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STATISTICAL ANALYSIS OF RAINFALL AND RUNOFF

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WRP

SYNTHETIC REGIONAL RAINFALL TIME DISTRIBUTIONS

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ABSTRACT

The design of hydraulic structures requires estimates of peak runoff rate and/or runoff volumes. To obtain estimates for small drainage areas, where streamgage data are generally not available, mathematical rainfall-runoff models requiring a distribution of rainfall are sometimes used. The Soil Conservation Service Type II (SCS II) distribution is a rainfall distribution widely used throughout most of the United States. While the SCS II provides an average design storm over a large area of the United States, it is unresponsive to regional differences. A set of four rainfall distributions is proposed to replace the SCS II in the 37 eastern and central states. The proposed set of distributions considers variation due to rainfall return period as well as variation due to regional differences.

INTRODUCTION

Criteria for design and evaluation of hydraulic structures require peak runoff rate and/or runoff volume that the structure will safely accommodate. Estimates of such runoff values can be made from analysis of streamgage records if such records are available. Because streamgage records for small drainage areas are generally not available, mathematical rainfall-runoff models are frequently used to obtain the required estimates. The distribution of rainfall intensities is one of the primary inputs to such a model. Rainfall intensities can be obtained from nearby raingages for a specific event, or data can be statistically analyzed to develop a synthetic event or distribution. If such an analysis is done over a large area, a regional synthetic rainfall distribution can be established.

A widely used 24-hour rainfall distribution is the Soil Conservation Service Type II (SCS II). The distribution represents high-intensity rainfall rates that are generally associated with convective storms over small drainage areas. The Soil Conservation Service (1969, 1973) uses the SCS II as a design storm distribution throughout the United States except parts of the states bordering the Pacific Ocean. The distribution was developed from rainfall frequency data for areas less than 400 square miles (1,076 km^2) (SCS 1973). The basic procedure is given next so the reader may better understand what is presented later in the paper. Generalized rainfall intensity-duration data for a selected return period were used for durations from 30 minutes to 24 hours. The data were broken down into 30-minute incremental values and the increments

It is more important to maintain the consistency of short-duration rainfall ratios than that of longer durations, because short-duration intense rainfall rates are more critical to estimating peak runoff than are the longer-duration, less intense rainfall rates. The 5- and 15-minute durations were selected as key durations to delineate differences in rainfall ratio patterns. Limits were assigned for each key ratio to divide the study area into four groups (labeled A through D). Four sets of groups were defined, one set for each of the two key ratios at each of the two return periods. The rainfall ratio breakpoints used to define the A through D groups are 0.09, 0.12, and 0.15 for the 5-minute key duration and 0.20, 0.25, and 0.30 for the 15-minute key duration. The geographical extent of each group is illustrated by the maps in appendix I.

The appendix I maps show that for a selected key duration some places have the same lettered group at both the 2- and 100-year return periods. Many places have a change of one lettered group and a few change two lettered groups between the two return periods. States in which two lettered group changes can be found include: coastal states from Virginia to Florida (Group C to A), Texas and Oklahoma (Group C to A and Group D to B) for the 5-minute key duration; and coastal states from South Carolina to Mississippi, Texas (Group C to A) and Oklahoma (Group C to A and Group D to B) for the 15-minute key duration. Generalization of rainfall data by key duration instead of solely by location help to reduce variation.

While selection of groups by keying on one duration maintains rainfall ratio consistency for that duration, the consistency of the rainfall ratios for the other durations is not necessarily maintained. To examine the consistency for all seven durations and to define a representative rainfall ratio for each duration in a group, the median rainfall ratios for each duration within a group were computed (table 2). The table shows general consistency of median rainfall ratios for the two key durations at both the 2-year and 100-year return period. There is also not much difference in median rainfall ratios between the two

