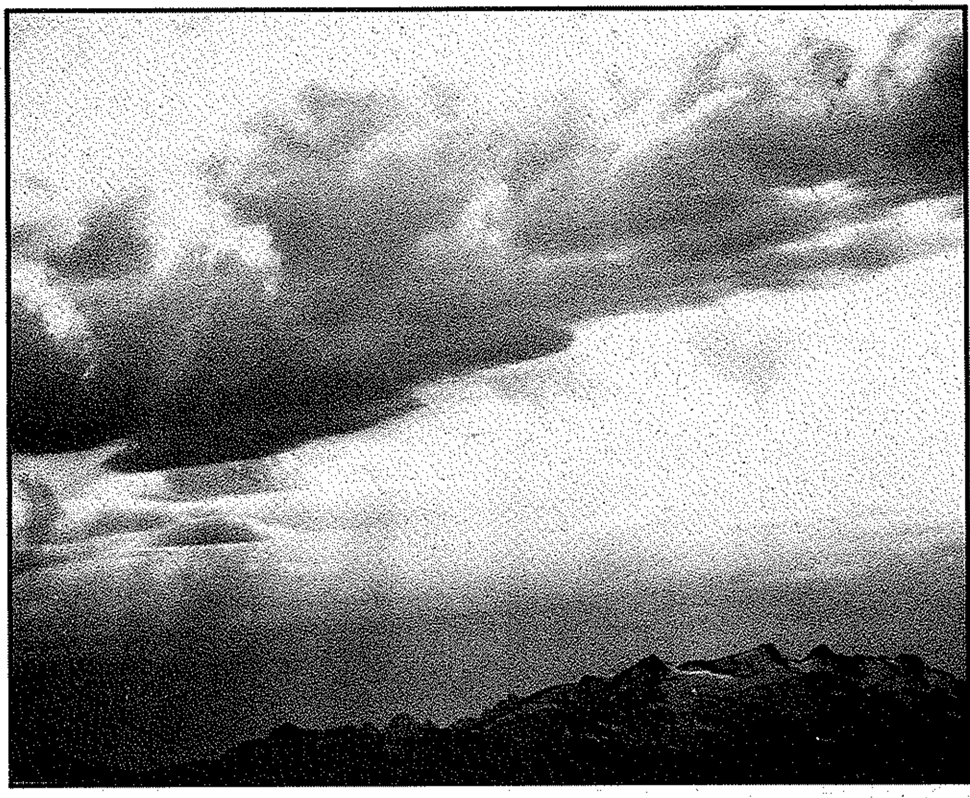

Characteristics of Extreme Precipitation Events in Washington State

Water Resources Program

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

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By Melvin G. Schaefer
Dam Safety Section

DSS-01

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ABSTRACT

Regional analyses were conducted on data from extreme storms for each of three storm durations and five climatologically homogeneous regions within Washington State. The primary objective of the study was to obtain probabilistic information about the temporal and spatial characteristics of extreme precipitation events for use in constructing synthetic storms for rainfall-runoff modeling.

Probabilistic analyses were conducted on those storm characteristics which are needed either to construct synthetic storms or to provide initial conditions for rainfall-runoff modeling. Those characteristics which were investigated included: seasonality of occurrence, macro storm patterns, precipitation depth-duration relationships, time of occurrence and temporal distribution of high intensity storm segments and the magnitude and frequency of occurrence of antecedent storms. Particular emphasis was placed on the analysis of the cross-correlation structure of the incremental precipitation amounts within storms. These analyses allowed the development of dimensionless probabilistic depth-duration curves which exhibited the statistical characteristics of observed extreme storms.

Methodologies were developed for assembly of synthetic storms using the probabilistic depth-duration data and associated storm characteristics for each of the five regions and three storm durations.

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INTRODUCTION

The occurrence of an extreme precipitation event and the resultant flood are critical considerations in the design of many types of hydraulic structures. Dams for water resource projects, large stormwater conveyance and/or detention facilities, bridges for important transportation links and flood barriers such as major dikes and levees are examples of structures which must accommodate extreme floods to function properly.

Estimation of the flood peak discharge or the entire flood hydrograph for the design of these facilities is commonly accomplished using rainfall-runoff models. While numerous factors can affect the magnitude of an extreme flood, the magnitude of the precipitation event and its associated temporal and spatial characteristics are often dominant factors. Successful rainfall-runoff modeling of extreme floods is, therefore, highly dependent upon the use of realistic storm characteristics in the modeling process.

Given these considerations, a program of study was developed to analyze the characteristics of extreme storms. One study element was the development of methodologies to provide at-site precipitation magnitude-frequency information. Particular emphasis was placed on obtaining reasonable estimates of extreme events with annual exceedance probabilities in the range of 10^{-2} to 10^{-4}. Regional analyses techniques were selected to meet that objective and they are the subject of a separate paper titled "Regional Analyses of Precipitation Annual Maxima in Washington State" [Schaefer, 1990].

Another study element was the probabilistic examination of the temporal and spatial characteristics of extreme storms and that is the subject of this paper.

In the Pacific Northwest, minimal information previously existed on many aspects of extreme storms which are needed to properly model extreme floods. It is intended that the findings from these studies will further the understanding of extreme storms and will allow improved modeling of extreme floods.

OVERVIEW

METHOD OF ANALYSIS

When an extreme storm occurs, it is the result of the interaction of a number of complex meteorological processes. The magnitude and/or intensity of any given meteorological process, which produces precipitation, is ultimately governed by atmospheric conditions having both random and deterministic components. This results in the measurable physical characteristics of a storm, such as the temporal and spatial distribution of the precipitation amounts, being highly variable and complex. It is, therefore, important that methods of analysis be used which recognize the stochastic nature of storms. For this reason, probabilistic methods of analysis have been used throughout this study.

OBJECTIVES AND STUDY CONTENTS

The primary objective of the study was to develop probabilistic information about the characteristics of extreme storms for use in the computer modeling of extreme floods. Specifically, information was needed for the construction of synthetic storm hyetographs which have the statistical properties of observed extreme storms. This required that information be obtained and probabilistic analyses be conducted on numerous aspects of observed storms. In addition, many of the meteorological characteristics associated with extreme storms have hydrologic implications in the modeling process. For example, knowledge about the season of occurrence of extreme storms allows inferences to be made about likely antecedent soil moisture conditions, initial streamflow magnitudes and, if appropriate, concurrent snowpack conditions. Thus meteorological characteristics, such as season of occurrence and the magnitude of antecedent storms, were also included in the study.

It was anticipated that the majority of applications of the information produced by this study would be on small watersheds.

Small watersheds are taken to be those having less than 50 square miles in drainage area, with most applications on watersheds having less than 10 square miles in drainage area. Because of the small size of the watersheds of interest, relative to the typical areal coverage of extreme storms, the emphasis of the study was directed towards at-site storm characteristics. Precipitation depth-area information has been excerpted from other sources to allow application of the results of this study on larger watersheds.

Given the aforementioned considerations, the following storm characteristics were selected for investigation:

Temporal Characteristics

- season of occurrence
- macro storm patterns
- time of occurrence and temporal distribution of high intensity segments within the storm
- correlation structure between incremental precipitation amounts within the storm and resultant depth-duration relationships
- magnitude and frequency of occurrence of storms antecedent to the extreme storm

Spatial Characteristics

- precipitation depth-area relationships
- areal coverage of thunderstorms in eastern Washington
- direction of storm movement and storm shape for thunderstorms in eastern Washington

HOMOGENEITY AND REGION DEFINITION

Inherent in the use of statistical methods is the desirability of obtaining representative samples of the data. Extreme storms, are, as the name implies, rare events. As such, insufficient data exists at any given station to produce a representative sample. To obtain sufficient data for a representative sample, data from numerous stations must be pooled for use in a "regional" analysis.

The validity of any regional analysis is dependent upon the actual homogeneity of the regional data. Herein, homogeneity refers to the condition that the particular data under analysis, either as directly observed or after some transformation, have common statistical properties. The statistical properties of interest in a particular analysis may refer to any or all of the following: mean; variance; coefficient of skew; probability distribution - and for data observed in pairs, the covariance and correlation coefficient could also be of interest.

The issues of region delineation and climatic homogeneity were a topic of much discussion and analyses in the companion paper on Regional Analyses of Precipitation Annual Maxima [Schaefer, 1990]. In that study, Washington State was subdivided into 13 climatically homogenous regions, where each region was comprised of recording stations within a small range of Mean Annual Precipitation (MAP). That produced a continuum from arid to rainforest climates where MAP ranged from 7 to 200 inches/yr, respectively. Extreme storms are a subset of the annual maxima and, thus, the aforementioned region formulation posed a logical starting point for defining homogeneous regions. However, a database of extreme storms is much smaller than a database of annual maxima. Thus, if regions were to be defined in terms of MAP it would be necessary to pool the extreme storm data over larger ranges of MAP which would result in a smaller number of regions.

A competing scheme for region definition was the formulation used by the National Weather Service (NWS) in their precipitation magnitude-frequency study, NOAA Atlas 2 [Miller et al, 1973].

In that scheme, four geographic regions were defined; comprised of the mountainous areas and central basin of eastern Washington and the lowlands and mountainous areas of western Washington (Figure 1a).

Comparison of the two schemes indicated compatibility in several areas. Regions defined geographically by the NWS were found to occupy reasonably distinct, although somewhat broad, ranges of MAP. In addition, preliminary analyses indicated homogeneity of seasonality and depth-duration characteristics from stations having either similar MAP or representing a specific geographic area.

Given the limitations of the database size, a formulation of 5 regions was proposed (Table 1) which had characteristics of both geographic delineation and definition by ranges of MAP (Figure 1b).

Table 1. Formulation for Region Definition

REGION	RANGE OF MEAN ANNUAL PRECIPITATION FOR REGION (inches)	AVERAGE VALUE OF MEAN ANNUAL PRECIPITATION OF RECORDING STATIONS (inches)	CORRESPONDS TO NWS REGION DESIGNATION	GEOGRAPHIC DESCRIPTION AND METEOROLOGIC COMPONENTS *
2	7 - 20	9.5	2	EASTERN WASHINGTON - CENTRAL BASIN Convergence
1	15 - 70	23.5	1	EASTERN WASHINGTON - MOUNTAINS Convergence and Orographic
3	20 - 70	42.0	3 partial region	WESTERN WASHINGTON - PUGET SOUND LOWLANDS Convergence
4	50 - 200	86.5	4	WESTERN WASHINGTON - MOUNTAINS Convergence and Orographic
5	70 - 120	89.0	3 partial region	WESTERN WASHINGTON - COASTAL LOWLANDS Convergence and Onshore Stimulation

* Convergence, Orographic, and Onshore Stimulation are Described in Definitions Section

Review of Table 1 reveals that the proposed regions occupy reasonably distinct ranges of MAP. Each region represents a different geographic area and is generally associated with a different mix of meteorologic components which produce precipitation.

Verification of the suitability of this formulation was accomplished by examining data homogeneity during the various analyses. In some cases, data from several regions were found to be homogeneous and were pooled for analyses. In other cases, separate analyses were conducted for each of the five regions.

In summary, the five region formulation, as described in Table 1 and delineated in Figure 1b, was found to yield reasonably homogeneous data and was accepted for use in the study.

