WWRC-83-08

DESIGN RAINFALL DISTRIBUTIONS FOR THE STATE OF WYOMING

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August, 1983

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Research Project Technical
Completion Report (A-036-WYO)
Agreement No. 14-34-0001-2154

Prepared for:
U. S. Department of the Interior

The research on which this report is based was financed in part by the U. S. Department of the Interior, as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

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University of Wyoming
Laramie, Wyoming

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INTRODUCTION

The design of hydraulic structures for use in ungaged drainage basins requires some estimate of flood flows and their frequency of occurrence. Because no historical streamflow data exist for these drainages, floods are estimated either by regional frequency analysis or, with the help of digital computers, by parametric rainfall-runoff event simulation.

Computer models dealing with rainfall-runoff event simulation are commonly used today by engineers and hydrologists. These models are used to predict flood hydrographs given an input rainfall volume, distributed over time in some manner, and certain geomorphic basin parameters.

Studies exist in the literature documenting the effects of time distribution of rainfall on runoff hydrographs. The reader is referred to works by Wei and Larson (1971), Yen and Chow (1980), and Shanholtz and Dickerson (1964) as examples. Because this relationship between the time distribution of rainfall and hydrograph characteristics exists, the separate study of storm rainfall is essential for accurate flood prediction regardless of other variables that also influence the runoff process. Additionally, methods of constructing design storms are available and in wide use, but they are general in nature and assume storms occur with the same temporal distribution across much of the country. Because of the drastic climatic differences between the areas encompassed by existing procedures, it was felt their design curves are not likely to be representative of the actual time distribution of storms in semi-arid regions such as Wyoming. It was, therefore, decided to develop a new design storm construction procedure applicable to the State of Wyoming based on observed storm rainfall in Wyoming. This new design storm methodology is the topic addressed herein.

REVIEW OF PREVIOUS WORK

Relatively few precipitation studies made to date deal with the temporal distribution of rainfall as used by hydrologists and engineers in parametric flood prediction.

The Soil Conservation Service (SCS) method (1973) presents two temporal rainfall distribution curves for runoff prediction. For studies in Hawaii, Alaska, and the coastal side of the Sierra Nevada and Cascade mountain ranges, the Type I and IA curves are used. The Type II curve is applied in the remaining part of the United States, Puerto Rico, and the Virgin Islands. These curves are based on generalized rainfall depth-duration curves obtained from published data of the U.S. Weather Bureau (National Oceanic and Atmospheric Administration). All design storms developed with this method, regardless of duration, are based on the 24-hour volume for a given frequency and location.

The Bureau of Reclamation method (1977) is developed in two parts, one for the United States east of the 105° meridian and the other for areas west of the 105° meridian. The procedure requires arranging hourly rainfall increments in a specified sequence depending on the duration and type of storm (thunderstorm or general storm). Maximum 6-hour point rainfall values are used in designing general storms, and maximum 1-hour point rainfall values are used in designing thunderstorms.

The U.S. Weather Bureau procedure (1961) uses depth-duration-frequency (DDF) curves in design storm construction. In this method rainfall intensities are obtained from the DDF curves for a given frequency and duration at a certain locality. These intensities are then rearranged arbitrarily to form a storm pattern.

Kerr, et al., (1974) present a method of hyetograph construction for the State of Pennsylvania. Cumulative dimensionless rainfall versus time graphs used by the method are derived from historical rainfall data. The curves allow the user much flexibility because, rather than define a single storm sequence, they bracket a range of possible storm patterns. Picking the time distribution of a design storm is up to the user, providing he stays within the limits of the bracketing curves and the minimum and maximum intensities given.

Huff (1967) presents a procedure derived from heavy storms observed in Illinois. His distribution patterns are based on the time quartile in which the majority of rain occurs for a given storm. For each quartile storm type, frequency values are given so that the user knows the return period of his design storm.

A method described in Keifer and Chu (1957) uses intensity-duration-frequency curves for hyetograph design at a given location. In general, the proposed storm pattern is fit to exponential growth and decay curves with the most intense part of the storm defined by a parameter termed the "advanceness ratio." This method was developed in Chicago for urban sewer design but can easily be used in other areas of the country where adequate rainfall records are available.

Frederick, et al. (1981) developed annual maximum precipitation events for different durations. The largest precipitation amounts for the selected durations which coincide with a given duration event are selected. The events are stratified according to magnitude and ratios of shorter to longer duration precipitation totals are formed. Accumulated probabilities of this ratio are suggested as a tool to estimate precipitation increments necessary in the synthesis of precipitation mass curves. By analyzing the relative timing of the shorter duration event within the longer duration event, a characteristic time distribution can be developed.

METHODOLOGY

Accumulation of Rainfall Data

The study of time distribution of rainfall requires historic data recorded as nearly continuously as possible. Because continuously recorded rainfall data were not available in the quantities needed for this study, discrete data were used. Hourly measurements from the National Oceanic and Atmospheric Administration (NOAA) publications (1948-1979) provided the data base for the study of general storms while the five-minute incremental precipitation data available in Rankl and Barker (1977) were used in thunderstorm analysis. Table I describes the precipitation stations used from both sources.

The definition of a storm had to be established before usable information could be obtained from the data. In this report, the criteria used for defining a storm are as follows:

General Storm - preceded and followed by at least two hours of zero rainfall

TABLE I.

PRECIPITATION STATIONS PROVIDING DATA FOR STUDY

Reference Number	Location Name or Number	Major Drainage Basin	Source	Recording Interval
1	Casper WSO AP	North Platte	NOAA[1]	Hourly
2	Cheyenne WSFO AP	North Platte	NOAA	Hourly
3	Douglas Aviation	North Platte	NOAA	HOURLY
4	Encampment	North Platte	NOAA	Hourly
5	Jelm	North Platte	NOAA	Hourly
6	Laramie 2 WSW	North Platte	NOAA	Hourly
7	Medicine Bow	North Platte	NOAA	Hourly
8	Oregon Trail Crossing	North Platte	NOAA	Hourly
9	Pathfinder Dam	North Platte	NOAA	Hourly
10	Phillips	North Platte	NOAA	Hourly
11	Pine Bluffs	North Platte	NOAA	Hourly
12	Rawlins FAA AP	North Platte	NOAA	Hourly
13	Saratoga 4 N	North Platte	NOAA	Hourly
14	Seminoe Dam	North Platte	NOAA	Hourly
15	Shirley Basin Station	North Platte	NOAA	Hourly
16	Torrington 1 S	North Platte	NOAA	Hourly
17	Wheatland 4 N	North Platte	NOAA	Hourly
18	Buffalo	Powder	NOAA	Hourly
19	Douglas 17 NE	Powder	NOAA	Hourly
20	Dull Center	Powder	NOAA	Hourly
21	Gillette 18 SW	Powder	NOAA	Hourly
22	Hat Creek 14 N	Powder	NOAA	Hourly
23	Lance Creek	Powder	NOAA	Hourly
24	Moorcroft	Powder	NOAA	Hourly
25	Mule Creek	Powder	NOAA	Hourly
26	Newcastle	Powder	NOAA	Hourly
27	Osage	Powder	NOAA	Hourly
28	Pine Tree 9 NE	Powder	NOAA	Hourly
29	Powder River	Powder	NOAA	Hourly
30	Recluse	Powder	NOAA	Hourly
31	Sheridan WSO AP	Powder	NOAA	Hourly
32	Story	Powder	NOAA	Hourly
33	Boysen Dam	Big Horn	NOAA	Hourly
34	Lander WSO AP	Big Horn	NOAA	Hourly
35	Meteetse 1 ESE	Big Horn	NOAA	Hourly
36	Powell Field Station	Big Horn	NOAA	Hourly
37	Riverton	Big Horn	NOAA	Hourly
38	Tensleep 4 NE	Big Horn	NOAA	Hourly
39	Thermopolis	Big Horn	NOAA	Hourly
40	Thermopolis 25 WNW	Big Horn	NOAA	Hourly
41	Worland	Big Horn	NOAA	Hourly
42	Big Piney	Green	NOAA	Hourly
43	Mountain View	Green	NOAA	Hourly