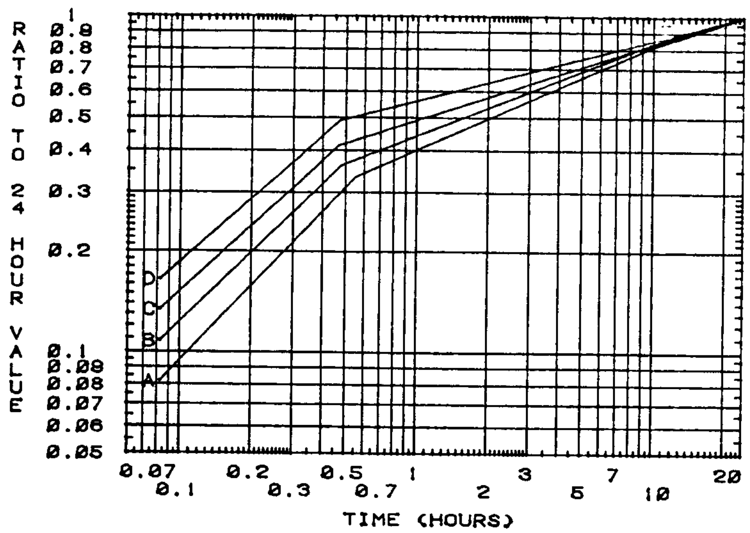

FIGURE 1 - GENERALIZED RATIOS FOR GROUPS

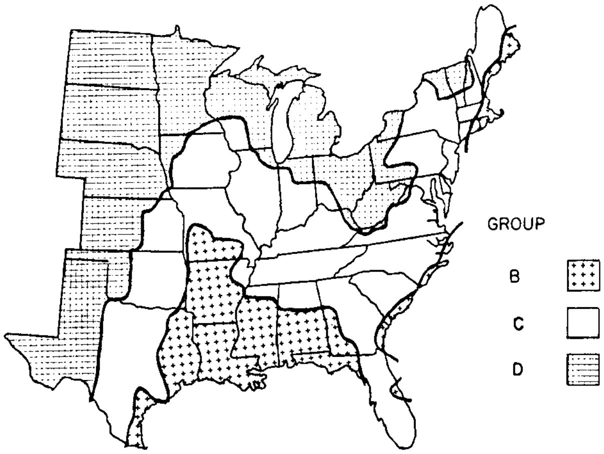

Figure I-1. Five-minute key duration groups for 2-year return period

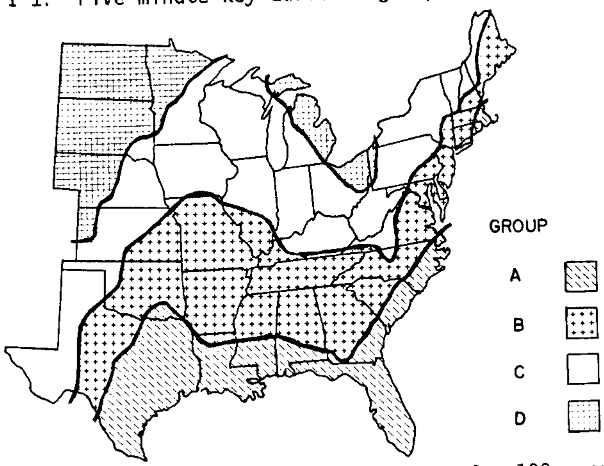

Figure I-2. Five-minute key duration groups for 100-year return period

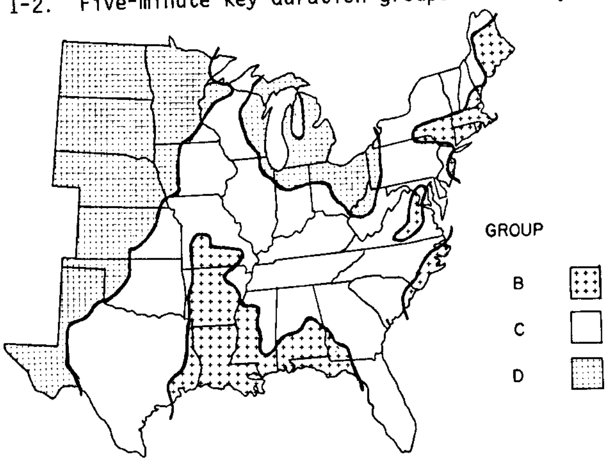

Figure I-3. Fifteen-minute key duration groups for 2-year return period

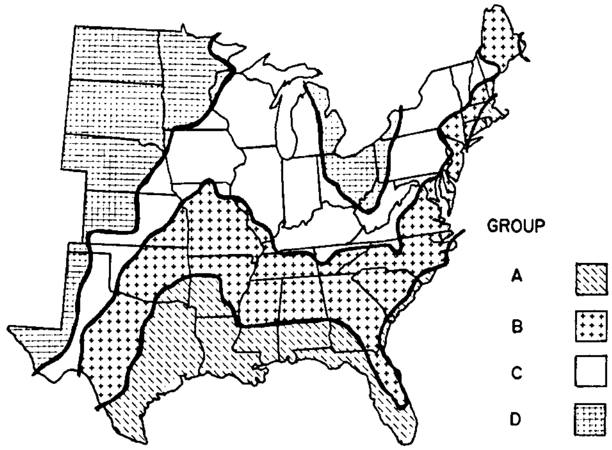

Figure I-4. Fifteen-minute key duration groups for 100-year return period

return periods. While the geographic extent of each group varies depending on whether 5 or 15 minutes is used as the key duration, the median rainfall ratios for all durations in each group will be about the same.