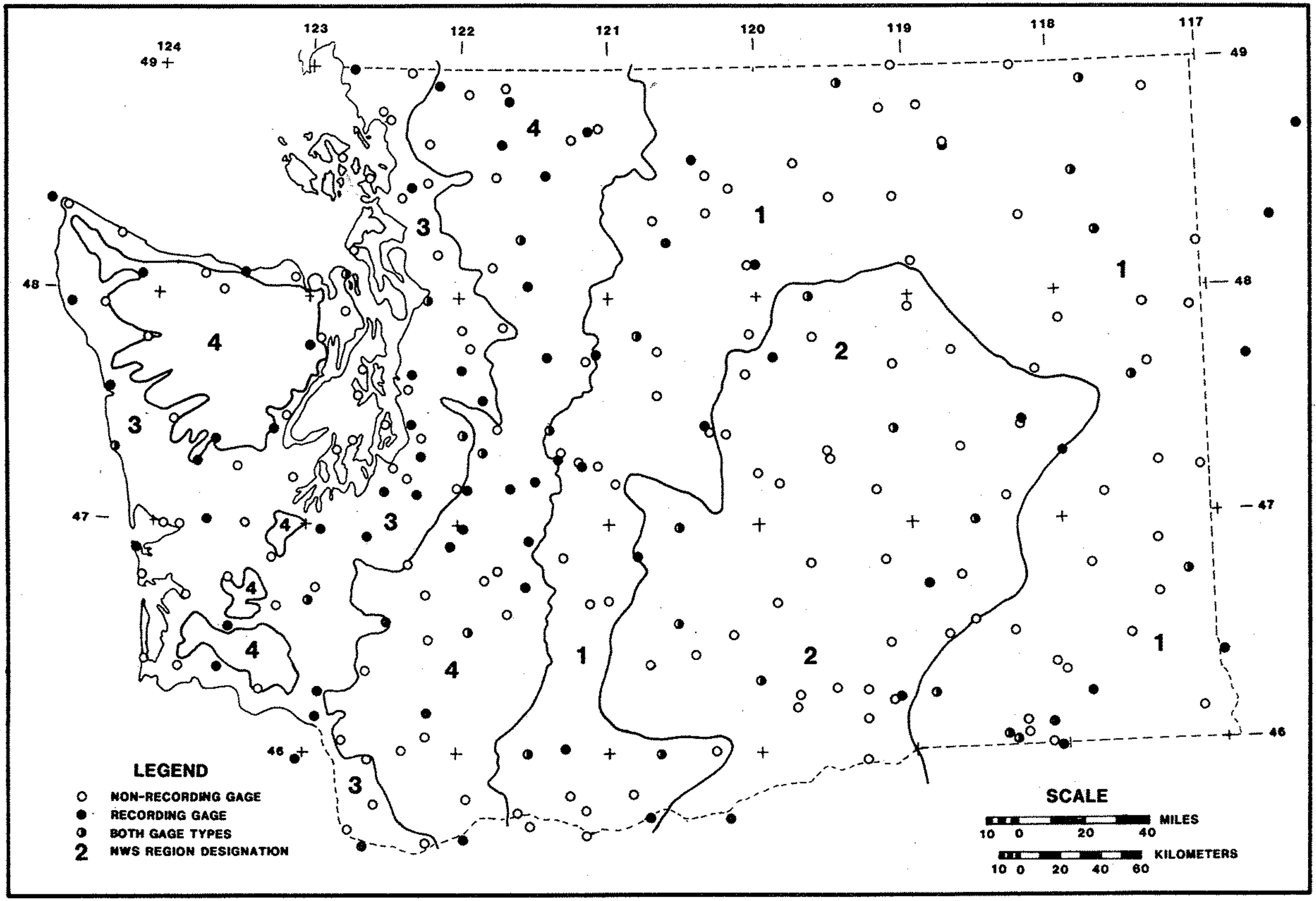


Figure 1a. Washington State Precipitation Gaging Network

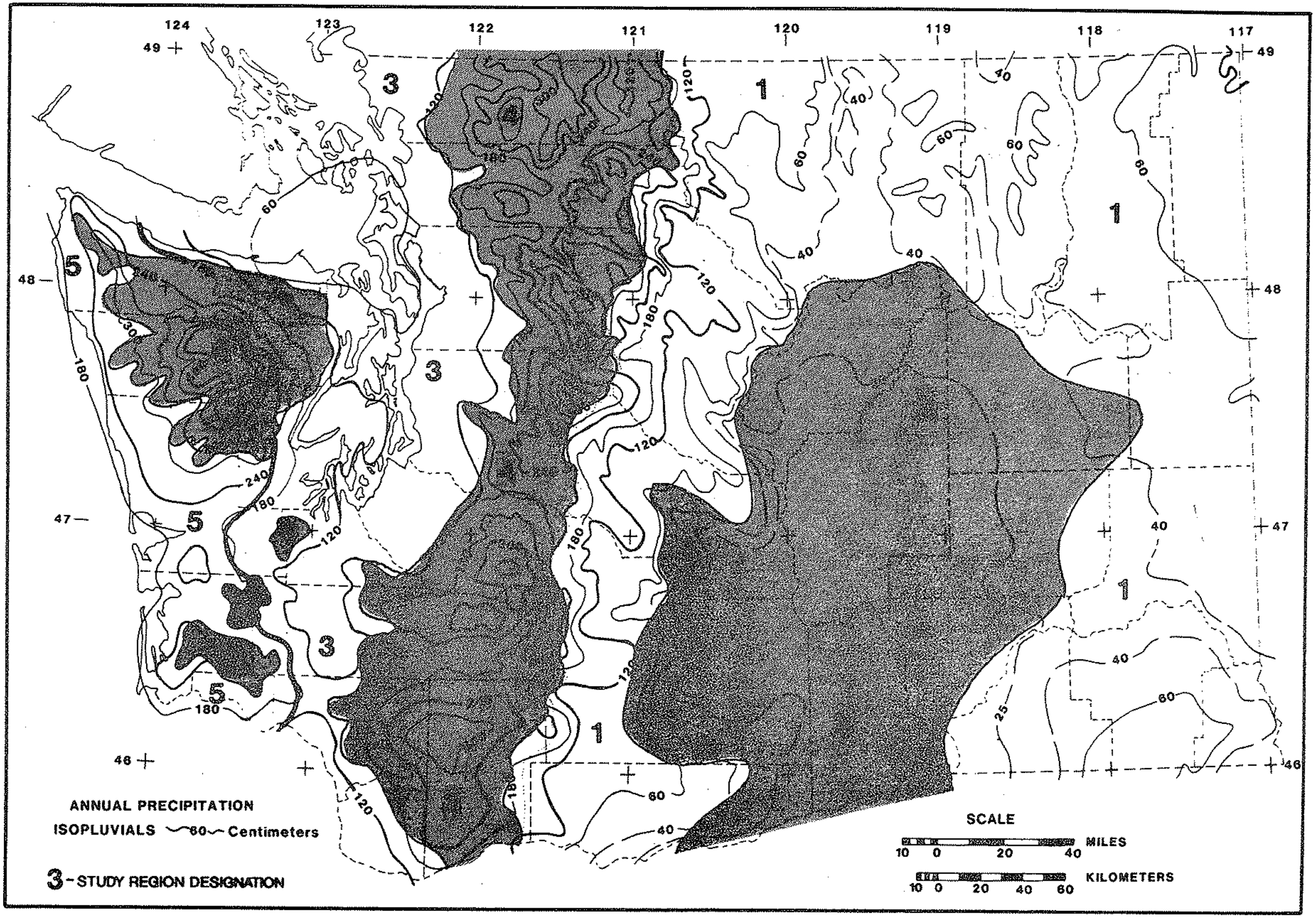


Figure 1b. Mean Annual Precipitation in Washington State and Delineation of Climatic Regions

EXTREME STORM CATALOG

To investigate the various storm characteristics, it was necessary to assemble a database of extreme storms for each of the five regions. The list of these databases is contained in Appendices 1A through 1E and is labeled the Extreme Storm Catalog.

PROCESS FOR SELECTION OF EXTREME STORMS

The term "extreme" as applied to precipitation events does not have a generally accepted meaning among the engineers and scientists who analyze and/or use the data. The selection of a threshold for defining extreme storms was made based on the needs of this study. There were three primary considerations. First, similitude considerations suggest that storms chosen for analyses should be of a similar magnitude/intensity to those which are desired for modeling of extreme floods. Second, prior studies by the NWS [Frederick et al, 1981] have shown that there are statistical differences between the characteristics of extreme events and common events. Based on these two considerations, the chosen threshold should certainly preclude the use of common events and should be set as high as practicable. Third, the threshold should be set at a level which yields databases of sufficient size to provide representative samples and thus allow valid statistical analyses.

These considerations resulted in setting the threshold for defining an extreme storm at an annual exceedance probability of 5%. Thus, any storm which contained precipitation amounts representing an at-site return period of 20 years or greater would be a candidate for inclusion in the catalog.

The following procedures were used to screen the storm data from each region and to assemble the extreme storm catalog:

- Three specific durations were selected for analyses; 2 hrs, 6 hrs, and 24 hrs.

- An annual maxima series was assembled for the precipitation data at each recording station (Figure 1a) for each of the three durations.

- Exceedance probabilities were computed for the annual maxima at each station for each duration using the Generalized Extreme Value distribution and regional analysis procedures as described by Schaefer [1990].

- The annual maxima and associated annual exceedance probabilities at each duration were then examined to identify the "extreme" storms and corresponding dates of occurrence.

- When an event, having extensive areal coverage, produced precipitation amounts which exceeded the extreme storm threshold at two or more stations within a region, only the station representing the rarest amount was retained in the catalog.

A review of the selected storm data disclosed that, occasionally, an individual event exceeded the extreme storm threshold at two or more durations. To avoid duplicity, it was decided that a storm event should only be contained in the database for a region at one of the three specified durations. Further, it was important for homogeneity considerations that storms of similar duration be grouped together in the analyses of storm characteristics. This necessitated that the databases be further screened to meet these two additional considerations.

Additional screening was accomplished wherein an extreme storm (storm date) could only appear in the catalog at one of the three durations. The selection of the duration which best represented the observed storm event was made using the following criteria:

- When a storm event was identified as extreme at two or more durations, it was placed in the database for the duration at which the corresponding precipitation amount was markedly the most rare (smallest annual exceedance probability).

- If a storm event was not markedly more rare at any specific duration, then the storm was examined to determine the effective duration [NWS, 1984]. The effective duration was defined as being the time period during which the bulk of the precipitation occurred; i.e., 90% of the total precipitation. The effective duration was then compared to the three durations under study and the criteria shown in Table 2 were used as a general guideline in selecting the representative duration.

Table 2 General Guideline for Selection of the Duration Most Representative of a Given Storm Event

REPRESENTATIVE STORM DURATION	SELECTION GUIDELINE
2 hours	effective duration < 3 hrs
6 hours	4 hrs < effective duration < 12 hrs
24 hours	15 hrs < effective duration

These procedures resulted in the selection of 252 extreme storms from 11,200 annual maxima. The 252 storms are listed in the storm catalog in Appendices 1A through 1E. These storms provided the databases which were used for all analyses on storm characteristics.

SEASONALITY OF EXTREME STORMS

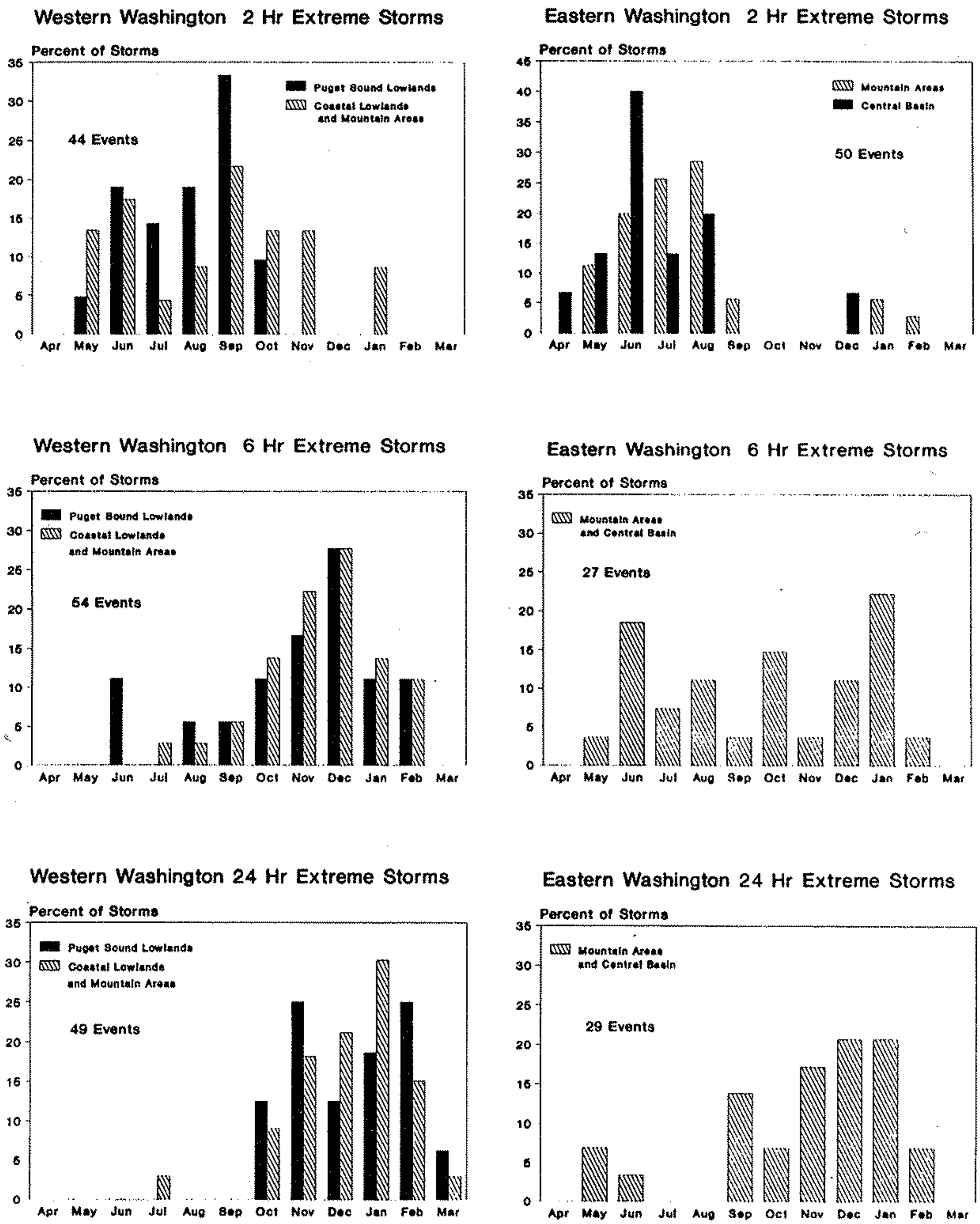
It is common knowledge that the majority of the precipitation that falls annually in the Pacific Northwest occurs in the winter months. However, only limited study [Frederick et al, 1981] has been conducted on the season of occurrence (seasonality) of extreme storms.

The principal application of seasonality information is in selecting the likely climatological and hydrologic conditions which will accompany an extreme storm event at a specific geographic location. Use of published climatological data [NCDC] and streamflow data [USGS] in combination with seasonality information can aid in the selection of antecedent soil moisture conditions, runoff characteristics, initial streamflow magnitudes, initial reservoir levels, etc. Where flood events produced by rain on snow are a consideration, selection of snowpack conditions can be made based on the historical record of snowfall in combination with seasonality information.

The seasonality of extreme storms was investigated in each region by constructing frequency histograms of the storm dates. In eastern Washington, there was insufficient data for the central basin at the 6 hour and 24 hour durations to provide representative samples. It was necessary to combine the central basin data (Region 2) with the data from the mountain areas (Region 1) for the seasonality analyses.

In western Washington, the amount of coastal data was marginally adequate to provide representative samples. Analyses of the coastal data (Region 5) indicated similarity to the data from the mountain areas (Region 4) at all three durations. Thus, the data from the two regions were combined in the seasonality analyses.

It can be seen in Figures 2a through 2f that, for each region and each duration, extreme storms occur in reasonably well-defined periods of the year. The short duration, 2 hour events, occur predominately in the warm season while the long duration, 24 hour events, occur in the late fall and winter months.



Figures 2a,2d Frequency Histograms for Seasonality
2b,2e of Extreme Storms in Washington State
2c,2f

In general, the long duration extreme storms are produced by synoptic scale cyclonic weather systems and associated fronts. These storms are characterized by large precipitation amounts and contain moderate and relatively uniform rainfall intensities.

The short duration extreme storms are commonly produced by strong convective activity which may or may not be associated with a precipitation producing weather feature identifiable at the synoptic scale. The short duration events are characterized by high intensity, but short lived rainfall. They are a warm weather phenomenon, deriving much of the needed energy from the sun. The importance of insolation in the development of convective cells can be seen in Figure 3 where the short duration storms are seen to occur predominately in the late afternoon and early evening during the warm season.

The intermediate duration extreme storms have seasonality characteristics reflecting the causative storm types. In eastern Washington, some 6 hour events are hybrids of the 2 hour storms occurring in the warm season. Other 6 hour storms occur in the cool season and have similarities to the 24 hour storms. In western Washington, the 6 hour storms are almost always associated with cyclonic weather systems and the cool season.