TABLE I. continued

PRECIPITATION STATIONS PROVIDING DATA FOR STUDY

Reference Number	Location Name or Number	Major Drainage Basin	Source	Recording Interval
44	Mud Springs	Green	NOAA	Hourly
45	Rock Springs FAA AP	Green	NOAA	Hourly
46	Lake Yellowstone	Yellowstone	NOAA	Hourly
47	Jackson	Snake	NOAA	Hourly
48	Moran 5 WNW	Snake	NOAA	Hourly
49	Evanston 1 E	Bear	NOAA	Hourly
50	06631150	North Platte	USGS[2]	5-minutely
51	06634910	North Platte	USGS	5-minutely
52	06634950	North Platte	USGS	5-minutely
53	06644840	North Platte	USGS	5-minutely
54	06648720	North Platte	USGS	5-minutely
55	06648780	North Platte	USGS	5-minutely
56	06312910	Powder	USGS	5-minutely
57	06312920	Powder	USGS	5-minutely
58	06313050	Powder	USGS	5-minutely
59	06313180	Powder	USGS	5-minutely
60	06316480	Powder	USGS	5-minutely
61	06382200	Powder	USGS	5-minutely
62	06233360	Big Horn	USGS	5-minutely
63	06238760	Big Horn	USGS	5-minutely
64	06238780	Big Horn	USGS	5-minutely
65	06256670	Big Horn	USGS	5-minutely
66	06267260	Big Horn	USGS	5-minutely
67	06267270	Big Horn	USGS	5-minutely
68	06274190	Big Horn	USGS	5-minutely

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[1] NOAA (1948-1979)

[2] Rankl and Barker (1977)

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- at least four hours in duration
- at least one. half (0.5) inch in volume

Thunderstorm
- preceded and followed by at least one hour of zero rainfall
- at least twenty minutes and at most four hours in duration
- at least one-half (0.5) inch in volume

These criteria are arbitrary but consistent with similar criteria put forth by Huff (1967), Ward (1973), and Croft and Marston (1950). Minimum duration requirements were used to make sure the time distribution of any storm was described by at least four data points. In all, 531 general storms and 72 thunderstorms were examined.

The period of record represented by the data at most stations covers the years 1969-1979, though the lack of definable storms at some stations required data from as far back as 1948. Because the development of design storms inherently assumes future rainfall events will occur with the same distribution as past events, the use of data from stations with variable periods of record is acceptable.

Description of Study Areas

The State of Wyoming was divided into its major surface water drainage basins for this study. This was done to see if differences in storm rainfall characteristics exist between basins. Figure 1 shows the entire State of Wyoming divided into these major drainages.

Analysis of Storm Parameters

Determining if differences in storm rainfall characteristics exist between basins requires statistical analysis of certain storm parameters.

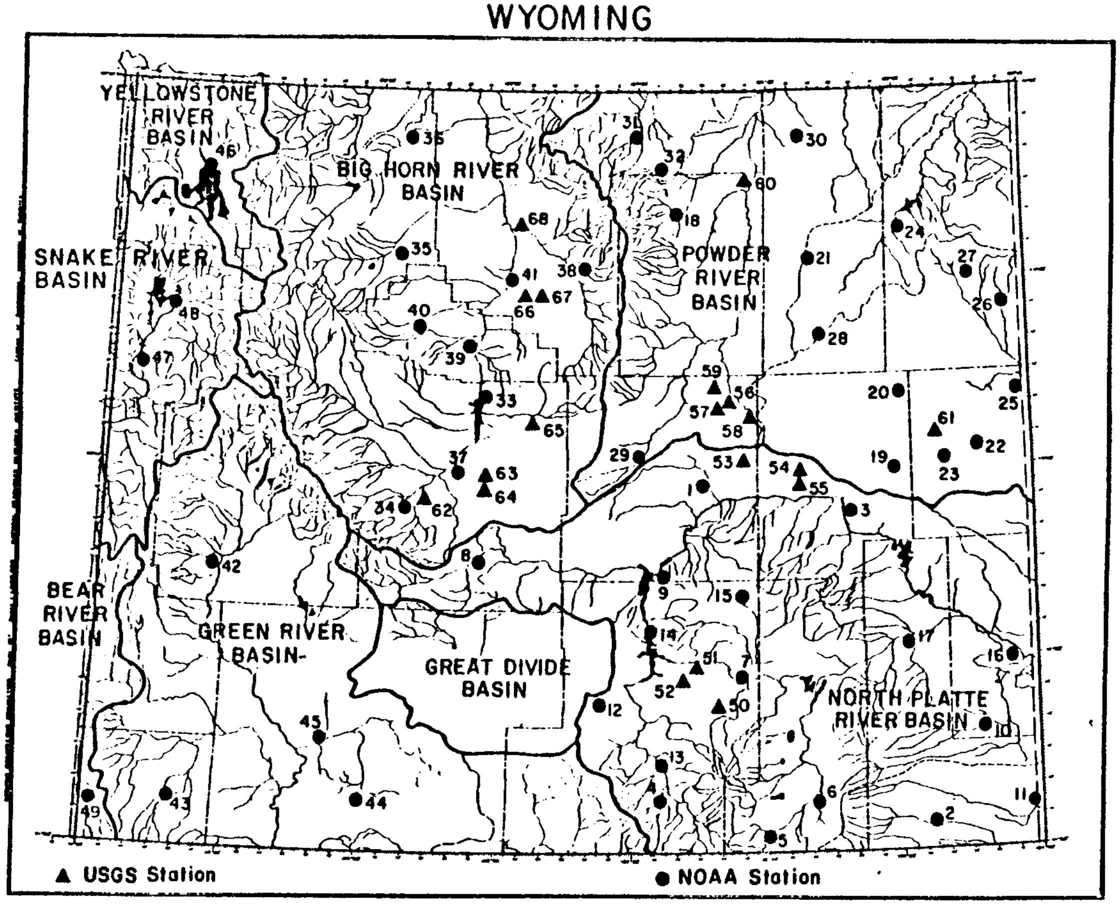

Figure 1. Map of the State of Wyoming showing the major surface water drainage basins. Station numbers refer to Table I.

