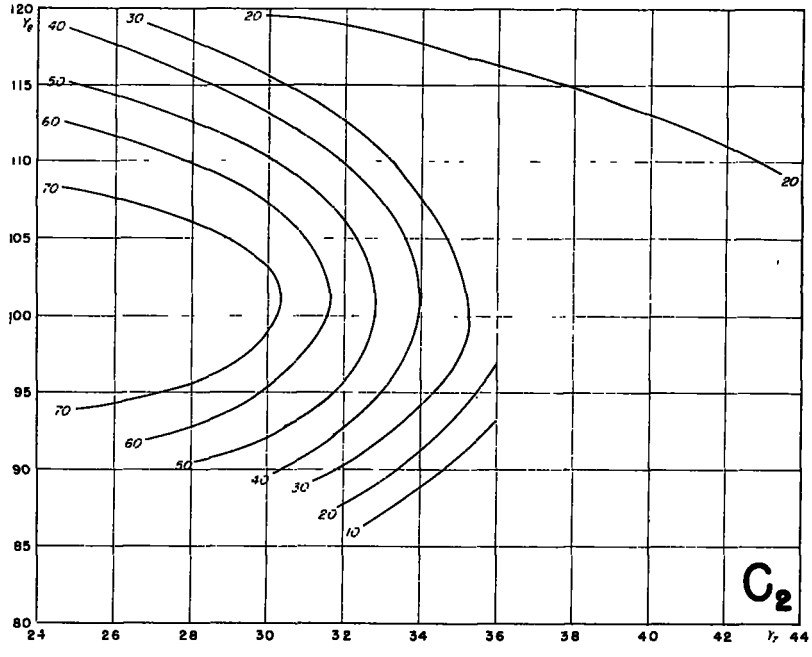

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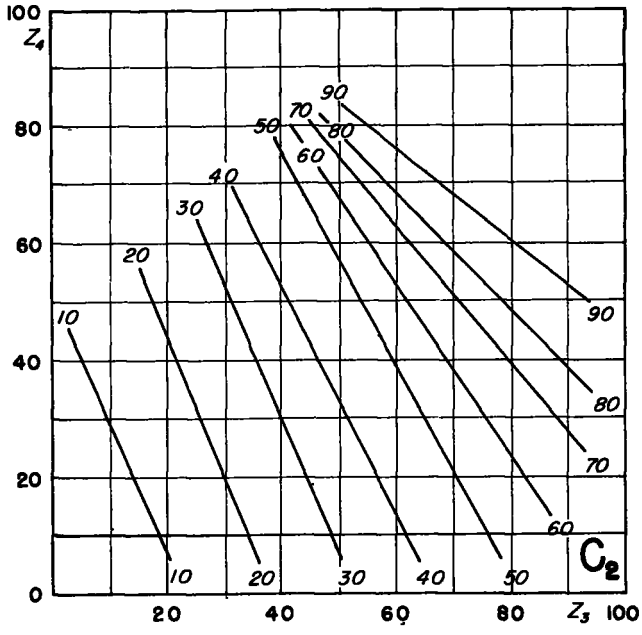

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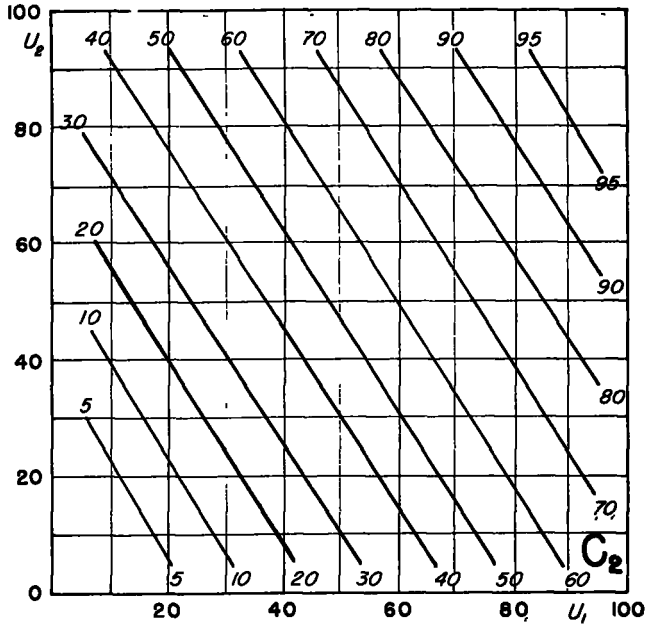