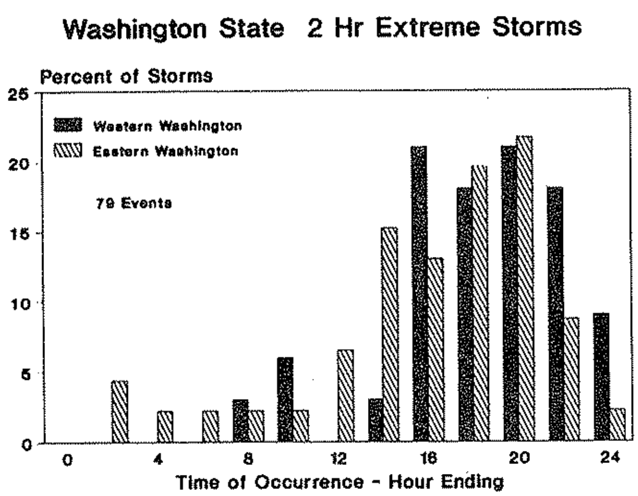


Figure 3. Frequency Histogram for Occurrence of 2 Hour Extreme Storms versus Time of Day

TEMPORAL DISTRIBUTION OF STORMS

The purpose of this component of the study was to develop probabilistic information about the temporal distribution of precipitation amounts during extreme storms. Elements of this component include probabilistic assessments of: macro storm patterns, depth-duration relationships and the time of occurrence and arrangement of high intensity storm segments.

DEFINITIONS - GLOSSARY OF TERMS

Storms are inherently complex. A discussion of the characteristics of extreme storms and the methods of analysis requires that a comprehensive nomenclature be utilized. Many of the terms used in this study are common to either meteorology or to statistical analyses. Other terms were created specific for use in this study. Most of the important terms are listed below. Those terms which are used in the study but not listed below should be found in most reference books on meteorology or statistics.

The reader may choose to review these terms now or may find it advantageous to wait until the terms are referenced in the paper.

At-site:
The term at-site is used in various ways. It may be used to distinguish analyses/data at a specific station (site) from regional analyses/data. It may be used in reference to a recording station and/or a specific geographic location. Observed at-site precipitation may be used synonymous with observed point rainfall.

Convergence Precipitation:
Convergence is intended to encompass all precipitation producing processes associated with the circulation of a cyclonic weather system.

Dependent Duration (DD):
Any specified period of time, internal to or exterior to the independent duration. The term dependent is used in the statistical sense of dependency. Precipitation during this period is dependent upon (correlated with) precipitation for the independent duration.

Depth-Duration Curve:
A precipitation mass curve created by rearrangement of observed incremental precipitation amounts in a manner which contains the largest incremental amounts at the start of the mass curve. See Appendix 2.

Effective Duration:
The period of time during which 90% of the total precipitation accumulated. This term assists in identifying the elapsed time during which the bulk of the precipitation occurred and eliminates periods of trace or small amounts which may precede or follow the period of heavy storm activity.

Extreme Storm:
An at-site precipitation amount, for a specified independent duration, which has an annual exceedance probability of 0.05 or less.

Hyetograph:
The hyetograph is a graphical representation of precipitation as it occurred with time. The graph may be discretized or continuous, displaying either incremental or accumulated (mass) precipitation or precipitation intensities.

Independent Duration (ID):
A continuous period of time during which extreme storm precipitation has occurred. Precipitation may have been continuous or intermittent during this period and precipitation may have also occurred prior to or following this period. Independent durations in these analyses are for the specific durations of 2 hrs, 6 hrs and 24 hrs.

Kernel Duration:

The dependent duration associated with the kernel ordinate.

Kernel Ordinate:

The initial dimensionless ordinate value selected in the development of probabilistic depth-duration curves. All other ordinates of the depth-duration curve are obtained by way of correlation relationships with the kernel value.

Local Storm:

A storm comprised of an isolated convective cell or group of cells, commonly referred to as a thunderstorm. Its occurrence is unrelated to any precipitation producing synoptic weather feature such as a cyclone or associated front.

Macro Storm Pattern:

A histogram describing the general shape of the incremental precipitation amounts during the total duration of the storm event.

Onshore Stimulation:

Precipitation which occurs from vertical instability and resultant lifting of atmospheric moisture in response to increased surface friction which accompanies the onshore movement of marine air.

Orographic Precipitation:

Precipitation which occurs from lifting of atmospheric moisture over mountain barriers.

Regional Analyses:

Analyses which are conducted on data collected from, and representative of, various sites within a specified region. Distinguished from at-site analyses which are conducted on data from a specific site.

Seasonality of Storms:

Frequency characteristics for the time of year (month) during which storms have been observed to occur.

Sequence:

Refers to the ordered arrangement of data. A sequence of 1342 indicates the largest data value occurred first, followed by the third, fourth and second largest values respectively.

Storm:

The term storm may be used in several ways. It may be used synonymous with the definition of "extreme storm" or it may be used generically in reference to the amount, total duration, temporal distribution or the areal coverage of precipitation.

Storm Segment:

Any selected time period and associated precipitation amount or dimensionless value.

Total Duration (TD):

A dependent duration representing a time period three times larger than the independent duration. The total duration would include the period of time containing the independent duration. The total duration must begin with precipitation, although precipitation need not be occurring at the end of the total duration.

Trisector:

Trisectors are used to subdivide the total duration into three equal periods of time. Each trisector has a duration equal in magnitude to the independent duration. Trisectors aid in categorizing and describing macro storm patterns.

MACRO STORM PATTERNS

This first element of the study investigated the temporal distribution of storms by examining the general arrangement (macro pattern) of the incremental precipitation amounts for each storm. The goal was to describe probabilistically the observed macro patterns for a given independent duration (ID) and region of occurrence.

In order to investigate the temporal characteristics of extreme storms, it was necessary to first establish a uniform approach for describing and categorizing the storms. The period of interest for investigation of storm activity was expanded to a total duration (TD) equal to three times the independent duration to include precipitation which may have preceded or followed the extreme event. The starting and ending times of the TD were selected such that precipitation was occurring at the start of the TD and the precipitation amount for the TD was the greatest for any window of time containing the ID. To facilitate the categorization of macro patterns, the total duration was subdivided into three equal time segments, called trisectors (Figure 4).

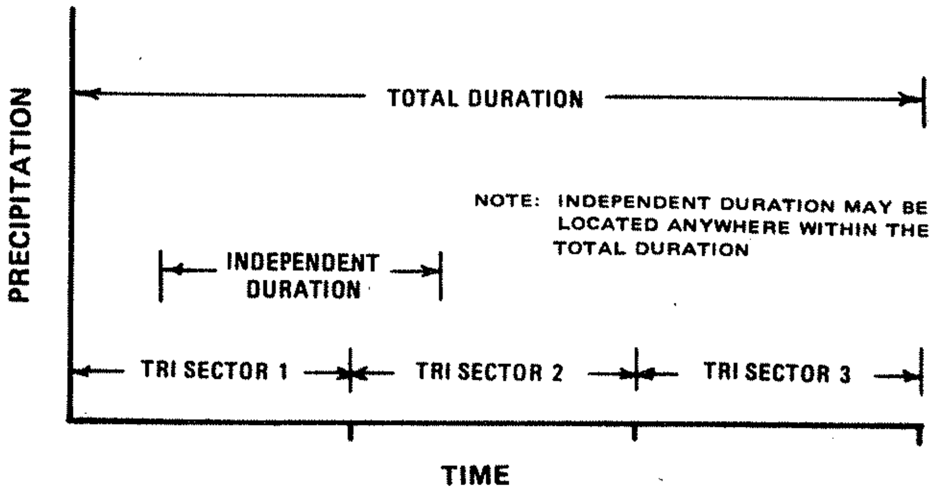


Figure 4 Example of Relationships between Independent Duration, Total Duration and Trisectors

The use of the trisector system allowed for 6 permutations in the storm pattern sequences. Consideration of both continuous and intermittent patterns produced the twelve generalized macro patterns which were used for categorizing storms (Figure 5).

To apply this categorization system, the precipitation amounts from a given storm were computed for each trisector and the amounts were compared and ordered in relative magnitude to form a sequence; i.e.: 312, 123, 213 etc. The effective duration and time of occurrence of the highest intensity were recorded and the precipitation was identified as either continuous or intermittent. Using the above information, the storm was categorized as one of the twelve macro patterns shown in Figure 5. Frequency histograms were then constructed (Figures 6a-6f) of the observed macro patterns for the various regions and independent durations.

Statistics were then compiled on the aforementioned storm characteristics. The percentage of storms which were continuous or intermittent are shown in Table 3. The typical values of the effective duration, time of highest intensity and macro storm patterns are shown in Table 4.

Table 3. Percentage of Extreme Storms which had Continuous or Intermittent Precipitation

REGIONS	INDEPENDENT DURATION (hours)	MACRO PATTERNS	
		CONTINUOUS %	INTERMITTENT %
1 & 2	2	100	0
3 & 4 & 5	2	93	7
1 & 2	6	90	10
3 & 4 & 5	6	93	7
1 & 2	24	75	25
3 & 4 & 5	24	67	33

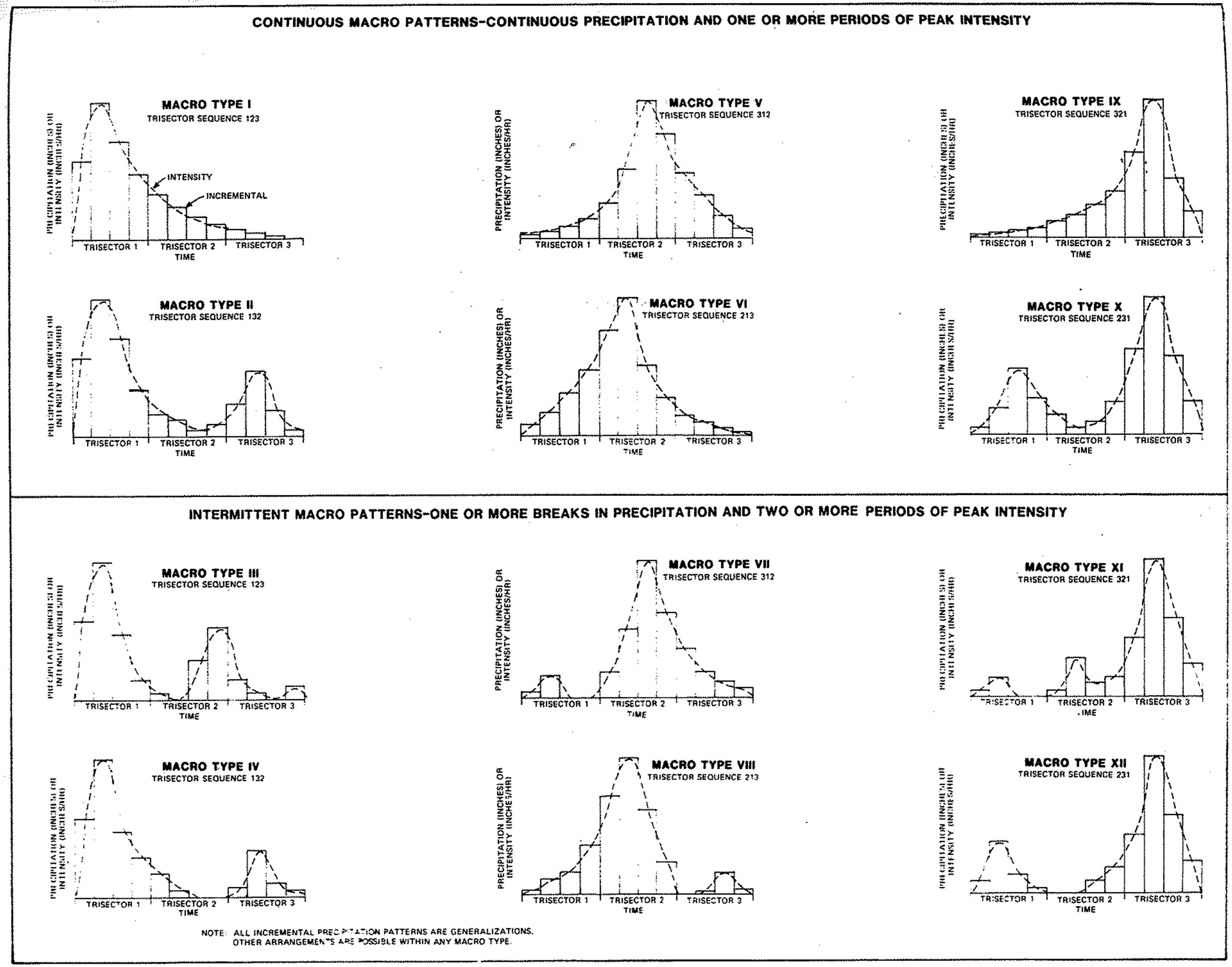
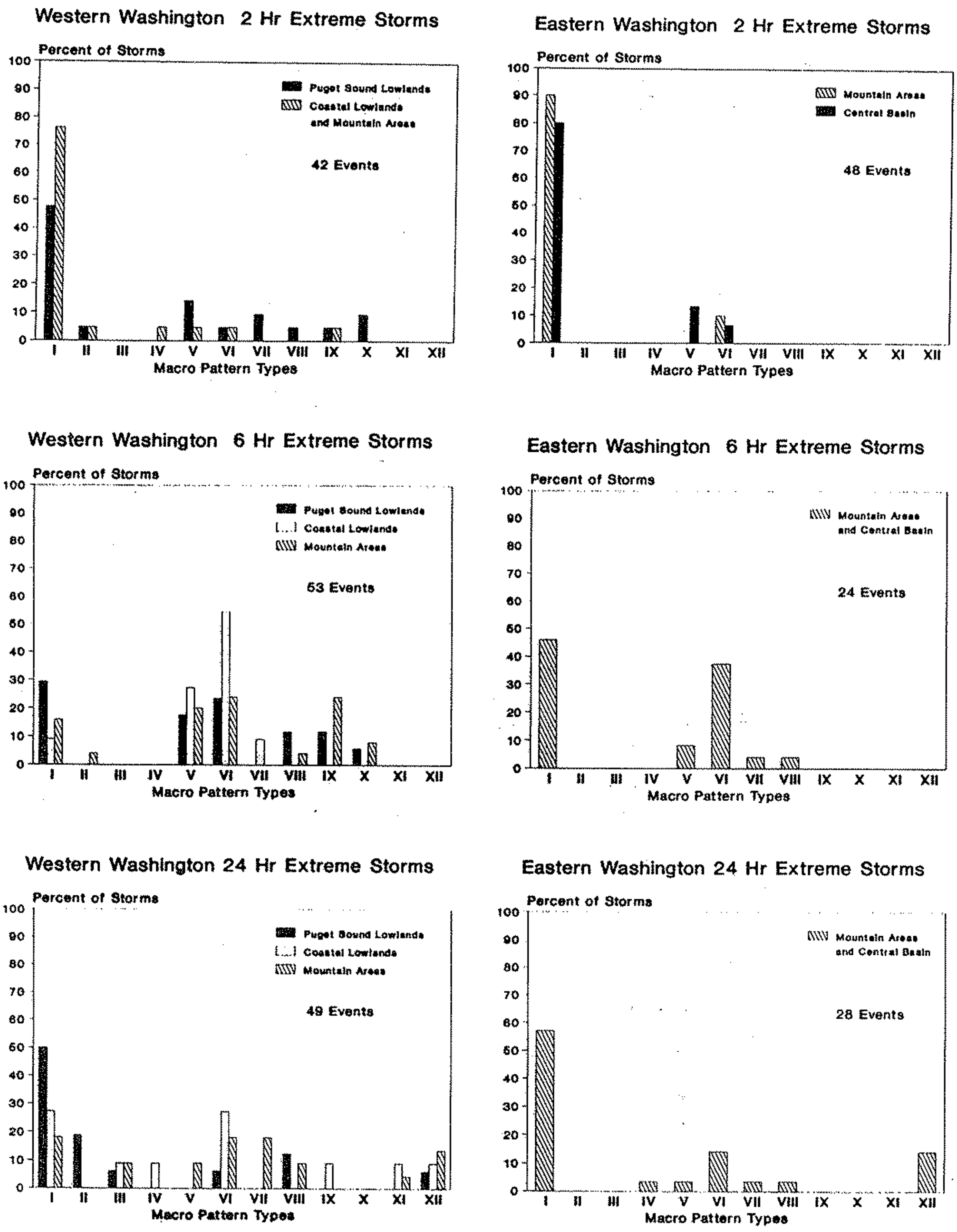