Definitions of parameters used in describing storm rainfall follow:

Storm Duration - the amount of elapsed time, in hours, from the beginning to the end of a storm.

Storm Volume - the total amount of rainfall measured during a storm, in inches.

Storm Intensity - the average rainfall rate during a storm, in inches per hour, calculated by dividing a storm's volume by its duration.

Percent Time to Peak Intensity - that amount of time, expressed as a percent of total storm duration, from the beginning of a storm to the period of most intense rainfall.

Pattern Index - the area beneath a dimensionless cumulative rainfall versus time curve, expressed as a decimal or as a percent.

Pattern Index and Percent Time to Peak Intensity were the parameters used for determining if differences in the time distribution of rainfall exist between basins. This determination was made using a one-way analysis of variance technique for samples of unequal size. The procedure, described in Miller and Freund (1977), tests for differences in the population means for the populations from which the samples were taken. Such tests indicate if significant differences in parameter values exist between all the major drainages. If differences existed, the state would have to be divided accordingly before design storms could be constructed. If no differences existed, the state as a whole could be analyzed with the resulting design storms applicable statewide.

Construction of Design Curves

All the observed dimensionless mass rainfall curves are superimposed on one graph to create a family of "probable" storm patterns. Such an approach to design storm development is described in Kerr, et al. (1974). The method's most attractive feature is its flexibility, allowing the user his choice of three given design hyetographs, as well as the freedom to construct his own hyetograph, within limits. Such flexibility is desirable when, for example, a person is designing a structure based on peak flowrate in one instance and on runoff volume in another. The use of several curves can allow maximization of either peak flowrate or runoff volume for a given storm volume. A single design curve does not have this ability.

Figure 2 is a set of design curves. All of the storms used in the development: of this set of curves are non-dimensionalized and plotted on one graph of percent rainfall versus percent time. The bold vertical lines at each ten percent time increment represent the range of all storm data used. In the center of the plot is the mean curve. The curve is fit through the points representing the average cumulative percent rainfall at each ten percent time increment. It should be noted that the mean curve does not describe the average observed storm, rather it shows average accumulated rainfall with time based on all storms used. Also drawn on the plot: are ten percent and 90 percent limit curves. The ten percent limit curve represents, at a given percentage of storm duration, that value above which ten percent of the storms had accumulated more precipitation. Similarly, ten percent of the storms had each accumulated less than the value described by the 90 percent limit line at a given percentage of storm duration. It is not correct to assume that ten percent of the storms were

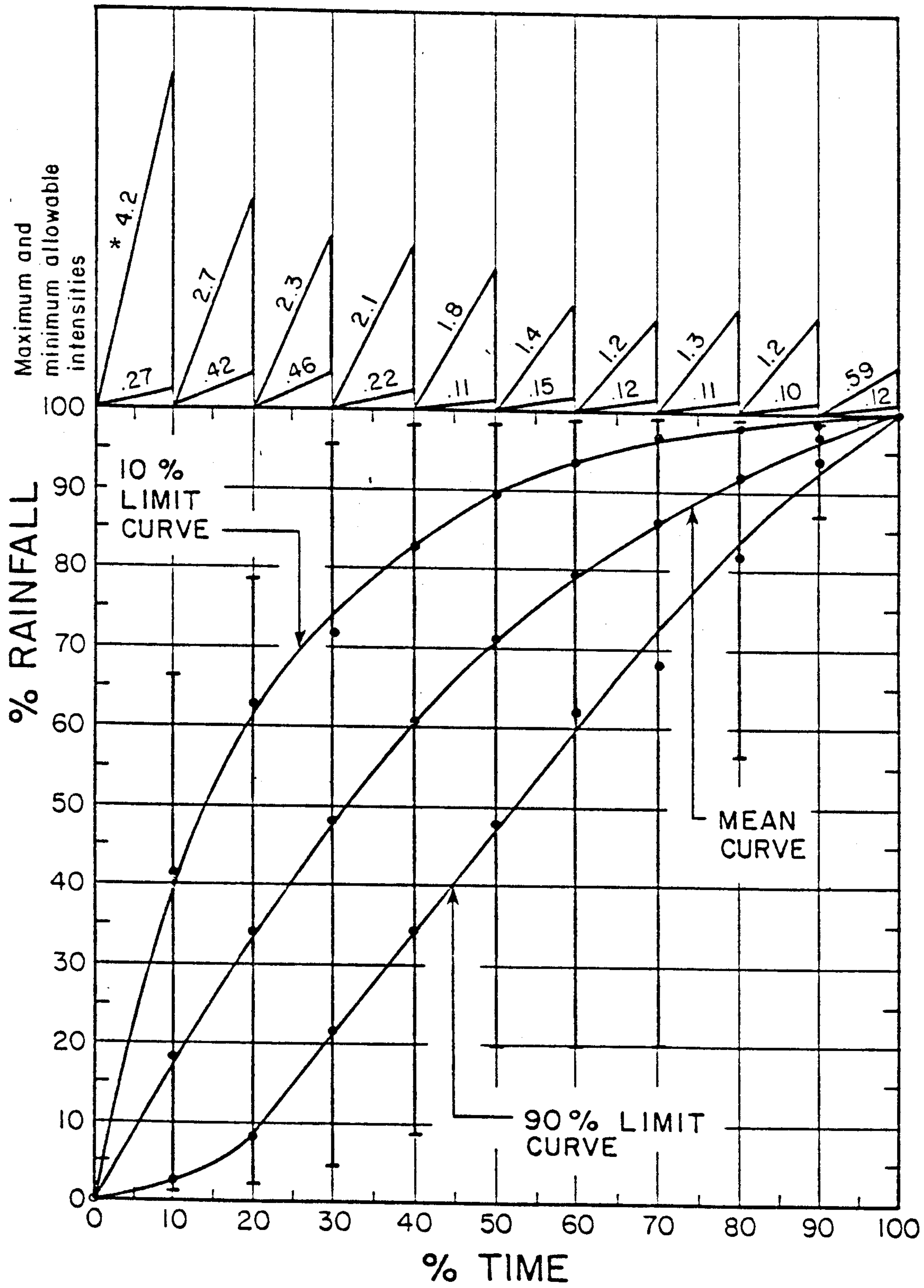

Figure 2. Dimensionless design mass curves for thunderstorms.
*Numbers with each line describe the slope of that line.

totally above the ten percent limit line or totally below the 90 percent limit line. The use of ten percent as the cutoff when defining the upper and lower limit lines is arbitrary but reasonable. Using a smaller cutoff percentage resulting in a broader set of enveloping limit curves would be too general to accurately predict probable storm patterns. A larger cutoff value would result in a narrower envelope and a loss in flexibility of the method.