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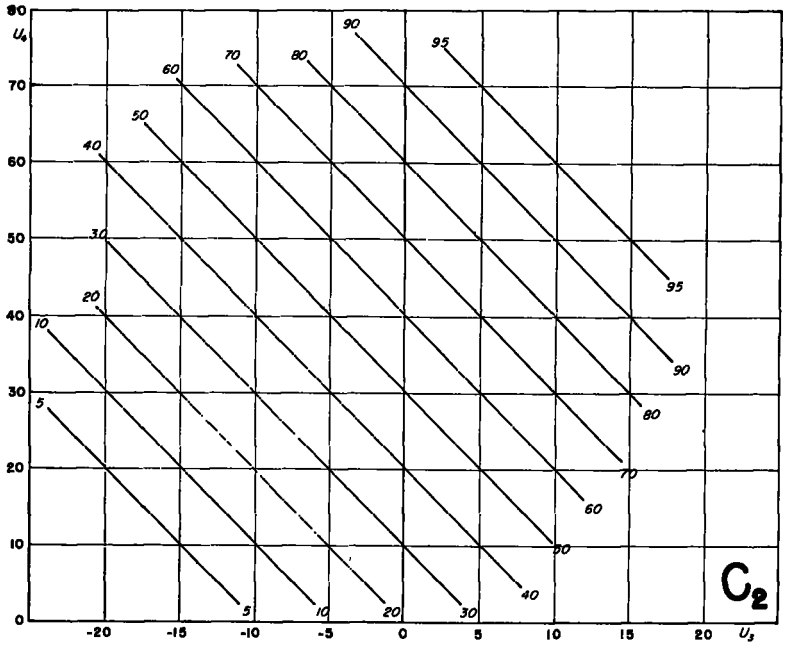

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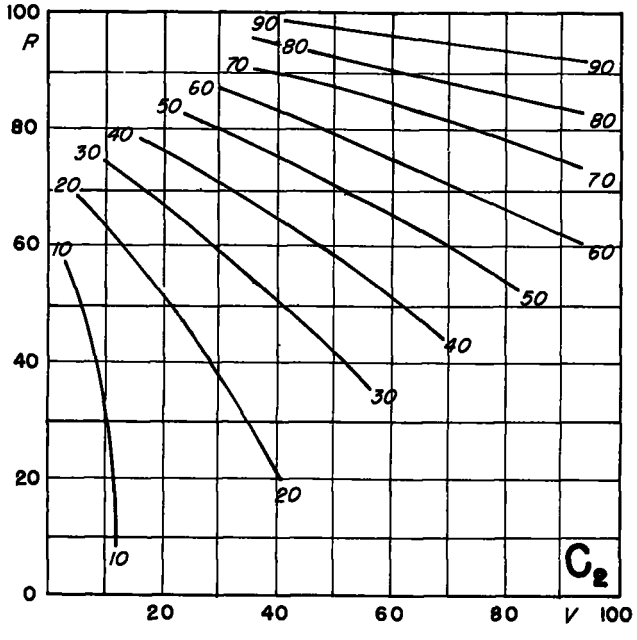

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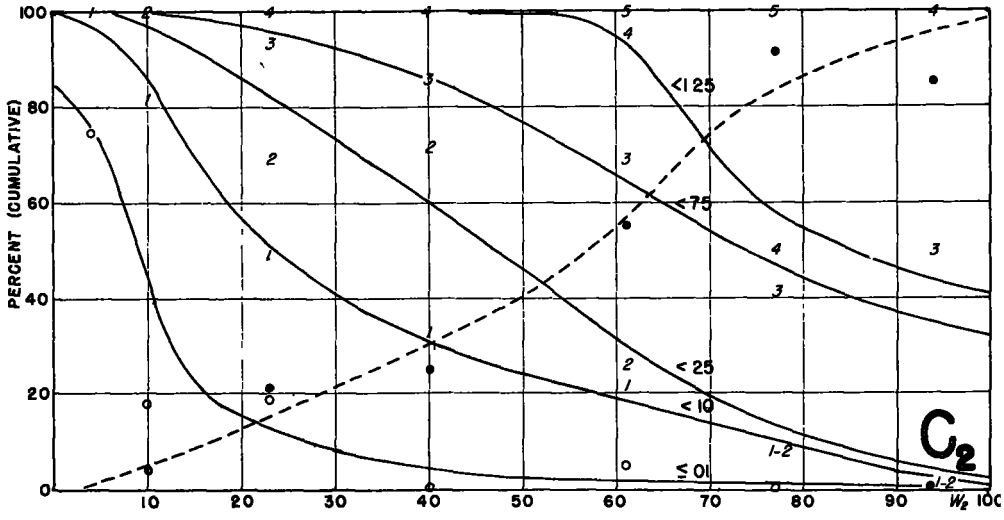

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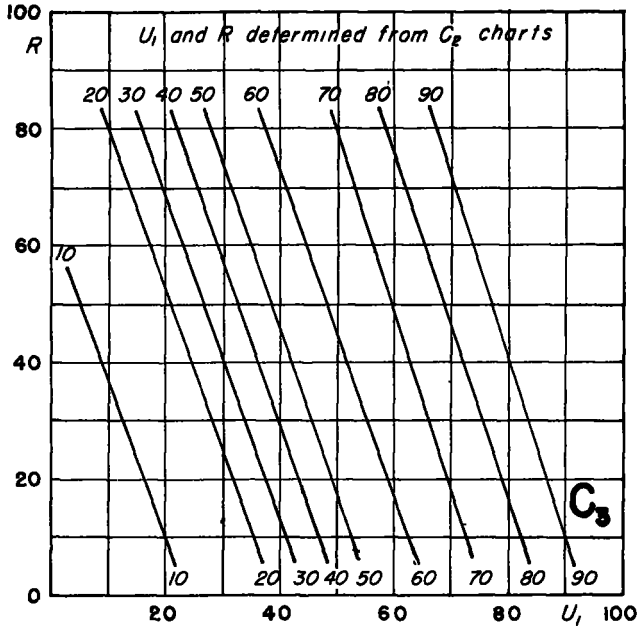

Figure 39