FIGURE 5. GENERALIZED MACRO STORM PATTERNS FOR CATEGORIZATION OF EXTREME STORMS.



Figures 6a,6d Frequency Histograms for Macro Patterns
6b,6e of Extreme Storms in Washington State
6c,6f

Table 4. Typical Macro Storm Characteristics For Extreme Storms

REGION	INDEPENDENT DURATION (hours)	TOTAL DURATION (hours)	MACRO STORM CHARACTERISTICS: TIME OF HIGHEST INTENSITY (hours) MEAN	STND. DEVIATION	EFFECTIVE DURATION (hours) MEAN	TYPICAL MACRO PATTERN
1 & 2	2	6	0.7	0.7	1.3	I
3 & 4 & 5	2	6	0.9	0.6	2.6	I
1	6	18	6.3	3.7	10.5	VI
2	6	18	6.3	3.7	9.0	VI
3	6	18	9.2	4.3	10.1	VI
4	6	18	9.2	4.3	12.5	VI
5	6	18	9.2	4.3	12.1	VI
1	24	72	23.7	16.7	40.8	I
2	24	72	15.6	13.5	30.4	I
3	24	72	25.5	14.2	38.1	I
4	24	72	33.6	14.5	45.3	VI
5	24	72	30.6	17.2	49.5	VI

A review of the results displayed in the frequency histograms and contained in Tables 3,4 reveals several trends. The 2 hour ID events, in all regions, had predominately Type I macro patterns with the high intensity segment near the beginning of the storm. Frequently, these storms were quite localized, convective events which dissipated rapidly after the occurrence of the high intensity segment. Storms of this type would carry the generic label of "thunderstorm".

Comparison of characteristics for mountain areas versus lowlands for the 6 hour and 24 hour ID storms, in either eastern or western Washington, revealed the mountain areas to always have larger effective durations. This results from persistence of the storm in mountain areas due to the orographic lifting of atmospheric moisture which is not present in lowland areas. The persistence of precipitation due to orographic effects will be quantified in the section on depth-duration relationships.

The short duration storms occurred almost exclusively as continuous events. As the duration of the storm increased, there was an increase in the percentage of intermittent macro patterns. Likewise, there was a tendency for greater variability in observed macro patterns as the storm duration became longer. While, the short duration events occured primarily as Type I macro patterns, the longer duration events exhibited a number of macro patterns which were nearly equally likely.

It will be seen later that a macro pattern for use in developing a synthetic storm will not be selected directly. Instead, the determination of an appropriate macro pattern will be governed by the selection of the time of occurrence and sequence of incremental precipitation amounts surrounding the high intensity segment. This issue will be discussed in the section on Assembly of Synthetic Storms.

ANALYSIS OF DEPTH-DURATION CURVES

The depth-duration curve [Chow, 1964], [WMO, 1974] is an analytical tool originally developed by meteorologists to allow precipitation depth and duration comparisons to be made between observed storms. In simple terms, the depth-duration curve is a precipitation mass curve created by rearrangement of observed storm precipitation in a manner which contains the largest incremental precipitation amounts at the start of the new mass curve. The primary application of depth-duration data is in the construction of synthetic storms for use in rainfall-runoff modeling.

Historically, depth-duration data have been used in a deterministic manner which does not incorporate the stochastic nature of storms. Depth-duration curves have usually been obtained from only a small number of "representative" storms and then scaled to the magnitude necessary for a specific application. An alternative procedure has been to prepare an "envelope" curve which envelopes all observed storms and which is intended to represent the most severe manner in which the storm might occur. Neither of these two procedures exploit the full amount of information contained in the observed storm data.

In this element of the study, regional analyses techniques will be utilized to statistically examine a large number of extreme storms. This procedure will allow the development of a family of probabilistic depth-duration curves which have the statistical characteristics of depth-duration data exhibited by observed extreme storms. The probabilistic framework employed herein will provide a methodology to predetermine the likelihood of the depth-duration characteristics which are used to assemble a given synthetic storm. Thus, a synthetic storm can be constructed which both suits the needs of a particular application and for which the likelihood of occurrence is reasonably known.

In the following sections, it is assumed that the reader is familiar with precipitation mass curves and with the construction of depth-duration curves. If needed, the reader may refer to Appendix 2 for a detailed discussion of depth-duration curves.

Methods of Analysis

Analyses of depth-duration curves/data were accomplished on a regional basis. Separate analyses were conducted on the collection of extreme storms at each of the three Independent Durations (IDs) for each region. A significant amount of data preparation was required prior to analysis and for sake of clarity, the progression of data preparation is listed below.

- For each storm, precipitation amounts were recorded at the time intervals shown in Table 7. A depth-duration curve was then assembled by accumulation of the incremental precipitation amounts using procedures contained in Appendix 2. Each duration for which mass precipitation was tabulated, except the ID, was labeled a Dependent Duration (DD).

Basic data needed to compute the curves were obtained either from weighing bucket charts from the National Climatic Data Center (NCDC), [NOAA, 1940-1986] or from incremental precipitation data contained in the Hourly Precipitation Data periodicals published by NCDC [NOAA, 1951-1986].

- The tabulated mass precipitation amounts at each dependent duration were made dimensionless by division by the precipitation amount for the independent duration.

- For curves which were based on incremental precipitation amounts obtained from NCDC periodicals, corrections were applied (Table 5) to the dimensionless tabulated amounts (ordinates) to account for systematic errors produced by recording precipitation at fixed intervals (Weiss, 1964).

These procedures transformed all mass precipitation amounts from the collection of extreme storms to a common scale. The dimensionless ordinates at each dependent duration could then be grouped together for analysis.

Table 5. Corrections Applied to Dimensionless Ordinates in Depth-Duration Curves

INDEPENDENT DURATION (hours)	DATA SOURCE	CORRECTIONS APPLIED TO DIMENSIONLESS DEPTH-DURATION ORDINATES — TABULATION TIMES - - DEPENDENT DURATIONS: MINUTES 15	30	45	60	75	90	HOURS 2	3	4	5	6
2	FP	1.12	1.03	1.02	1.01	1.01	1.00	1.00	1.00	0.99	0.99	0.99
2	HR	--	--	--	1.09	--	--	1.00	0.99	0.98	0.97	0.97

INDEPENDENT DURATION (hours)	DATA SOURCE	CORRECTIONS APPLIED TO DIMENSIONLESS DEPTH-DURATION ORDINATES — TABULATION TIMES - - DEPENDENT DURATIONS: MINUTES 15	30	60	HOURS 2	3	6	9	12	15	18	24	36	48	60	72
6	FP	1.13	1.04	1.02	1.01	1.00	1.00	1.00	1.00	1.00	1.00					
6	HR	--	--	1.12	1.03	1.02	1.00	1.00	0.99	0.99	0.99					
24	FP	1.13	1.04	1.02	1.01	1.01	1.00	1.00	1.00	--	1.00	1.00	1.00	1.00	1.00	1.00
24	HR	--	--	1.13	1.04	1.03	1.01	1.00	1.00	--	1.00	1.00	1.00	1.00	1.00	1.00

FP -- Fisher Porter recording gage .. reporting at 15 minute intervals
HR -- Hourly recording gage .. reporting at clock-hour intervals

Stage 1 of Analyses

Probabilistic analyses were accomplished in two stages for the depth-duration data for each ID within each region. The first stage was patterned after techniques used by the NWS [Frederick et al, 1981] wherein frequency analyses were conducted on the dimensionless ordinates at each of the dependent durations. In the NWS study, the Extreme Value Type I distribution [Fisher and Tippett, 1929] was used to model the magnitude-frequency characteristics of the ordinate data. Upon review of the ordinate data it was determined that the Beta Distribution [Benjamin and Cornell, 1970] would be a better choice. The four parameter Beta distribution was selected because it is extremely flexible, being capable of modeling data with either a positive or negative skew as exhibited by the ordinate data at various dependent durations.

The Beta distribution also incorporates both an upper and lower bound which is consistent with the physical constraints inherent in the construction of depth-duration curves (Figure 7).

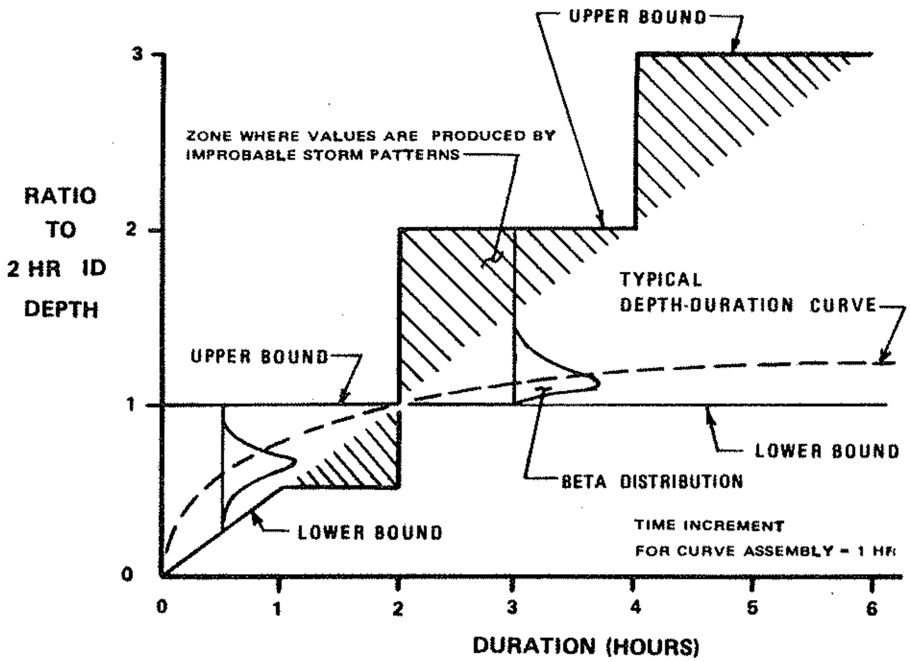


Figure 7. Depth-Duration Curve for 2 Hour ID Extreme Storm Depicting Typical Characteristics and Physical Boundaries

The probability density function for the Beta distribution is:

$$f(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\ \Gamma(\beta)} \left[(\delta_2-\delta_1)^{1-\alpha-\beta} \right] (x-\delta_1)^{\alpha-1} \ (\delta_2-x)^{\beta-1} \qquad (1)$$

where:

δ_1 and δ_2 are the lower and upper bounds respectively
α and β are distribution parameters
$\Gamma(\ )$ is the Gamma function

The conventional moments for the Beta distribution are:

$$\mu_x = \delta_1 + (\delta_2 - \delta_1) \left[\frac{\alpha}{(\alpha+\beta)} \right] \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$\sigma_x^2 = (\delta_2 - \delta_1)^2 \left[\frac{\alpha\beta}{(\alpha+\beta)^2 \ (\alpha+\beta+1)} \right] \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$\gamma_x = \frac{\alpha}{\sigma_x^3 \ (\alpha+\beta)} \left[\frac{(\alpha+2)(\alpha+1)}{(\alpha+\beta+2)(\alpha+\beta+1)} - \frac{3\alpha(\alpha+1)}{(\alpha+\beta)(\alpha+\beta+1)} + \frac{2\alpha^2}{(\alpha+\beta)^2} \right] \quad (4)$$

where:

μ_x, σ_x^2 and γ_x are the mean, variance and skew coefficient respectively

The method of moments was used to estimate the distribution parameters and quantile estimates where obtained for the ordinate values by numerical integration of the density function.

The results of the magnitude-frequency analyses are displayed in Figures 8a,b,c,d,e,f. It should be noted that the analysis of the ordinate data at each of the dependent durations is accomplished separately and without consideration of the ordinate data at other DDs. Thus, while this type of analysis provides valid magnitude-frequency information at a given DD, this information, alone, is insufficient to assemble synthetic depth-duration curves. For there are innumerable combinations in which the ordinate values, and a resultant depth-duration curve, can be assembled.

Further information is needed on the interrelationships between the ordinate values to determine the statistical dependencies. This type of analysis will be conducted in Stage 2 and will ultimately allow decisions to be made regarding which combinations are "best" and reflect observed storm characteristics.