Under the assumption that future rainfall events will have the same time distribution as past events, these limit curves are the boundaries of a region of probable storm sequences. The user of the curves has the freedom to use either limit curve, or the mean curve, when choosing a design storm. In fact, he may pick his own storm sequence as long as he stays between the limit curves at all times and adheres to the maximum and minimum slope guidelines printed at the top of Figure 2. These guidelines are constructed in a manner similar to the limit curves in that for each ten percent time interval they represent intensities exceeded by ten percent of the storms (the steeper line) as well as intensities exceeded in 90 percent of the storms (the less steep line). In using these intensity guidelines, the designer cannot create a storm with an intensity greater than the value defined by the steep line or less than that defined by the shallow line for the appropriate ten percent increment of storm duration. The number accompanying each of these lines at the top of Figure 2 is the slope of that line.

Designing storms in this manner makes the utmost use of historical rainfall patterns while allowing the user flexibility in choosing the time distribution which will provide the critical peak flowrate or runoff volume for his purpose.

Comparison of Storm Design Methods

The creation of new storm patterns for use in a particular region is logically accompanied by a comparison of the results of using the new method with results obtained using established design storm techniques. Such a comparison will prove the need for the new region-specific design curves if the existing general methods do not produce similar runoff characteristics when applied to a given event.

The different storm designs are compared by inputting them to four different rainfall-runoff simulation models and examining the runoff hydrographs produced. Thunderstorm and general storm runoff are simulated with each model. For each model and storm type the infiltration parameters are held constant so that any differences noted in outflow hydrograph characteristics can be attributed to differences in the input hyetographs. The models used are described in Table II. In addition to the design storm construction method presented in this paper, techniques given by the U.S. Soil Conservation Service (1973) and the U.S. Bureau of Reclamation (1977) are used for comparative purposes. These last two methods have already been described in the review of previous work.

DESIGN STORM RESULTS

Statistical Analysis

Examination of the linear regression and analysis of variance (ANOVA) tests performed on the rainfall data leads to the following conclusions:

1. A difference in the time distribution of thunderstorm rainfall

TABLE II

DESCRIPTION OF DIGITAL COMPUTER MODELS USED IN DESIGN STORM COMPARISONS

Model	Citation	Method of estimating infiltration	Method of constructing outflow hydrograph
SCS Triagular Hydrograph	U.S. Soil Conservation Service (1972).	Uses a "minimum infiltration rate" and runoff curve number based on soil type.	Relates incremental excess precipitation to incremental runoff with a hydrograph that is triangular in shape.
HEC-1	U.S. Army Corps of Engineers (1973).	Uses an exponentially decaying function that depends on rainfall intensity and antecedent losses.	Derives outflow hydrograph from either (1) unitgraph input by either, or (2) Clark (1945) synthetic unitgraph.
HYMO	Williams and Hann (1973). U.S. Department of Agriculture.	Similar to SCS method above; uses curve number and minimum infiltration rate.	Uses dimensionless unitgraph (described by exponential expressions relating flowrate to time) and a "dimensionless shape parameter."
USGS	Dawdy, David R., John C. Shaake, Jr., and William M. Alley (1978). U.S. Geological Survey.	Uses the Philip (1954) variation of the Green-Ampt (1911) equation. Method includes soil-moisture accounting between storms.	Performs finite difference solution of kinematic wave equation for each channel and overland flow segment in drainage basin.

compared to general storm rainfall exists for the entire State of Wyoming.

2. The time distribution of both thunderstorms and general storms is not dependent upon the drainage basin in which the storms occur.
3. No relationship exists between time distribution characteristics and duration of general storms or thunderstorms.

Inferred by 1 and 2 above is the need for only one set of general storm design curves and one set of thunderstorm design curves for use statewide. Conclusion 3 says that design storms of varying duration, i.e., 1-, 2-, or 3-hour thunderstorms or 6-, 12-, or 24-hour general storms, can all be handled with the same set of design curves. Table III lists the results of selected important linear regression and ANOVA tests used in drawing these conclusions. The rest of the statistical analysis results can be found in Tyrrell (1982).

Probably the most outstanding characteristic of the storms analyzed is their individual diversity. This same finding is corroborated in the paper by Kerr, et al. (1974) for storms in Pennsylvania. It is precisely because of this diversity that the use of an enveloping set of curves is preferred to the use of a single storm pattern when attempting to predict runoff.

Presentation and Use of Design Curves

Figures 2 and 3 are the design curves for thunderstorms and general storms, respectively, constructed according to the procedures outlined previously. Figure 2 is to be used when the duration of the design storm

TABLE III

RESULTS OF SELECTED STATISTICAL ANALYSIS OF RAINFALL CHARACTERISTICS

Linear Regression

Dependent Variable	vs	Independent Variable	Correlation Coefficient(R)	Conclusion
Pattern Index for all storms.		Duration of all storms.	.167	No significant relationship.
*Duration of all general storms-North Platte drainage.		Percent time to Peak Intensity-general storms-North Platte drainage.	.055	No significant relationship.
*Duration of all thunderstorms-North Platte drainage.		Percent time to Peak Intensity-thunderstorms-North Platte drainage.	.170	No significant relationship.

TABLE III, continued

RESULTS OF SELECTED STATISTICAL ANALYSIS OF RAINFALL CHARACTERISTICS

Analysis of Variance

Null Hypothesis (H_o)	F Statistic Data	$F_{.05}$	$F_{.10}$	Conclusion
Pattern Index values for general storms are equal for all five major drainages.	1.22	2.44	1.99	Do not reject H_o; conclude no difference in Pattern Index due to drainage basin location.
Pattern Index values for thunderstorms are equal for three major drainages.	.79	3.14	2.38	Do not reject H_o; conclude no difference in Pattern Index due to drainage basin location.
*Pattern Index values are equal for thunderstorms and general storms-North Platte River drainage.	24.65	3.91	2.74	Reject H_o; conclude some difference in Pattern Index due to type of storm.

*Results from the North Platte drainage data analysis are presented as an example. Results from the other basins are similar.