Weighted median rainfall ratios were developed for each of the seven durations in each group. This was done using median rainfall ratios (table 2) and weighting by the number of grid points each ratio represented. Ratios were included for both return periods and the 5- and 15-minute key durations. Equations were developed for each group to provide direct solution of rainfall ratios at durations other than those of the basic data. The equations were of the following form:

$$\text{Ratio} = C\,(D)^{x}$$

where Ratio is the ratio of the D duration rainfall to the 24-hour rainfall; D is the duration in hours, and C and x are fitting parameters.

Visual inspection indicated three equations would fit the seven durations in each of groups A, B and C, while only two were necessary to fit the durations in group D. Table 3 contains the equations for each group along with the applicable range of durations. Figure 1 illustrates the solution of the equations. Table 4 shows the values computed for rainfall ratios at each of the seven durations as well as the weighted median rainfall ratios. Most of the weighted median rainfall ratios are closely approximated by the equations. Exceptions include the 2-hour group B ratio and the 2-, 3-, and 12-hour group D ratios.

RAINFALL INTENSITY ORDER

Now that equations define continuous rainfall ratio relationships for each of the four groups, the ratios need to be ordered to form synthetic 24-hour rainfall distributions. For the southeastern states, Frederick (1979) analyzed 6,000 station-years of rainfall data from 277 stations. He found that the most intense hour of an event is likely to occur near the beginning of the event. He recognized that for hydrologic design this may not be critical timing and, therefore, shifting the most intense hour to a point later in the event may not be unrealistic.

Table 2. Median rainfall ratios for each group in the four sets of groups

Group	Return period	Key duration	Number grid points	Rainfall ratios for durations of --						
				5 min	15 min	60 min	2 hr	3 hr	6 hr	12 hr
	(years)	(minutes)								
A	2	5	1	0.090	0.186	0.402	0.480	0.500	0.700	0.900
		15	4	0.097	0.187	0.334	0.440	0.512	0.702	0.860
	100	5	71	0.081	0.184	0.403	0.500	0.560	0.697	0.852
		15	79	0.083	0.186	0.403	0.505	0.561	0.699	0.852
B	2	5	96	0.114	0.242	0.441	0.544	0.597	0.721	0.863
		15	84	0.114	0.240	0.433	0.537	0.589	0.718	0.864
	100	5	176	0.105	0.224	0.446	0.551	0.605	0.727	0.867
		15	153	0.105	0.223	0.446	0.550	0.605	0.727	0.867
C	2	5	217	0.133	0.269	0.468	0.567	0.621	0.739	0.876
		15	259	0.134	0.270	0.472	0.568	0.622	0.739	0.876
	100	5	174	0.136	0.283	0.524	0.586	0.638	0.750	0.889
		15	154	0.133	0.277	0.518	0.582	0.635	0.750	0.888
D	2	5	201	0.167	0.324	0.540	0.608	0.654	0.764	0.893
		15	168	0.170	0.334	0.548	0.616	0.662	0.770	0.894
	100	5	94	0.163	0.329	0.604	0.642	0.682	0.778	0.907
		15	129	0.157	0.324	0.600	0.636	0.682	0.778	0.907

Table 3. Generalized rainfall ratio equations for 5- and 15-minute key duration groups

Group	Equations	Range of D (hours)
A	Ratio = .517 $(D)^{.741}$	0.083 to 0.555
	Ratio = .401 $(D)^{.309}$	0.555 to 10.029
	Ratio = .480 $(D)^{.231}$	10.029 to 24
B	Ratio = .597 $(D)^{.688}$	0.083 to 0.482
	Ratio = .442 $(D)^{.276}$	0.482 to 9.791
	Ratio = .515 $(D)^{.209}$	9.791 to 24
C	Ratio = .676 $(D)^{.651}$	0.083 to 0.471
	Ratio = .492 $(D)^{.229}$	0.471 to 16.046
	Ratio = .559 $(D)^{.183}$	16.046 to 24
D	Ratio = .780 $(D)^{.625}$	0.083 to 0.475
	Ratio = .561 $(D)^{.182}$	0.475 to 24

Table 4. Comparison of the weighted median and equation values at the basic data durations