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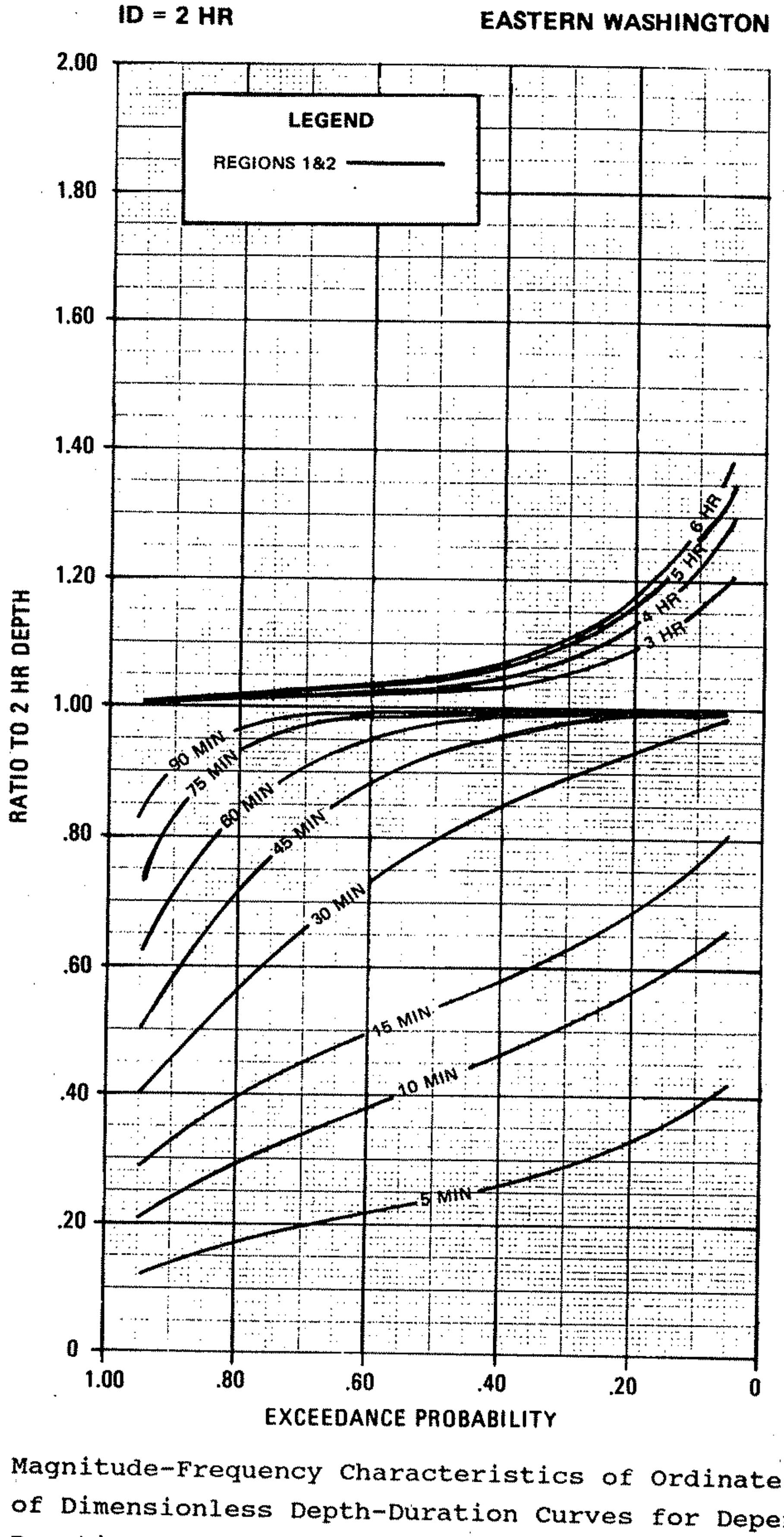

Figure 8a. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 2 Hour Extreme Storms in Eastern Washington

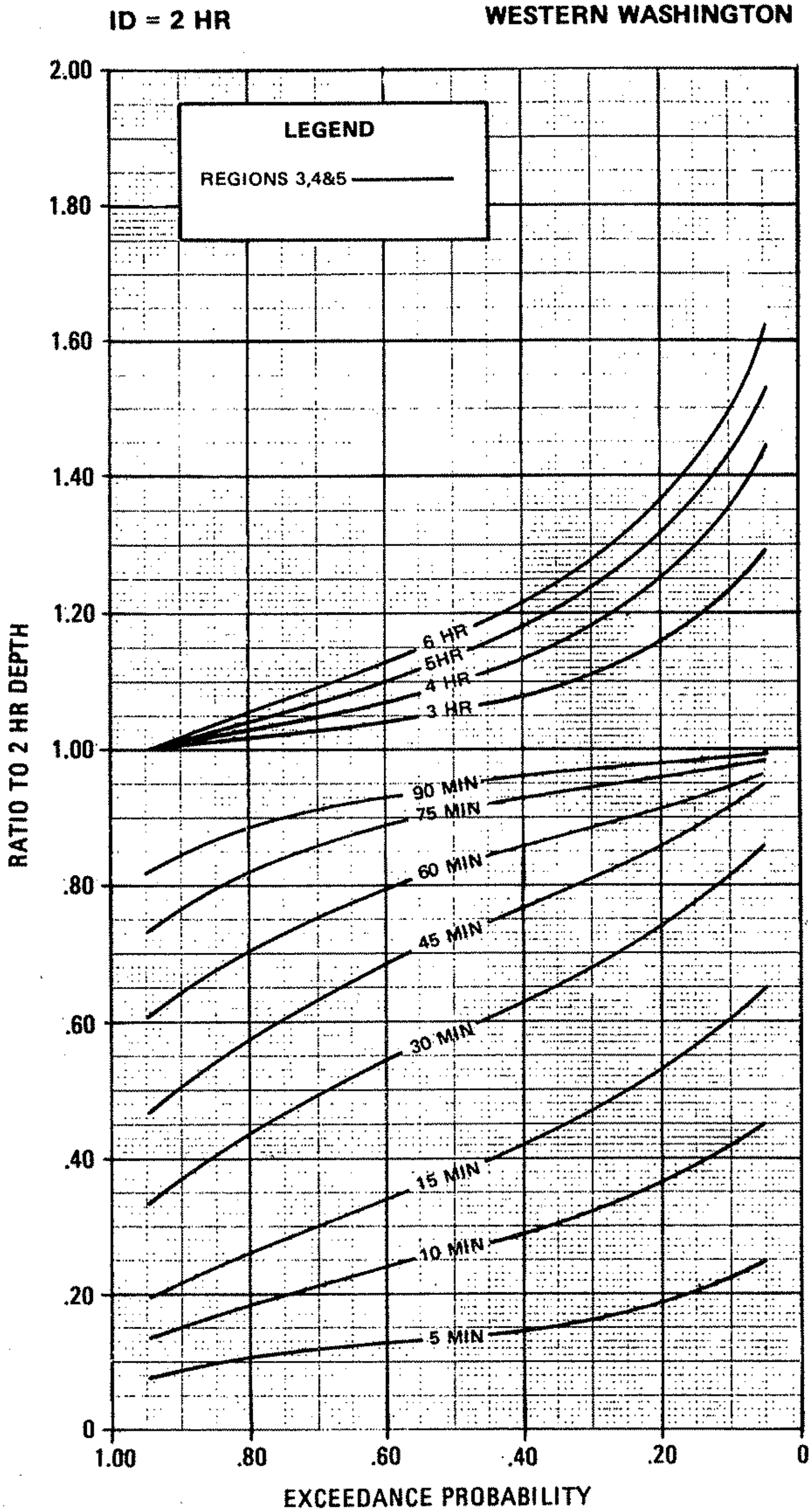

Figure 8b. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 2 Hour Extreme Storms in Western Washington

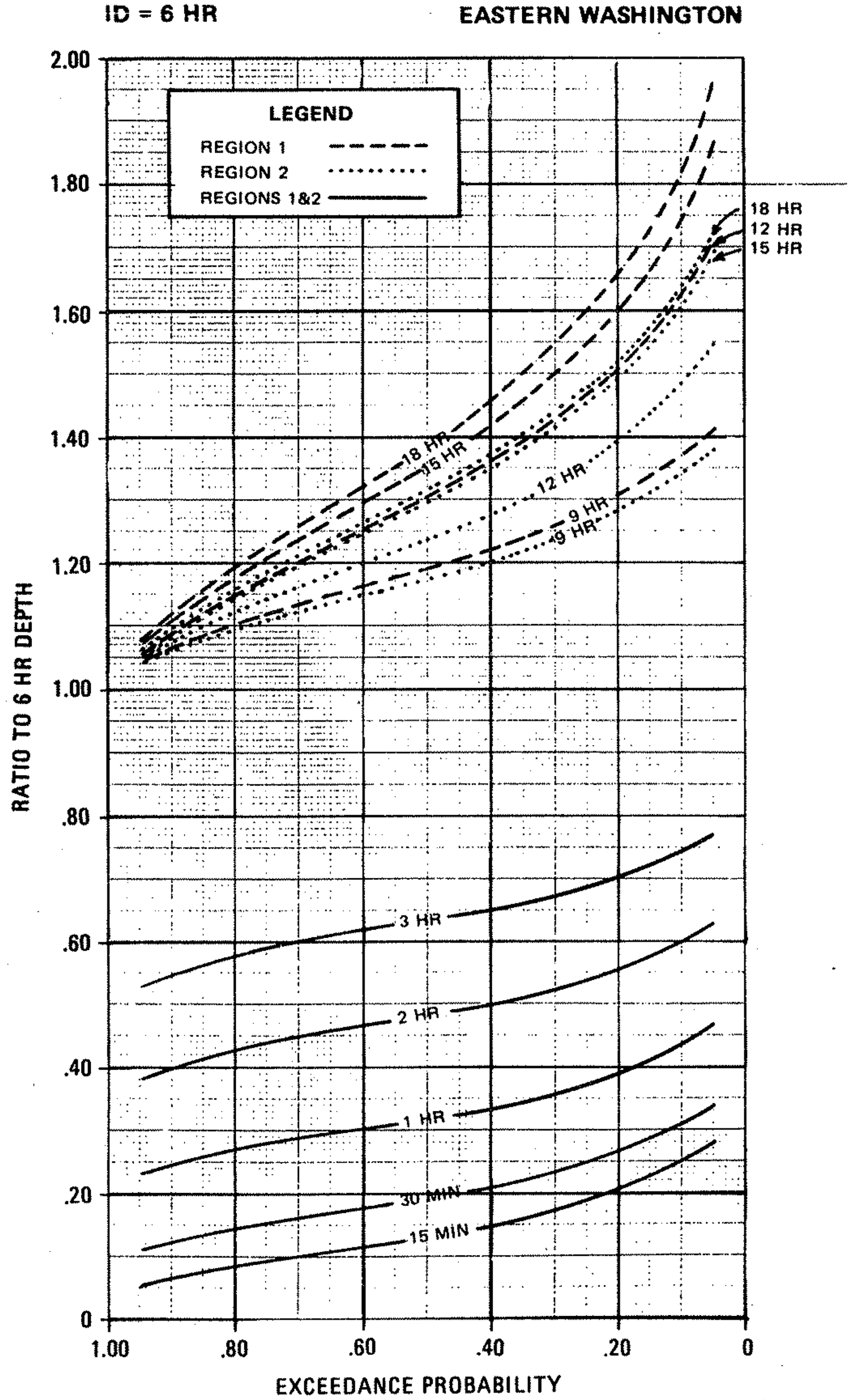

Figure 8c. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 6 Hour Extreme Storms in Eastern Washington

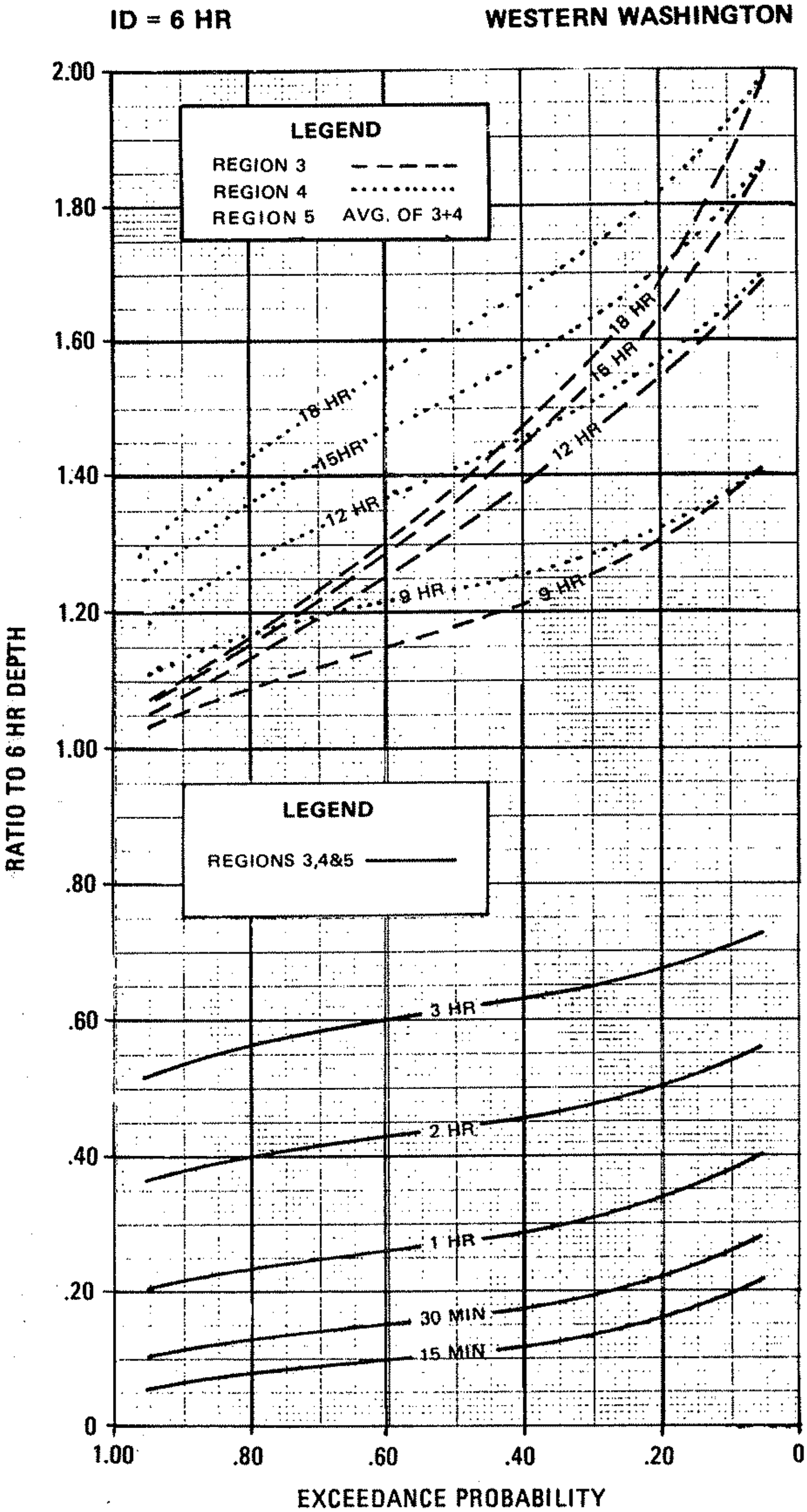

Figure 8d. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 6 Hour Extreme Storms in Western Washington