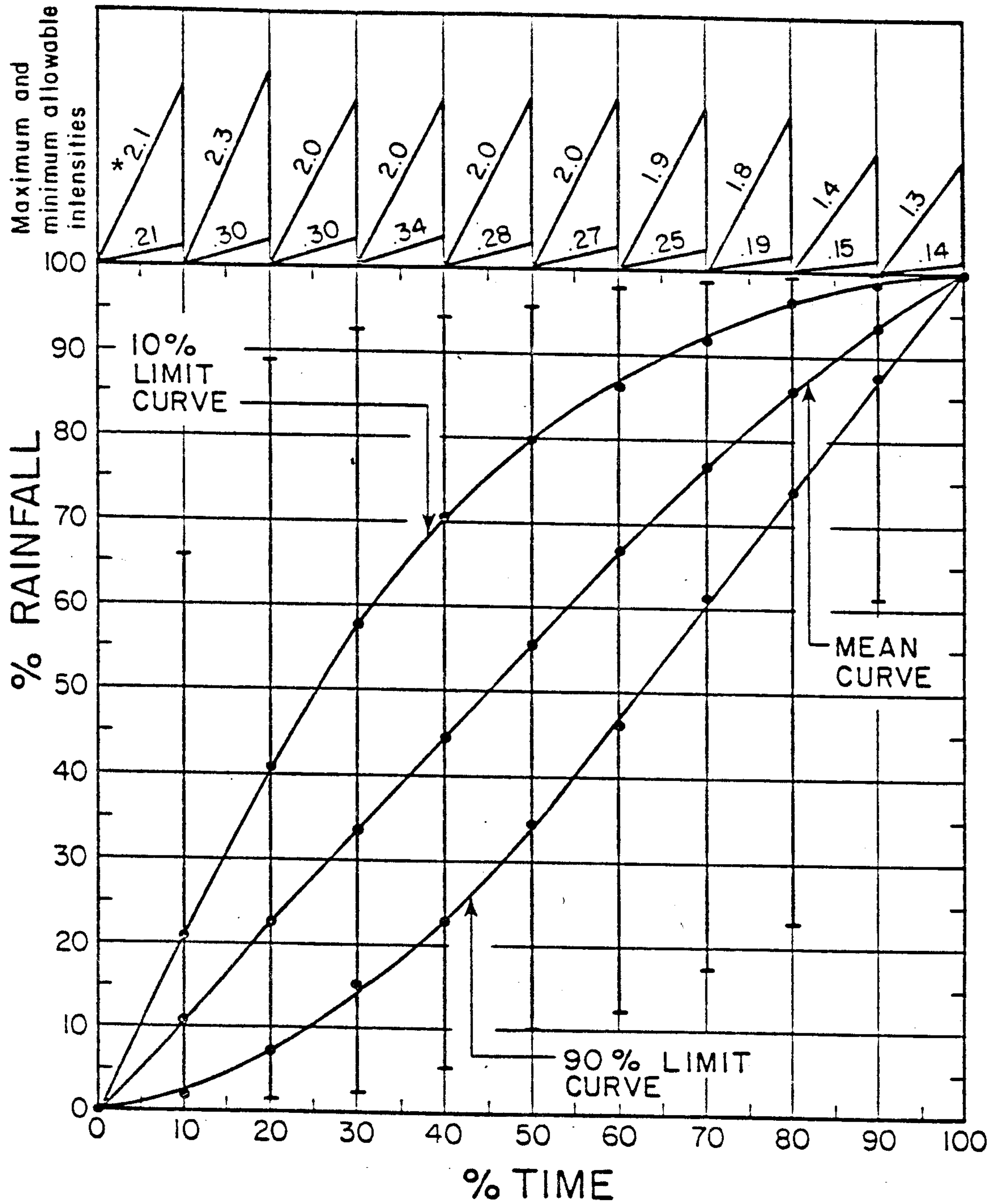

Figure 3. Dimensionless design mass curves for general storms.

*Numbers with each line describe the slope of that line.

of interest is less than four hours. Figure 3 is used for events four hours long or longer.

Following is a list of steps involved in using the design curves:

1. Select the storm type to be simulated at a certain location; for example, the 10-year, 6-hour event at Buffalo, Wyoming. Consult some source of rainfall frequency data, such as the Rainfall Frequency Atlas by Miller, et al. (1973), to find the volume of rain expected for this event.
2. Select the appropriate set of design curves. For the example above, the general storm curves (Figure 3) are applicable because the duration is longer than four hours.
3. Select one curve from the plot, either the ten percent or ninety percent limit curve, the mean curve, or some non-standard curve. When choosing a non-standard curve, the user must remember to stay on or between the limit curves at all times. Also, the steepness (intensity) of a curve in any ten percent time interval is dictated by the "maximum and minimum allowable intensities" shown at the top of the design curves. A non-standard curve must not be more steep than the steeper of these two lines (the maximum intensity line), or less steep than the line with smaller slope (the minimum intensity line) in any given ten percent interval of storm time. Examples of non-standard time distributions are given in following sections of this report.
4. Using the curve from Step 3, select the percent rainfall values that correspond to the percent time values. A maximum time

interval length of one hour is suggested. Table IV recommends percent time increments to be used for storms of varying duration.

TABLE IV

RECOMMENDED TIME INTERVALS AND CORRESPONDING PERCENT TIME INCREMENTS FOR OBTAINING RAINFALL VERSUS TIME DATA FROM DESIGN CURVES

Storm Duration	Recommended Time Interval	Number of Intervals	Interval as a Percent of Storm Duration
30 minute	5 minute	6	16.67%
1 hour	10 minute	6	16.67%
2 hour	15 minute	8	12.50%
3 hour	15 minute	12	8.33%
6 hour	30 minute	12	8.33%
12 hour	1 hour	12	8.33%
24 hour	1 hour	24	4.17%

5. Organize the data obtained in Step 4 into the form required by whatever model is being use; i.e., rainfall either as actual depth or a percent of storm value, sequences either cumulative or incremental.
6. Run the model with infiltration and geomorphic parameters as required.

It is recommended that the user run several simulations with different hyetographs to determine the critical runoff volume or peak flowrate. The suite of design curves used probably will include both limit curves, the mean curve, and several curves chosen arbitrarily by the user.

A parameter not included in this study is the areal distribution of rainfall. Therefore, the user of the method presented here is obliged to reduce point rainfall values when working with large drainage basins. Methods of reducing point rainfall with increasing drainage basin area are presented in Design of Small Dams (U.S. Bureau of Reclamation, 1977) and in the Rainfall Frequency Atlas (Miller, et al., 1973). These reductions are necessary because of the tendency of point rainfall values to overestimate actual areal precipitation on large areas.

Because this new design method depicts "probable" events, rather than extreme events (i.e., ultra-high-intensity bursts or long periods of very intense rain), it should not be used when designing for runoff due to "probable maximum" rainfall. Existing methods for probable maximum design (as in Small Dams) should be consulted for those cases.

RESULTS OF DESIGN STORM COMPARISONS

General Information

The purpose of this section is to compare the use of differing design storms in parametric flood prediction. Computer models used are HEC-1, HYMO, HYDRO (SCS Triangular Hydrograph method), and USGS (USGS distributed routing model). The reader is referred back to Table II for descriptions of these models. Design storms recommended by the U.S. Bureau of Reclamation (1977) and the U.S. Soil Conservation Service (1973) are used in the comparison.

The procedure followed in the comparison was to input differing design storms to a model, while leaving all geomorphic and loss parameters unchanged, and examine differences in the simulated outflow hydrograph peak and volume. Variations thus found are attributable to variations in the input hyetograph.