	Rainfall ratios for durations of --						
Kind of value	5 min	15 min	60 min	2 hr	3 hr	6 hr	12 hr
Group A							
Weighted Median	0.082	0.185	0.401	0.501	0.559	0.698	0.852
Equation	0.082	0.185	0.401	0.497	0.563	0.698	0.852
Difference	0.000	0.000	0.000	-0.004	+0.004	0.000	0.000
Group B							
Weighted Median	0.108	0.230	0.443	0.547	0.601	0.724	0.866
Equation	0.108	0.230	0.442	0.535	0.599	0.725	0.866
Difference	0.000	0.000	-0.001	-0.012	-0.002	+0.001	0.000
Group C							
Weighted Median	0.134	0.274	0.491	0.574	0.628	0.743	0.881
Equation	0.134	0.274	0.492	0.577	0.633	0.742	0.881
Difference	0.000	0.000	+0.001	+0.003	+0.005	-0.001	0.000
Group D							
Weighted Median	0.165	0.328	0.566	0.622	0.667	0.771	0.899
Equation	0.165	0.328	0.561	0.636	0.685	0.777	0.882
Difference	0.000	0.000	-0.005	+0.014	+0.018	+0.006	-0.017

Placing the most intense rain after runoff begins will produce higher peak discharges than if it occurs before runoff begins. Since the purpose of the distributions is to encompass a wide range of return periods and runoff volumes, placing the most intense portion further from the beginning of the distribution is necessary to ensure that the most intense rainfall period will occur after runoff begins for all anticipated applications. The center of the distribution is a convenient point sufficiently far away from the beginning of the distribution to ensure runoff has begun.

The SCS II uses the center (hour 12) point as a starting point for its distribution. While the same starting point as the SCS II is used, the proposed distributions are ordered differently. There are two drawbacks to the SCS II data ordering. First, the SCS II is "built" using 30-minute incremental intensities. If another increment is used, for example, 10-minutes, a different rainfall distribution would be generated. Second, interpolation of some kind within each 30-minute increment is required to convert the distribution to shorter time increments. No interpolation procedure has been published for the distribution, and use of graphical or mathematical interpolation procedures can produce different interpolated values. To overcome these problems, a symmetric distribution pattern is recommended. These patterns can be developed for any time increment (5 minutes or greater) from the equations in table 3. They will also be consistent no matter what increment is used. The generated distributions for the four groups are shown in figure 2.

EFFECT ON RUNOFF

Now that the rainfall distributions have been generated, is there enough difference in peak runoff rates from these to warrant four groupings? To evaluate the distributions, peak runoff rates for the same conditions were computed for each distribution using the RNOFFX subroutine of the SCS TR-20 computer program (SCS 1965). An SCS II interpolated to 0.1 hour increments was included also. For consistency with the SCS II, the rainfall distributions for each group were also defined at 0.1 hour increments.

A typical situation of runoff curve number 75 (SCS 1969, 1972, 1973, 1975); 24-hour rainfall of 5.67 inches (144 mm); and 1-mi^2 (2.6-km^2)

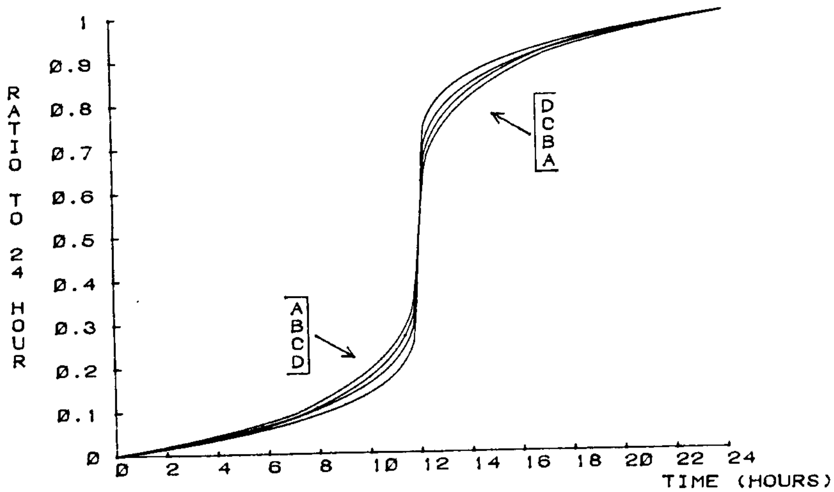

FIGURE 2 - RAINFALL DISTRIBUTION CURVES

drainage area were used to produce a runoff volume of 3.0 inches (76 mm). Runoff hydrographs were generated for thirteen values of time of concentration (T_c) between 0.1 and 10 hours. Peak discharges were

selected from the runoff hydrograph in cubic feet per second. The peaks were converted to cubic meters per second and displayed in table 5. The maximum percentage of differences among the four groups and the deviations of the groups from the SCS II are also in the table.