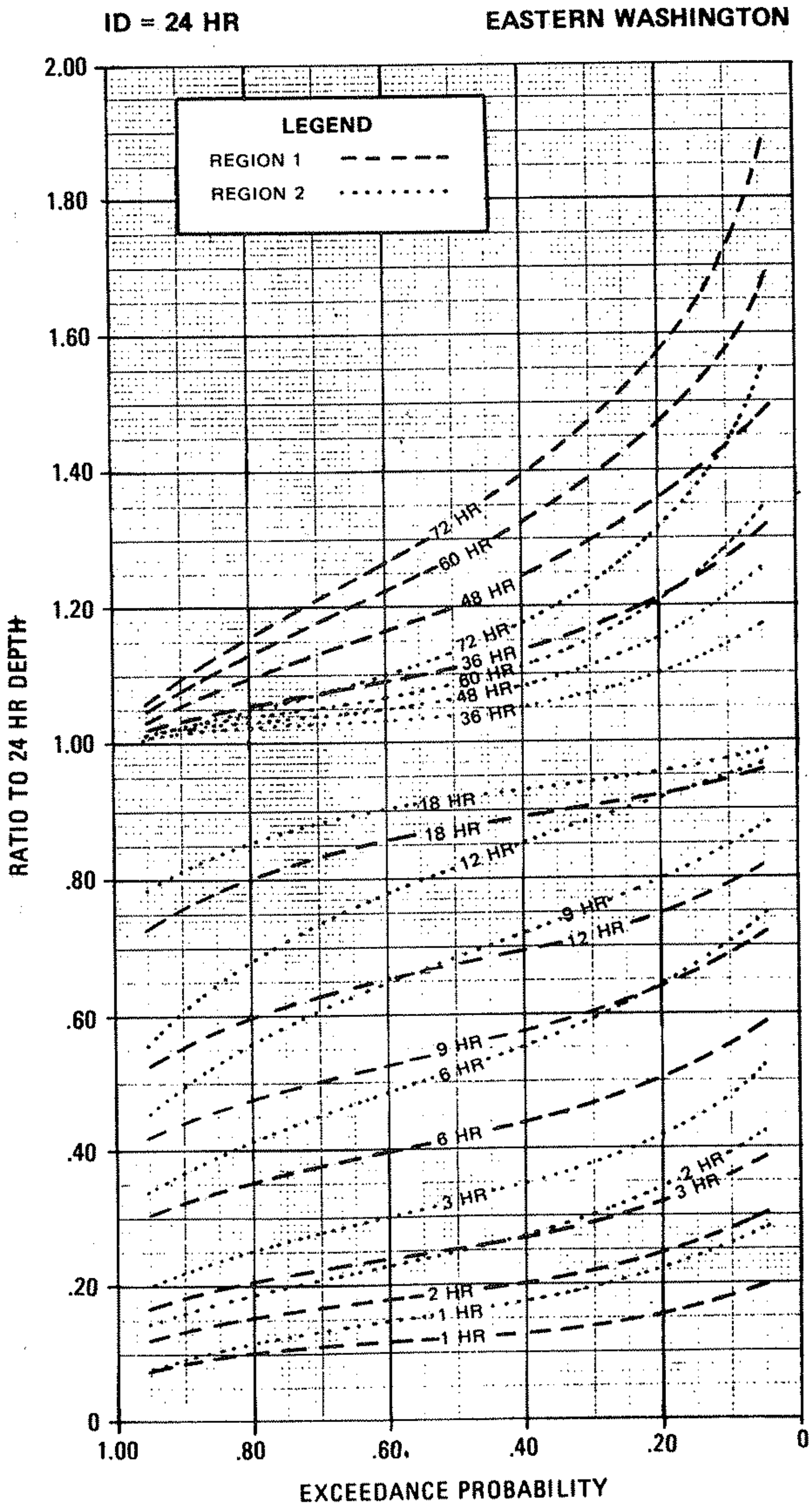

Figure 8e. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 24 Hour Extreme Storms in Eastern Washington

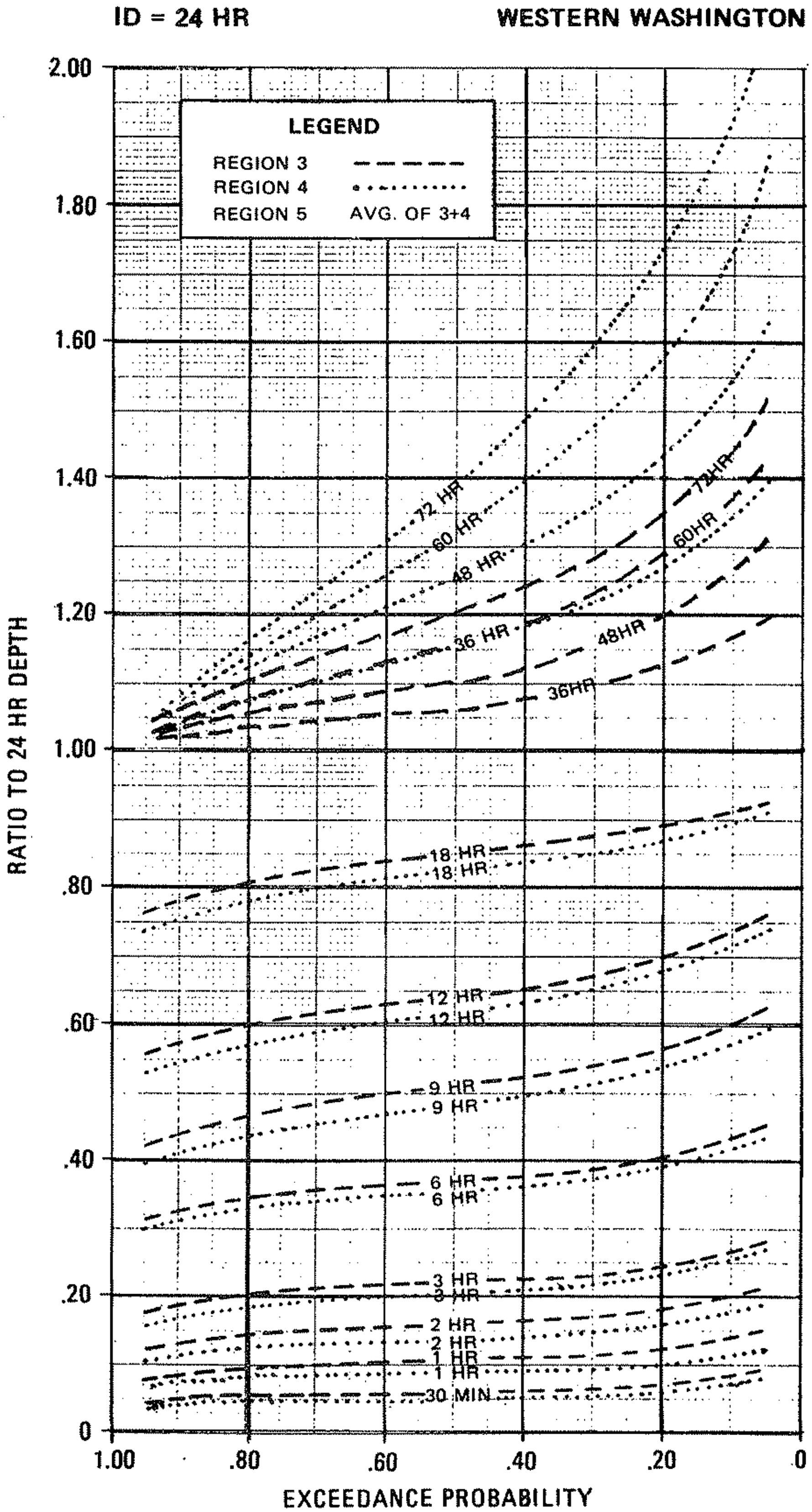

Figure 8f. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 24 Hour Extreme Storms in Western Washington

Stage 2 of Analyses

The second stage of analysis was employed to determine the interrelationships between the ordinates at the various Dependent Durations (DDs). This required an investigation of the correlation structure of the DD ordinate values. Use of the correlation structure provided information by which selection of the ordinate value for a specific DD would allow realistic selection of the ordinate values at other DDs.

The analysis was initiated by computing correlation coefficients for all DD ordinate pairs at each of the three IDs in each of the five regions. Cross-correlation matrices were then assembled for inspection. A review of the magnitude of the correlation coefficients for some typical cross-correlation matrices (Tables 6a,b,c) reveals that the DD ordinates are highly correlated. In addition, given any specific DD, the correlation coefficients are seen to decay in absolute magnitude with DDs progressively further from the starting DD. Strong correlation interrelationships exist for the short duration 2 hour ID events and there is a movement towards weaker correlation structure for the longer duration 24 hour ID events where the time increment between DDs becomes greater.

To properly utilize this information, a methodology was needed to allow the correlation structure to be incorporated into the selection of DD ordinates values for the development of the depth-duration curves. One approach available was to develop a stochastic model for generating synthetic storms. The correlation decay characteristics of the depth-duration data were indicative that models such as the Auto Regressive (AR) or Auto Regressive Moving Average (ARMA) models [Box and Jenkins, 1976] might be applicable. Variations of models of precipitation point processes such as those discussed by Woolhiser and Osborn [1985] or Istok and Boersma [1989] could also provide suitable alternatives.

After due consideration, it was determined that nothing as sophisticated as these models was needed. The primary objective of this element of the analyses was to develop a finite number of depth-duration curves which would span the range exhibited in observed storms. Therefore, a simple way to include the correlation structure would be to use disaggregation techniques

Table 6a. Cross-Correlation Matrix for Dependent Duration Ordinates for 2 Hour Extreme Storms in Eastern Washington

CROSS-CORRELATION MATRIX

2 HOUR EXTREME STORMS - - EASTERN WASHINGTON REGIONS 1 & 2

DEPENDENT DURATION (hours)	DEPENDENT DURATION (hours) .08	.17	.25	.50	.75	1.00	1.25	1.50	3.00	4.00	5.00	6.00
.08	1.00	.89	.77	.74	.71	.74	.72	.70	-.74	-.66	-.47	-.42
.17	.89	1.00	.93	.78	.75	.75	.70	.67	-.67	-.63	-.43	-.33
.25	.77	.93	1.00	.86	.81	.81	.71	.68	-.71	-.66	-.57	-.49
.50	.75	.78	.86	1.00	.93	.90	.82	.77	-.79	-.73	-.63	-.58
.75	.71	.75	.81	.93	1.00	.97	.94	.88	-.79	-.72	-.64	-.60
1.00	.74	.75	.81	.90	.97	1.00	.99	.95	-.71	-.73	-.72	-.68
1.25	.72	.70	.71	.82	.94	.99	1.00	.98	-.89	-.84	-.70	-.65
1.50	.70	.67	.68	.77	.88	.95	.98	1.00	-.93	-.89	-.77	-.72
3.00	-.74	-.67	-.71	-.79	-.79	-.71	-.89	-.93	1.00	.94	.89	.88
4.00	-.66	-.63	-.66	-.73	-.72	-.73	-.84	-.89	.94	1.00	.95	.93
5.00	-.47	-.43	-.57	-.63	-.64	-.72	-.70	-.77	.89	.95	1.00	.99
6.00	-.42	-.33	-.49	-.58	-.60	-.68	-.65	-.72	.88	.93	.99	1.00

Table 6b. Cross-Correlation Matrix for Dependent Duration Ordinates for 6 Hour Extreme Storms in Western Washington Mountains

CROSS - CORRELATION MATRIX

6 HOUR EXTREME STORMS - - WESTERN WASHINGTON REGION 4

DEPENDENT DURATION (hours)	DEPENDENT DURATION (hours) .25	.50	1.00	2.00	3.00	9.00	12.00	15.00	18.00
.25	1.00	.98	.91	.90	.91	-.34	-.70	-.75	-.74
.50	.98	1.00	.85	.77	.46	-.25	-.39	-.47	-.63
1.00	.91	.85	1.00	.93	.75	-.31	-.36	-.33	-.36
2.00	.90	.77	.93	1.00	.84	-.47	-.55	-.46	-.44
3.00	.91	.46	.75	.84	1.00	-.35	-.51	-.51	-.47
9.00	-.34	-.25	-.31	-.47	-.35	1.00	.87	.73	.66
12.00	-.70	-.40	-.36	-.55	-.51	.87	1.00	.91	.85
15.00	-.75	-.47	-.33	-.46	-.51	.73	.91	1.00	.97
18.00	-.74	-.63	-.36	-.44	-.47	.66	.85	.97	1.00

Table 6c. Cross-Correlation Matrix for Dependent Duration Ordinates for 24 Hour Extreme Storms in Puget Sound Lowlands

CROSS-CORRELATION MATRIX

24 HOUR EXTREME STORMS - - WESTERN WASHINGTON REGION 3

DEPENDENT DURATION (hours)	DEPENDENT DURATION (hours) 1.00	2.00	3.00	6.00	9.00	12.00	18.00	36.00	48.00	60.00	72.00
1.00	1.00	.92	.82	.67	.44	.74	.62	-.45	-.43	-.31	-.33
2.00	.92	1.00	.91	.74	.51	.69	.69	-.36	-.27	-.18	-.24
3.00	.82	.91	1.00	.78	.56	.70	.72	-.34	-.24	-.20	-.24
6.00	.67	.74	.78	1.00	.86	.82	.62	-.35	-.24	-.17	-.27
9.00	.44	.51	.56	.86	1.00	.85	.59	-.39	-.22	-.13	-.20
12.00	.74	.69	.70	.82	.85	1.00	.74	-.42	-.31	-.21	-.30
18.00	.62	.69	.72	.62	.59	.74	1.00	-.22	-.02	.07	.06
36.00	-.45	-.36	-.34	-.35	-.39	-.42	-.22	1.00	.90	.87	.80
48.00	-.43	-.27	-.24	-.24	-.22	-.31	-.02	.90	1.00	.89	.78
60.00	-.31	-.18	-.20	-.17	-.13	-.21	.07	.87	.89	1.00	.94
72.00	-.33	-.24	-.24	-.27	-.20	-.30	.06	.80	.78	.97	1.00

[Valencia and Schaake, 1973] and standard correlation methods to preserve the correlation structure. Specifically, this could be accomplished by selecting a representative DD and using the appropriate regression parameters of slope and intercept from the cross-correlation analyses to estimate the "expected values" of the ordinates at all other DDs.