Some problems were encountered in the use of existing design storms. For example, the SCS method, rather than using a rainfall volume based on a certain duration for a given frequency, uses the 24-hour amount for designing storms of all durations. This practice results in slightly different storm volumes than those found in the Miller, et al. (1973), publication for varying durations. Despite this anomaly, the SCS hyetograph was used without a volume correction. Thus, a valid method-by-method comparison is ensured. The Bureau of Reclamation (BUREC) method also involves an odd twist basing its storm volumes on fractions and multiples of the 6-hour value for a given frequency. Modern practice has corrected this deficiency by allowing the use of volumes expected for various durations, not a manipulation of the 6-hour amount, while retaining the recommended time sequence. The BUREC method also typically calls for basing designs on runoff from a 3-hour thunderstorm and an 18-hour general storm. Because there exists no 18-hour duration precipitation data, no storms of this length were used in comparison. Also, a 2-hour thunderstorm was deemed most representative of short duration events (thus, the 3-hour event was not used).

Storms selected for the comparisons were 2, 6 and 24 hours in duration. The 2-hour event is considered a thunderstorm; the other two are general storms. A small drainage in the Powder River Basin provided the geomorphic data for the simulations. Storm volumes (U.S. Weather Bureau, 1961) for the duration's listed above (with a 10-year return period) at this location are:

2-hour - 1.60"
6-hour - 2.00"
24-hour - 2.75"

while the geomorphic parameters for the basin are:

Drainage Area - 0.83 mi^2
Water Course Length - 1.38 mi.
Elevation Difference - 125 feet

Model Parameters

Table V lists the loss parameters used with each model. The values of these parameters were not changed at any time. "NA" means the particular model does not use that parameter. It should be emphasized that values of loss parameters for the HYDRO, HYMO, USGS, and HEC-1 models are not calibrated values; they are values presented by Haie (1980) as representative for the Powder River Basin of Wyoming. A requirement of the USGS program, however, forced optimization of PSP. An optimization range of 4.0 - 6.0 was, therefore, used. The resulting small fluctuations in the value of PSP were not felt to harm the objectivity of the testing procedure. Because of the soil moisture accounting capability of the USGS model, antecedent rainfall and evaporation data was needed to "prepare" the soil prior to the occurrence of the storm event. Arbitrary, but consistent, amounts of .03 inches of daily precipitation and .01 inches of daily evaporation were applied for thirty days leading up to the simulated storm.

Because all the results presented herein were obtained using non-calibrated infiltration parameters, they are useful for comparison purposes only.

TABLE V

LOSS PARAMETERS USED WITH RAINFALL RUNOFF MODELS FOR STORM COMPARISON

Model	Curve Number	Mon. Infiltration Rate (in/hr)	STRKR[1]	DRTKR[1]	RTIOL[1]	ERAIN[1]	TC[1]	R[1]
HYDRO	72	.15	NA	NA	NA	NA	NA	NA
HYMO	72	.15	NA	NA	NA	NA	NA	NA
HEC-1	NA	NA	.80	.20	2.75	.70	1.0	5.0

	PSP*	KSAT*	RGI*	BMSN*	EVC*	RR*	DRN/(24·KSAT)*
USGS	5.0	0.10	10.0	5.0	0.7	0.9	0.5

*For definition of parameters refer to dawdy, et al. (1978).

[1] The reader is referred to the HEC-1 users manual (U.S. Army Corps of Engineers, 1973) for definitions of these infiltration parameters.

Design Hyetographs

Tables VI, VII, and VIII present the design hyetographs used for each duration given as cumulative rainfall amounts. The "WYO" distribution sequences come from the curves presented in Figures 2 and 3. Those WYO storms designated A, B, C. etc., correspond to non-standard curves arbitrarily picked by the authors. These hyetographs can be graphically constructed by plotting the tabular values on a percent rainfall versus percent time basis, if the reader wishes to compare them

TABLE VI

COMPARATIVE HYETOGRAPHS FOR 10 YEAR, 2-HOUR THUNDERSTORM

Cumulative Rainfall (inches)

Time, Minutes	*SCS Type II	BUREC	WYO: Mean	10% Limit	90% Limit	A	B	C	D	E	F	G	H
0	----	----	----	----	----	----	----	----	----	----	----	----	----
15	.06	.14	.35	.75	.06	.30	.67	.75	.35	.35	.30	.35	.35
30	.15	.36	.66	1.10	.24	.38	.77	1.02	.66	.66	.38	.58	.66
45	.45	.65	.91	1.30	.50	.50	.83	1.09	.91	.91	.50	.64	.80
60	1.17	1.26	1.14	1.44	.75	.83	.85	1.12	.98	1.14	.75	.75	.82
75	1.30	1.39	1.30	1.50	1.01	1.10	1.01	1.15	1.01	1.17	1.01	1.01	1.01
90	1.37	1.49	1.42	1.55	1.25	1.34	1.25	1.25	1.25	1.25	1.25	1.25	1.25
105	1.43	1.55	1.52	1.58	1.44	1.57	1.44	1.44	1.44	1.44	1.44	1.44	1.44
120	1.47	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60

*Based on 10 year, 24-hour volume (2.75")

TABLE VII

COMPARATIVE HYETOGRAPHS FOR 10 YEAR, 6-HOUR GENERAL STORM

Cumulative Rainfall (inches)

Time, Minutes	*SCS Type II	BUREC	WYO: Mean	10% Limit	90% Limit	C	G
0	----	----	----	----	----	----	----
30	.04		.18	.34	.04	.04	.34
60	.10	.14	.36	.68	.10	.10	.68
90	.17		.56	1.00	.22	.36	.84
120	.24	.32	.74	1.24	.34	.68	.88
150	.41		.92	1.44	.50	1.00	.94
180	1.41	.54	1.12	1.60	.68	1.34	.98
210	1.62		1.30	1.72	.90	1.68	1.04
240	1.72	1.50	1.46	1.82	1.12	1.82	1.12
170	1.80		1.64	1.88	1.34	1.88	1.34
300	1.86	1.82	1.76	1.94	1.56	1.94	1.56
330	1.92		1.90	1.98	1.78	1.98	1.78
360	1.96	2.00	2.00	2.00	2.00	2.00	2.00

*Based on 10 year, 24-hour volume (2.75")

TABLE VIII

COMPARATIVE HYETOGRAPHS FOR 10 YEAR, 24-HOUR GENERAL STORM
Cumulative Rainfall (inches)