Table 5. Comparative peak runoff rates from different rainfall distributions

T_c	Group A	Group B	Group C	Group D	Maximum Difference	SCS II	Deviation from SCS II
(hours)	(m^3/s)	(m^3/s)	(m^3/s)	(m^3/s)	(percent)	(m^3/s)	(percent)
0.10	52.0	65.4	78.9	95.0	83	83.0	-37 to +14
0.25	44.8	54.7	64.7	76.7	71	61.8	-28 to +24
0.50	35.4	41.0	47.1	54.8	55	43.3	-18 to +27
1.00	24.5	27.2	30.3	34.3	40	27.3	-10 to +26
2.00	15.3	16.5	17.8	19.5	27	16.4	- 7 to +19
3.00	11.5	12.3	13.0	14.1	23	11.9	- 3 to +18
4.00	9.25	9.75	10.2	11.0	19	9.74	- 5 to +13
5.00	7.88	8.22	8.51	8.98	14	7.91	0 to +14
6.00	6.79	7.02	7.21	7.60	12	6.96	- 2 to + 9
7.00	6.14	6.35	6.48	6.75	10	6.06	+ 1 to +11
8.00	5.46	5.61	5.67	5.89	8	5.48	0 to + 7
9.00	5.00	5.11	5.15	5.30	6	4.98	0 to + 6
10.00	4.67	4.78	4.83	4.96	6	4.55	+ 3 to + 9

KEY DURATION SELECTION

The generalized equations developed are applicable to both the 5- and 15-minute key durations, but only one key duration can be used if the proposed rainfall distributions are to be consistently applied. The areal extent of the same lettered group (A, B, C, or D) defined by the two key durations is different. (See appendix I maps.) To evaluate which key duration produces the most accurate results, the grid point rainfall ratios were compared to the ratio from the generalized equations at each of the basic data durations. Each grid point at a basic data duration was classified in one of the lettered groups depending on which generalized equation produced the smallest deviation. This lettered group was then compared to the lettered group defined by the key duration. If the lettered groups from the two methods were the same, the key duration lettered group was correct. If the lettered group classification by the generalized equation was further into the alphabet than the key duration group classification, the point was underestimated by the key duration group. The group was overestimated if the opposite was true. For example, if the key duration placed a grid point in group B, it would be underestimated if the equations classified it as group C or D; overestimated if the equations classified it as A, and correct if the equations classified it as B. Table 6 contains a summary of the number of grid points misclassified for each of the key durations. Data from the 2- and 100-year return periods were combined in the table. The total number of points for each duration is 1,030.

The most accurate classification occurred at durations equal to the key durations. This is not surprising as the 15-minute key duration has fewer misclassified points (underestimated, overestimated or total) than the 5-minute key except for the 5-minute and 12-hour durations. The 5-minute duration as defined by the 5-minute key is most accurate because the key duration is the duration that grouped the data originally. Neither key is very accurate at classifying the 12-hour duration (greater than 27% underestimated, greater than 28% overestimated and greater

Table 6. Misclassification of grid points into groups by key durations

Key duration	Kind of misclassification	Number of misclassifications for durations of -- 5 min	15 min	60 min	2 hr	3 hr	6 hr	12 hr
5 min	Underestimate	0	66	182	190	145	202	285
	Overestimate	23	100	280	241	390	279	290
	Total	23	166	462	431	454	481	575
15 min	Underestimate	57	0	118	147	108	172	281
	Overestimate	94	45	256	227	302	278	299
	Total	151	45	374	374	410	450	580

than 55% total). Misclassification is less important for longer- than for shorter-duration ratios. Table 5 shows that for T_c longer than 6 hours the variation in peak flow between all groups is less than 10%. It is at the longer T_c's that the longer data durations start to contribute to the peak flow. Based on table 6 the 15-minute key duration should be used to define groups.

CONCLUSIONS

The use of more than one design rainfall distribution for the 37 eastern most states is warranted. The difference in rainfall intensity and consequently peak runoff is substantial enough to subdivide the area studied into groups. The subdivision by grouping includes many assumptions and contains much variation, but is considered better than the use of only one representative distribution for the entire area. To be in error by one grouping at a given location is more accurate than having only one distribution for the entire area.

The ability to change the rainfall distribution with return period at a location reduces variation. An average distribution representing all return periods at one location probably would not fit data from both return periods. The use of a single ratio of 15-minute rainfall/24-hour rainfall provides the flexibility for selecting a rainfall distribution group for any return period between 2 and 100 years.

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APPENDIX I

Maps of areal extent of groups for each combination of key duration (5 and 15 min) and return period (2 and 100 years).