The selection of a representative DD for each of the IDs was made with consideration of several factors. First, estimation of the flood peak discharge is often the item of primary interest in rainfall-runoff modeling. And, the occurrence of the high intensity segment of a storm normally produces the flood peak discharge. Therefore, the representative DD should be a relatively short duration DD within the ID. Second, a review of the cross-correlation matrices revealed the short duration DDs to be highly correlated. Thus, the selection of a specific DD among the shorter duration DDs was not critical. Based on these considerations, the representative DD for use in developing probabilistic depth-duration curves for each ID was chosen such that it was from 1/4 to 1/3 the duration of the IDs. These representative durations were labeled as "Kernels" (Table 7) because they defined the initial ordinate from which all other DD ordinates would be obtained.

Table 7. Time Increments Used in Various Elements of the Study of the Temporal Distribution of Extreme Storms

INDEPENDENT DURATION (hours)	ASSEMBLY OF DEPTH DURATION CURVES (minutes)	KERNEL DEPENDENT DURATION (minutes)	HIGH INTENSITY STORM SEGMENTS (minutes)
2	60	30	15
6	180	120	60
24	360	360	60

After selection of the kernel DDs, the next step was to refine the estimates of the regression parameters obtained from the cross-correlation analyses. Improved estimates of the regression parameters were made based on a smoothing of either the correlation coefficients or the slope parameters. In either instance, the parameters to be smoothed were obtained from the cross-correlation analyses for the case where the kernel duration was the independent variable (see for example, graytone blocks in Tables 6a,b,c).

Three separate smoothing functions were employed (Figure 9). A first order polynomial was fit to the correlation coefficient data for DDs less than the kernel DD and a second order polynomial was fit to the data for DDs greater than the kernel DD but less than the ID. In both cases, the solution polynomials were constrained to a value of unity at the kernel DD. Improved estimates of the regression parameters were then made based on the new estimates of the cross-correlation coefficients and the observed sample statistics for the kernel and DD ordinate data.

Thus, for linear correlation where: $Y = a + bX$ . . . . (5)
Improved estimates of the regression parameters a and b are:

$$\bar{Y} = \hat{a} + \hat{b}\bar{X} \qquad \text{or} \qquad \bar{Y} = \hat{a} + \hat{\rho}(S_y/S_x)\,\bar{X} \quad . . . . (6)$$

where:

$\hat{\rho}$ is the improved estimate of the correlation coefficient
$\hat{a}$ and $\hat{b}$ are the improved estimates of the intercept and slope
$\bar{X}$ and S_x are the mean, standard deviation of the Kernel ordinate data
$\bar{Y}$ and S_y are the mean, standard deviation of some specified DD data

For DDs greater than the ID, the slope parameters from the regression analyses were plotted against the DDs and a second order polynomial was fit to the coefficients (Figure 9). The slope parameters were used in lieu of the correlation coefficients because they generally allowed a simpler function description. The solution for this case was constrained to a value of zero slope at the ID. Improved estimates of the intercept parameters were then made based on the new estimates of the slope parameters and the observed sample statistics for the kernel and DD ordinate data (equation 6).

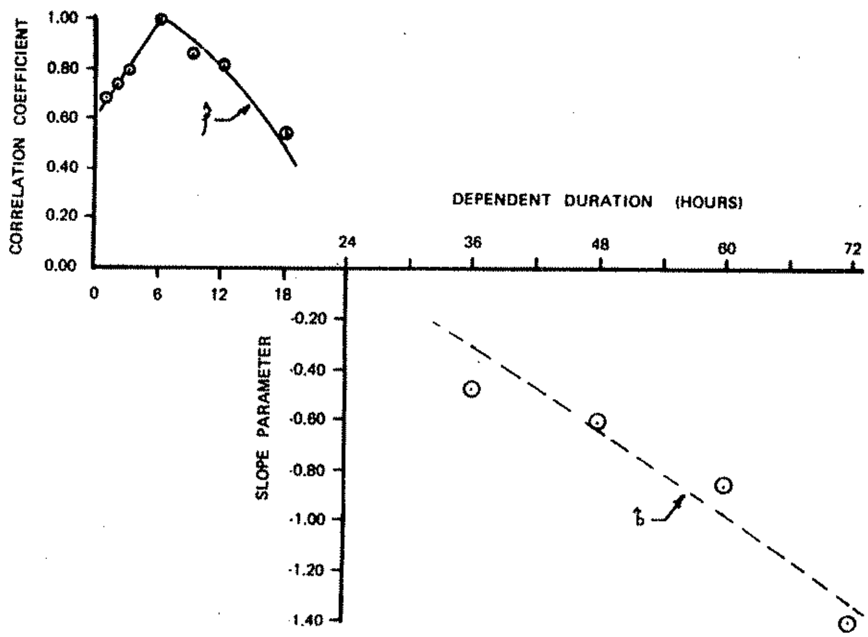

Figure 9. Smoothing Functions for Improving Regression Parameters Example - 24 Hour ID Storms for Puget Sound Lowlands

CONSTRUCTION OF PROBABILISTIC DEPTH-DURATION CURVES

The stage 1 and 2 solutions provided the framework for the construction of the probabilistic depth-duration curves. Curves were generated for each ID and region as follows:

- Nine levels of exceedance probability were selected for use in developing probabilistic depth-duration curves.

- The kernel ordinate was computed for each of the nine exceedance probabilities based on the results of fitting the Beta distribution to the ordinate data for the kernel DD. (Stage 1 solution).

- The ordinate values of each probabilistic depth-duration curve were then computed using the previously computed kernel ordinate and the improved estimates of the regression parameters from the cross-correlation analyses. (Stage 2 solutions).

The resultant depth-duration curves were then examined to verify the existence of a reasonably smooth monotonically increasing function with the the first derivative, the slope of the curve, exhibiting a continuously decreasing positive magnitude over the initial period of time equal to the ID. Both of these characteristics are desirable properties of synthetic depth-duration curves. For some curves, minor adjustments of the ordinate values were made to produce the characteristics described above.

Probabilistic depth-duration curves generated by these procedures are shown in Tables 8a,b,c,d,e,f,g,h,i,j,k,l. After developing these curves, it is appropriate to examine their characteristics. A review of typical correlation matrices (Tables 6a,b,c) in combination with the curves in Tables 8a to 8l, reveals several common characteristics. For DDs which are shorter than the ID, there is positive correlation between DDs: i.e. above average ordinates are associated with above average ordinates; below average ordinates are associated with below average ordinates. For DDs which are longer than the ID, there is negative correlation with ordinates for DDs which are less than the ID. This produces synthetic depth-duration curves having certain characteristic shapes regardless of the ID. Curves with sharp rising limbs have predominately flat tails. Conversely, curves with more flattened rising limbs have heavier (steeper) tails (Figure 10). These characteristic shapes simply reflect the observed correlation structure of observed storms - it is quite rare to have the dimensionless depth-duration curve from an observed storm with an unusually steep rising limb <u>and</u> an unusually heavy tail.

With those thoughts in mind, an interpretation can be made of the probabilistic labels attached to the curves. In general, for a curve with a 0.20 exceedance probability, there would be a 20% chance that any given extreme storm would have a steeper rising limb, reflecting more severe rainfall intensities, than that for the 20% curve. In addition, these curves are comprised of expected values for all DD ordinates conditioned on the magnitude of the kernel ordinate. Thus, the depth-duration curve with a 20% label represents the most likely manner in which the curve will occur, given that the 20% kernel ordinate has occurred.

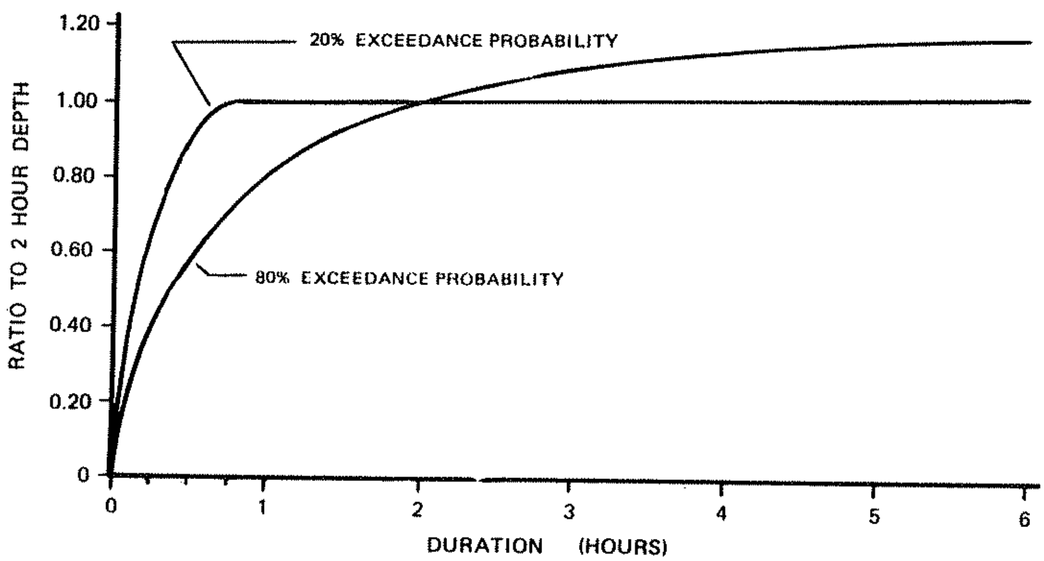

Figure 10. Typical Shape Characteristics of Depth-Duration Curves Example - 2 Hour ID Storms for Eastern Washington

Tables 8a,b Dimensionless Depth-Duration Curves for 2 Hour Extreme Storms in Washington State

ORDINATE VALUES
DIMENSIONLESS DEPTH-DURATION CURVES
2 HOUR EXTREME STORMS - EASTERN WASHINGTON - ALL AREAS - REGIONS 1 & 2
KERNEL VALUES AT 0.50 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.08	.17	.25	.50	.75	1.00	1.25	1.50	2.00	3.00	4.00	5.00	6.00
.95	.123	.223	.277	.422	.560	.686	.797	.900	1.000	1.160	1.208	1.242	1.246
.90	.149	.264	.331	.483	.621	.733	.829	.915	1.000	1.139	1.180	1.210	1.216
.80	.188	.325	.411	.574	.712	.803	.877	.937	1.000	1.106	1.138	1.162	1.171
.67	.227	.387	.492	.685	.804	.875	.925	.960	1.000	1.074	1.095	1.114	1.126
.50	.266	.449	.572	.794	.896	.945	.973	.982	1.000	1.041	1.057	1.070	1.082
.33	.297	.499	.636	.882	.969	1.000	1.000	1.000	1.000	1.015	1.027	1.037	1.044
.20	.318	.531	.679	.940	1.000	1.000	1.000	1.000	1.000	1.008	1.014	1.018	1.021
.10	.330	.551	.704	.975	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
.05	.335	.559	.714	.989	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

ORDINATE VALUES
DIMENSIONLESS DEPTH-DURATION CURVES
2 HOUR EXTREME STORMS - WESTERN WASHINGTON - ALL AREAS - REGIONS 3, 4 & 5
KERNEL VALUES AT 0.50 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.08	.17	.25	.50	.75	1.00	1.25	1.50	2.00	3.00	4.00	5.00	6.00
.95	.091	.158	.211	.355	.498	.639	.776	.888	1.000	1.166	1.265	1.328	1.356
.90	.098	.176	.240	.387	.529	.668	.792	.895	1.000	1.155	1.246	1.306	1.335
.80	.110	.202	.283	.440	.582	.711	.830	.905	1.000	1.138	1.218	1.273	1.303
.67	.123	.232	.332	.504	.641	.761	.857	.917	1.000	1.119	1.187	1.236	1.268
.50	.139	.267	.386	.586	.712	.814	.888	.931	1.000	1.097	1.149	1.193	1.226
.33	.155	.304	.442	.671	.783	.867	.920	.945	1.000	1.074	1.111	1.148	1.183
.20	.172	.337	.493	.747	.849	.916	.949	.969	1.000	1.053	1.089	1.120	1.144
.10	.188	.368	.542	.821	.911	.962	.977	.990	1.000	1.037	1.074	1.099	1.106
.05	.197	.390	.575	.871	.955	.980	.989	.996	1.000	1.021	1.047	1.060	1.078

Tables 8c,d Dimensionless Depth-Duration Curves for 6 Hour Extreme Storms in Eastern Washington

ORDINATE VALUES
DIMENSIONLESS DEPTH-DURATION CURVES
6 HOUR EXTREME STORMS - EASTERN WASHINGTON - MOUNTAINS - REGION 1
KERNEL VALUES AT 2.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)									
	.25	.50	1.00	2.00	3.00	6.00	9.00	12.00	15.00	18.00
.95	.079	.134	.235	.405	.575	1.000	1.314	1.475	1.587	1.621
.90	.087	.144	.247	.420	.588	1.000	1.299	1.453	1.560	1.595
.80	.099	.158	.266	.440	.606	1.000	1.276	1.421	1.522	1.558
.67	.111	.173	.286	.464	.626	1.000	1.251	1.386	1.481	1.519
.50	.126	.191	.309	.498	.650	1.000	1.222	1.345	1.432	1.472
.33	.143	.210	.335	.534	.676	1.000	1.190	1.300	1.379	1.420
.20	.159	.230	.361	.571	.703	1.000	1.158	1.254	1.324	1.368
.10	.178	.252	.391	.613	.733	1.000	1.121	1.203	1.263	1.309
.05	.194	.271	.416	.648	.758	1.000	1.090	1.159	1.211	1.259