Time, hours	SCS Type II	BUREC	WYO: Mean	10% Limit	90% Limit	A	B	C	D	E	F	G	H
0	---	---	---	---	---	----	----	----	----	----	----	----	----
1	.03	.05	.11	.22	.03	.03	.03	.03	.03	.22	.22	.22	.22
2	.06	.14	.25	.47	.06	.06	.06	.06	.06	.47	.47	.47	.47
3	.09	.22	.36	.72	.08	.08	.08	.08	.08	.72	.72	.72	.61
4	.13	.33	.50	.94	.14	.14	.14	.14	.14	.94	.94	.94	.63
5	.17	.44	.66	1.16	.22	.22	.22	.25	.22	1.16	1.16	1.10	.66
6	.22	.55	.77	1.38	.30	.30	.30	.50	.30	1.38	1.38	1.16	.72
7	.28	.66	.91	1.54	.39	.39	.39	.72	.39	1.54	1.54	1.18	.74
8	.34	.80	1.02	1.71	.47	.47	.58	.94	.47	1.71	1.60	1.21	.77
9	.41	.96	1.16	1.84	.58	.58	.80	1.18	.58	1.84	1.65	1.27	.83
10	.51	1.71	1.27	1.98	.69	.74	1.02	1.38	.69	1.93	1.68	1.29	.85
11	.65	1.95	1.40	2.09	.80	.96	1.27	1.62	.80	1.98	1.71	1.32	.88
12	1.82	2.09	1.54	2.20	.94	1.18	1.49	1.84	.94	2.01	1.73	1.35	.94
13	2.13	2.15	1.65	2.28	1.07	1.40	1.71	2.06	1.18	2.04	1.76	1.38	1.07
14	2.26	2.20	1.79	2.37	1.24	1.62	1.93	2.31	1.40	2.06	1.79	1.43	1.24
15	2.34	2.25	1.90	2.45	1.38	1.84	2.15	2.45	1.62	2.09	1.84	1.49	1.38
16	2.42	2.31	2.01	2.50	1.54	2.09	2.37	2.50	1.84	2.12	1.87	1.54	1.54

TABLE VIII continued

COMPARATIVE HYETOGRAPHS FOR 10 YEAR, 24-HOUR GENERAL STORM

Cumulative Rainfall (inches)

Time, hours	SCS Type II	BUREC	WYO: Mean	10% Limit	90% Limit	A	B	C	D	E	F	G	H
17	2.48	2.37	2.12	2.53	1.68	2.28	2.53	2.53	2.06	2.15	1.90	1.68	1.68
18	2.54	2.42	2.26	2.59	1.84	2.50	2.59	2.59	2.26	2.17	1.90	1.84	1.84
19	2.58	2.47	2.34	2.64	2.01	2.64	2.64	2.64	2.48	2.20	2.01	2.01	2.01
20	2.62	2.53	2.42	2.67	2.15	2.67	2.67	2.67	2.64	2.20	2.15	2.15	2.15
21	2.66	2.59	2.53	2.70	2.28	2.70	2.70	2.70	2.70	2.28	2.28	2.28	2.28
22	2.70	2.64	2.61	2.72	2.45	2.72	2.72	2.72	2.72	2.45	2.45	2.45	2.45
23	2.72	2.69	2.67	2.72	2.59	2.72	2.72	2.72	2.72	2.59	2.59	2.59	2.59
24	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75

visually with the standard 10%, 90% and mean WYO curves. The reader can see that, due to the discrepancy previously described, the SCS storm volumes do not quite equal the volumes given by the BUREC and WYO storms in Tables VI and VII.

The 6-hour event was the last of the three to be evaluated. Results from the earlier runs for the 2- and 24-hour events were used to indicate which of the lettered (A, B, C, etc.) WYO curves would probably give the largest peak runoff flowrate. As a result, the 6-hour event was run with only the "C" and "G" arbitrary curves used in addition to the mean, ten percent limit, and 90 percent limit curves.

Tables IX, X, and XI present the results of the model runs for the 2-hour, 6-hour and 24-hour events, respectively. Generally, results from HEC-1, HYMO, and HYDRO simulations show that for longer events the WYO curves produce less runoff (Peak and Volume) than the other methods, while for shorter events the WYO curves produce greater runoff. Results from USGS model runs differed from the other models* results by predicting, for all three storm durations, smaller runoff peaks and volumes due to the WYO design curves when compared to established procedures. Because of these results, it is suggested that current methods may lead to consistent over-design of hydraulic structures, at least when long (durations of 6 or more hours) events are stated as part of the design criteria. Also, the ability of any one of the group of WYO curves to produce greater runoff than the others is dependent upon the model used. These results are further detailed in the following section.

TABLE IX

RUNOFF CHARACTERISTICS FOR 10 YEAR 2-HOUR THUNDERSTORM

	MODEL: HYDRO		HYMO		HEC-1		USGS	
Design Storm	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)
SCS Type II	47.8	.098	11.7	.036	38	.39	41.1	.162
BUREC	65.3	.137	17.3	.053	36	.38	40.2	.162
WYO-Mean	61.7	.139	12.9	.040	28	.31	16.0	.094
10% Limit	61.8	.123	19.9	.061	42	.45	33.2	.146
90% Limit	76.1	.135	30.7	.100	29	.32	20.6	.107
-A	79.6	.134	41.7	.133	31	.34	24.7	.118
-B	75.3	.133	30.9	.100	32	.39	23.1	.124
-C	62.2	.124	17.2	.064	34	.42	22.2	.138
-D	72.6	.132	30.7	.100	29	.35	19.3	.105
-E	62.5	.130	21.0	0.80	28	.34	18.0	.102
-F	76.1	.135	30.7	.100	27	.31	19.9	.105
-G	76.1	.135	30.7	.100	27	.32	19.2	.103
-H	76.7	.134	30.7	.100	28	.33	18.9	.103

TABLE X

RUNOFF CHARACTERISTICS FOR 10 YEAR 6-HOUR GENERAL STORM

	MODEL:							
	HYDRO		HYMO		HEC-1		USGS	
Design Storm	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)
SCS Type II	85.3	.175	42.7	.143	36	.38	47.1	.184
BUREC	81.6	.251	37.6	.205	20	.23	19.4	.116
WYO-Mean	52.8	.275	18.9	.094	2	.03	6.7	.065
10% Limit	50.5	.208	26.9	.103	11	.14	8.5	.075
90% Limit	83.6	.287	54.8	.261	10	.12	12.4	.085
-C	89.1	.221	49.4	.164	18	.22	16.7	.101
-G	83.6	.226	55.8	.261	10	.16	10.5	.082

TABLE XI

RUNOFF CHARACTERISTICS FOR 10 YEAR 24-HOUR THUNDERSTORM

	MODEL:							
	HYDRO		HYMO		HEC-1		USGS	
Design Storm	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)	Peak (cfs)	Vol. (in.)
SCS Type II	138.6	.346	57.9	.285	30	.34	43.1	.189
BUREC	95.5	.268	45.9	.221	14	.16	14.4	.103
WYO-Mean	0	0	0	0	0	0	1.49	.043
10% Limit	24.3	.107	14.7	.091	0	0	2.22	.051
90% Limit	8.0	.085	6.5	.074	0	0	2.88	.056
-A	50.9	.428	35.5	.352	0	0	5.16	.072
-B	37.6	.400	29.0	.327	0	0	4.91	.070
-C	50.9	.384	36.6	.319	0	0	5.18	.069
-D	37.6	.412	27.7	.343	0	0	4.94	.071
-E	24.3	.134	1.7	.005	0	0	2.22	.057
-F	24.3	.120	14.7	.099	0	0	2.31	.057
-G	8.1	.075	6.1	.063	0	0	2.82	.056
-H	8.1	.085	6.5	.074	0	0	2.88	.056

DISCUSSION OF RESULTS

The most significant difference between the WYO design storm methodology and those developed by the Soil Conservation Service and Bureau of Reclamation is the use of totally dimensionless curves. By non-dimensionalizing the time axis, the average intensities of designed storms is decreased as the storm durations are increased. For example, if two general storms of the same volume but differing durations, say 6 hours and 12 hours, were distributed over time according to the mean curve of Figure 3, the 12-hour storm would have half the intensity of the 6-hour event at any point along the curve. This explains why the WYO curves tend to produce smaller runoff peaks than the other methods for long events, and larger peaks for short events. Such a change in intensity with duration may seem inappropriate at first, but analysis of one hundred runoff-producing storms recorded by Ranki and Barker (1977) shows that, while there is not a good linear relationship (R = 53%), the peak intensity of a storm appears to decrease with increasing storm length. Figure 4 suggests this graphically. It, therefore, seems reasonable for the WYU storm design technique to make long storms generally less intense than short storms.

Lower rainfall intensity, as obtained from the WYO curves, is the reason zero runoff is predicted in some instances for the 24-hour event. For example, referring to Table XI, no runoff is produced using the WYO mean curve with the HYDRO and HYMO models. One will notice that, for general storms, the WYO mean curve is almost a 45° line indicating an almost constant intensity storm. For the 24-hour event, this constant intensity (.11 in/hour) is less than the minimum infiltration loss of .15 in/hour. Thus, no runoff occurs. Similarly, the HEC-1 model produces zero

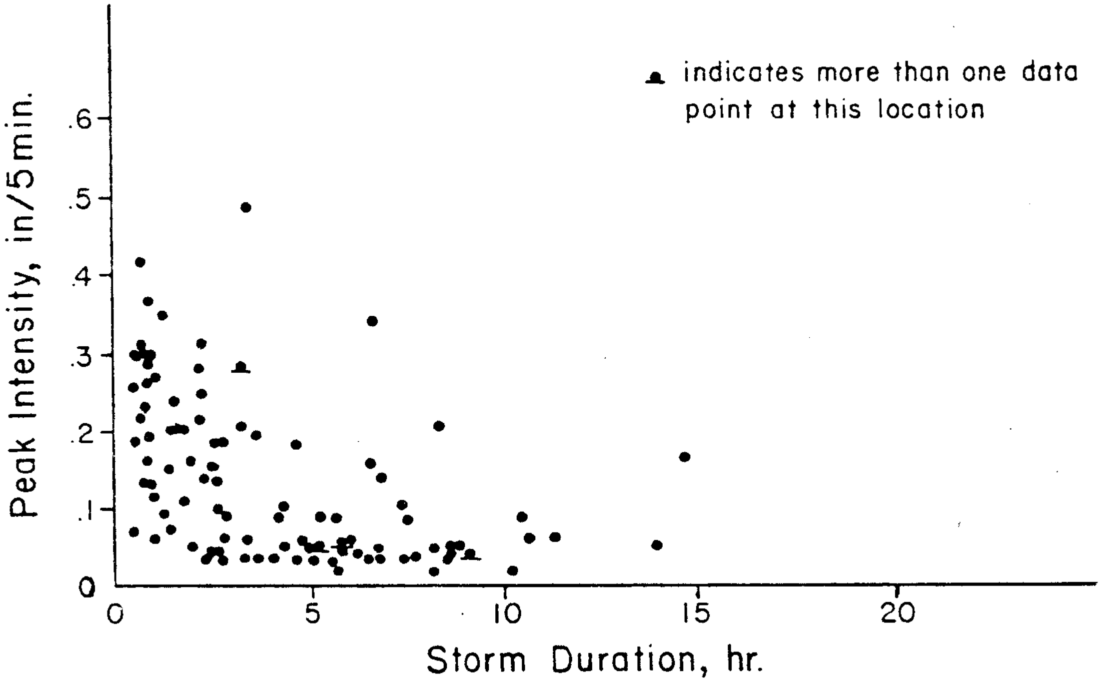

Figure 4. Variation in peak intensity with storm duration.

runoff in several instances. Because shorter storms do produce runoff according to HEC-1, the reason for zero predicted runoff in the longer storms obviously also involves low rainfall intensity and associated infiltration losses.

It is interesting to note that choosing a WYO curve for producing peak runoff flowrate or volume depends on the computer model to be used. For instance, referring to Table IX, the WYO 90 percent limit curve produces more runoff (peak and volume) than the ten percent limit curve when HYDRO and HYMO are used. When HEC-1 is used, the ten percent limit curve yields the greatest runoff peak and volume. The user of these curves is, therefore, warned not to assume that a peak-producing hyetograph for one model will perform similarly with a different simulation scheme. Always test several curves for their peak-producing ability when changing models, or when changing storm durations with the same model.

SUMMARY AND CONCLUSIONS

Summary

Parametric flood prediction on ungaged basins in Wyoming requires the use of temporal storm patterns that realistically represent anticipated local rainfall events. Because methods of hyetograph construction currently in use are very general in application, this requirement is not met. Therefore, a design storm methodology based on analysis of time distribution characteristics of 603 observed storms in Wyoming is presented. The "WYO" method of storm design uses not one, but several mass rainfall curves, allowing flexibility of use and maximization of runoff from a given storm volume.

Comparisons were made between the WYO method and design storms recommended by the U.S. Soil Conservation Service and U.S. Bureau of Reclamation using HEC-1, HYMO, HYDRO (Triangular Hydrograph), and USGS Distributed Routing rainfall-runoff models.

Conclusions

1. The time distribution of both thunderstorms and general storms is not dependent upon the drainage basin in which the storms occur.
2. The most outstanding characteristic of the storms analyzed is their individual diversity. No relationship exists between time

distribution characteristics and duration of general storms or thunderstorms. However, a difference in the time distribution of thunderstorm rainfall, compared to general storm rainfall, exists.

3. One set of thunderstorm design curves and one set of general storm design curves can be used to create design hyetographs for the entire State of Wyoming.
4. The "WYO" design storm methodology should not be used to design for "probable maximum" type events because the most intense rainfall values have been neglected by the definition of ten percent and 90 percent limit curves.
5. Simulation of runoff peak and volume using WYO design curves is sensitive to storm duration and choice of model.
6. WYO curves typically predict greater runoff peaks than Soil Conservation Service or Bureau of Reclamation synthetic hyetographs for short duration events, and less runoff for long duration events, according to HEC-1, HYMO, and HYDRO model results.
7. WYO curves consistently produce less runoff than Soil Conservation Service or Bureau of Reclamation synthetic hyetographs when the USGS Distributed Routing model is used.

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