ORDINATE VALUES
DIMENSIONLESS DEPTH-DURATION CURVES
6 HOUR EXTREME STORMS - EASTERN WASHINGTON - CENTRAL BASIN - REGION 2
KERNEL VALUES AT 2.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)									
	.25	.50	1.00	2.00	3.00	6.00	9.00	12.00	15.00	18.00
.95	.079	.134	.235	.405	.575	1.000	1.289	1.410	1.487	1.511
.90	.087	.144	.247	.420	.588	1.000	1.274	1.388	1.460	1.485
.80	.099	.158	.266	.440	.606	1.000	1.251	1.356	1.422	1.448
.67	.111	.173	.286	.464	.626	1.000	1.226	1.321	1.381	1.409
.50	.126	.191	.309	.498	.650	1.000	1.197	1.280	1.332	1.362
.33	.143	.210	.335	.534	.676	1.000	1.165	1.235	1.279	1.310
.20	.159	.230	.361	.571	.703	1.000	1.133	1.189	1.224	1.258
.10	.178	.252	.391	.613	.733	1.000	1.096	1.138	1.169	1.199
.05	.194	.271	.416	.648	.758	1.000	1.065	1.094	1.122	1.149

Tables 8e,f Dimensionless Depth-Duration Curves for 6 Hour Extreme Storms in Western Washington

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

6 HOUR EXTREME STORMS - WESTERN WASHINGTON - PUGET SOUND LOWLANDS - REGION 3

KERNEL VALUES AT 2.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)									
	.25	.50	1.00	2.00	3.00	6.00	9.00	12.00	15.00	18.00
.95	.075	.121	.210	.384	.557	1.000	1.248	1.401	1.495	1.533
.90	.080	.128	.219	.394	.566	1.000	1.241	1.389	1.481	1.520
.80	.089	.139	.233	.410	.581	1.000	1.231	1.372	1.461	1.500
.67	.099	.151	.249	.428	.597	1.000	1.220	1.353	1.438	1.478
.50	.111	.166	.268	.450	.617	1.000	1.205	1.329	1.410	1.450
.33	.124	.184	.290	.482	.640	1.000	1.189	1.301	1.378	1.418
.20	.139	.202	.314	.515	.664	1.000	1.171	1.272	1.344	1.385
.10	.156	.224	.341	.554	.692	1.000	1.151	1.239	1.304	1.346
.05	.170	.242	.364	.587	.716	1.000	1.134	1.210	1.270	1.312

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

6 HOUR EXTREME STORMS - WESTERN WASHINGTON - MOUNTAINS - REGION 4

KERNEL VALUES AT 2.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)									
	.25	.50	1.00	2.00	3.00	6.00	9.00	12.00	15.00	18.00
.95	.075	.121	.210	.384	.557	1.000	1.296	1.486	1.611	1.689
.90	.080	.128	.219	.394	.566	1.000	1.291	1.478	1.601	1.679
.80	.089	.139	.233	.410	.581	1.000	1.283	1.466	1.586	1.665
.67	.099	.151	.249	.428	.597	1.000	1.274	1.453	1.569	1.648
.50	.111	.166	.268	.450	.617	1.000	1.264	1.436	1.548	1.627
.33	.124	.184	.290	.482	.640	1.000	1.252	1.417	1.523	1.604
.20	.139	.202	.314	.515	.664	1.000	1.239	1.397	1.498	1.579
.10	.156	.224	.341	.554	.692	1.000	1.224	1.374	1.468	1.550
.05	.170	.242	.364	.587	.716	1.000	1.211	1.354	1.443	1.525

Table 8g Dimensionless Depth-Duration Curves for 6 Hour Extreme Storms in Western Washington

EXCEEDANCE PROBABILITY FOR KERNEL	ORDINATE VALUES DIMENSIONLESS DEPTH-DURATION CURVES 6 HOUR EXTREME STORMS - WESTERN WASHINGTON - COASTAL LOWLANDS - REGION 5 KERNEL VALUES AT 2.00 HOURS DURATION (hours)									
	.25	.50	1.00	2.00	3.00	6.00	9.00	12.00	15.00	18.00
.95	.075	.121	.210	.384	.557	1.000	1.272	1.444	1.554	1.612
.90	.080	.128	.219	.394	.566	1.000	1.266	1.434	1.542	1.601
.80	.089	.139	.233	.410	.581	1.000	1.257	1.420	1.524	1.583
.67	.099	.151	.249	.428	.597	1.000	1.247	1.403	1.504	1.563
.50	.111	.166	.268	.450	.617	1.000	1.235	1.382	1.479	1.539
.33	.124	.184	.290	.482	.640	1.000	1.220	1.359	1.450	1.511
.20	.139	.202	.314	.515	.664	1.000	1.205	1.334	1.420	1.481
.10	.156	.224	.341	.554	.692	1.000	1.188	1.305	1.385	1.447
.05	.170	.242	.364	.587	.716	1.000	1.173	1.281	1.355	1.418

Tables 8h,i Dimensionless Depth-Duration Curves for 24 Hour Extreme Storms in Eastern Washington

ORDINATE VALUES
DIMENSIONLESS DEPTH-DURATION CURVES
24 HOUR EXTREME STORMS - EASTERN WASHINGTON - MOUNTAINS - REGION 1
KERNEL VALUES AT 6.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.038	.072	.130	.177	.308	.439	.570	.826	1.000	1.180	1.303	1.393	1.458
.90	.041	.079	.140	.190	.323	.455	.586	.832	1.000	1.173	1.292	1.380	1.445
.80	.049	.090	.156	.209	.351	.481	.608	.841	1.000	1.162	1.275	1.361	1.425
.67	.059	.102	.173	.230	.382	.509	.634	.850	1.000	1.151	1.257	1.339	1.403
.50	.070	.117	.194	.256	.420	.544	.665	.862	1.000	1.136	1.235	1.314	1.377
.33	.084	.133	.217	.285	.462	.586	.699	.874	1.000	1.120	1.210	1.285	1.347
.20	.097	.150	.241	.315	.506	.630	.735	.888	1.000	1.104	1.184	1.255	1.317
.10	.113	.169	.269	.349	.555	.679	.775	.903	1.000	1.085	1.155	1.222	1.282
.05	.126	.185	.292	.378	.597	.721	.809	.915	1.000	1.069	1.133	1.193	1.253

ORDINATE VALUES
DIMENSIONLESS DEPTH-DURATION CURVES
24 HOUR EXTREME STORMS - EASTERN WASHINGTON - CENTRAL BASIN - REGION 2
KERNEL VALUES AT 6.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.054	.107	.164	.219	.360	.501	.641	.848	1.000	1.087	1.150	1.189	1.262
.90	.062	.116	.177	.236	.380	.522	.661	.855	1.000	1.082	1.141	1.178	1.250
.80	.072	.128	.195	.258	.413	.553	.688	.865	1.000	1.074	1.129	1.162	1.233
.67	.083	.142	.214	.282	.447	.584	.716	.875	1.000	1.067	1.116	1.146	1.216
.50	.095	.157	.238	.309	.487	.624	.748	.887	1.000	1.058	1.101	1.127	1.196
.33	.108	.173	.261	.337	.528	.665	.782	.900	1.000	1.049	1.086	1.107	1.175
.20	.124	.188	.284	.366	.570	.707	.816	.912	1.000	1.040	1.071	1.087	1.155
.10	.135	.206	.310	.396	.615	.752	.852	.928	1.000	1.030	1.054	1.066	1.132
.05	.147	.220	.332	.422	.652	.789	.883	.943	1.000	1.022	1.040	1.048	1.114

Tables 8j,k Dimensionless Depth-Duration Curves for 24 Hour Extreme Storms in Western Washington

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

24 HOUR EXTREME STORMS - WESTERN WASHINGTON - PUGET SOUND LOWLANDS - REGION 3

KERNEL VALUES AT 6.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.043	.076	.133	.179	.311	.441	.569	.806	1.000	1.095	1.157	1.214	1.255
.90	.046	.080	.139	.187	.320	.452	.584	.812	1.000	1.092	1.152	1.208	1.249
.80	.050	.086	.147	.197	.335	.472	.604	.820	1.000	1.088	1.146	1.200	1.240
.67	.055	.091	.155	.208	.354	.493	.624	.829	1.000	1.083	1.139	1.192	1.232
.50	.060	.098	.165	.221	.376	.517	.648	.840	1.000	1.078	1.132	1.182	1.221
.33	.065	.106	.175	.235	.400	.544	.675	.851	1.000	1.073	1.123	1.172	1.210
.20	.071	.114	.186	.249	.424	.571	.702	.862	1.000	1.067	1.115	1.161	1.199
.10	.078	.122	.198	.265	.452	.602	.732	.875	1.000	1.061	1.105	1.149	1.186
.05	.083	.130	.209	.279	.475	.629	.758	.886	1.000	1.055	1.097	1.139	1.175

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

24 HOUR EXTREME STORMS - WESTERN WASHINGTON - MOUNTAINS - REGION 4

KERNEL VALUES AT 6.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.033	.059	.111	.159	.287	.411	.534	.779	1.000	1.211	1.329	1.436	1.537
.90	.036	.063	.116	.165	.294	.421	.545	.790	1.000	1.206	1.321	1.427	1.526
.80	.039	.068	.123	.174	.310	.437	.562	.803	1.000	1.199	1.311	1.414	1.511
.67	.043	.073	.130	.184	.327	.455	.581	.811	1.000	1.192	1.300	1.400	1.494
.50	.048	.080	.140	.197	.348	.478	.604	.821	1.000	1.182	1.287	1.382	1.472
.33	.054	.087	.150	.211	.371	.503	.630	.832	1.000	1.172	1.271	1.362	1.449
.20	.060	.095	.162	.225	.397	.532	.658	.844	1.000	1.160	1.255	1.341	1.423
.10	.067	.105	.175	.243	.426	.565	.691	.858	1.000	1.147	1.236	1.316	1.393
.05	.073	.113	.186	.258	.453	.595	.720	.870	1.000	1.135	1.219	1.294	1.367

Table 81 Dimensionless Depth-Duration Curves for 24 Hour Extreme Storms in Western Washington

EXCEEDANCE PROBABILITY FOR KERNEL	ORDINATE VALUES DIMENSIONLESS DEPTH-DURATION CURVES 24 HOUR EXTREME STORMS - WESTERN WASHINGTON - COASTAL LOWLANDS - REGION 5 KERNEL VALUES AT 6.00 HOURS DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.038	.067	.122	.167	.297	.425	.553	.798	1.000	1.158	1.255	1.343	1.412
.90	.040	.071	.127	.174	.308	.437	.566	.804	1.000	1.154	1.249	1.335	1.403
.80	.044	.077	.135	.184	.324	.456	.585	.811	1.000	1.148	1.241	1.324	1.391
.67	.049	.082	.143	.195	.342	.476	.605	.820	1.000	1.142	1.232	1.313	1.377
.50	.054	.089	.152	.207	.364	.500	.628	.830	1.000	1.135	1.221	1.299	1.362
.33	.059	.097	.163	.221	.388	.527	.654	.841	1.000	1.127	1.209	1.284	1.344
.20	.065	.104	.174	.236	.412	.555	.682	.853	1.000	1.119	1.197	1.268	1.326
.10	.072	.113	.187	.253	.441	.587	.713	.866	1.000	1.109	1.183	1.250	1.305
.05	.077	.121	.198	.267	.466	.615	.741	.878	1.000	1.101	1.170	1.234	1.287

In actual application, these procedures will preserve the three most important statistical characteristics of depth-duration curves, namely: the marginal distribution at the kernel duration (Stage 1); the correlation relationships between ordinate values, through the use of expected values of the ordinates at the various dependent durations (Stage 2); and the desired storm magnitude, through its use to directly scale the dimensionless ordinates.

In summary, the probabilistic depth-duration curves produced by these procedures, and displayed in the previous Tables, are descriptive of a wide range of observed depth-duration curves. These curves should be useful in rainfall-runoff modeling for examining the flood response of a watershed for a wide range of storm characteristics.

Depth-Duration Curves Conditioned on the Total Storm Depth

The depth-duration curves discussed up to this point have all been constructed conditioned on the magnitude of a high intensity storm segment. This was done because the high intensity segment of the storm is primarily responsible for producing the flood peak discharge. However, there are design cases where the volume of the flood is more important than the flood peak discharge. If the design of a facility is dependent on flood volume, then the 24 hour ID event (largest precipitation depth) would be the extreme storm of interest. A depth-duration curve for use in flood volume critical cases should, therefore, be conditioned on the magnitude of an ordinate for a long duration DD from the 24 ID storm.

The procedures for generating depth-duration curves conditioned on a long duration DD were essentially the same as those discussed previously. The following procedures were employed:

- The 48 hour duration was selected as the kernel DD.

- Nine levels of exceedance probability were selected to describe characteristic depth-duration curves.

- The 48 hour kernel ordinate was computed for each of the nine exceedance probabilities based on the results of fitting the Beta distribution to the ordinate data for the kernel DD (Stage 1 solution, Figures 8e,f).

- Improved estimates of the regression parameters from the cross-correlation analyses at the 48 hour DD were obtained using smoothing functions in a manner similar to that used in the Stage 2 solutions. A first order polynomial was fit to the correlation coefficients for DDs longer than the 48 hour kernel DD. The correlation coefficient at the 36 hour DD was retained as originally computed. A second order polynomial was fit to the slope parameters for DDs between 6 hours and 24 hours. For DDs less than 6 hours, the 6 hour ordinate amount was disaggregated in the same manner as was accomplished in Stage 2.

- The ordinate values of each probabilistic depth-duration curve were then computed using the previously computed 48 hour kernel ordinate and the improved estimates of the regression parameters from the cross-correlation analyses.

The depth-duration curves generated by these procedures are contained in Tables 9a,b,c,d,e. Differences between these curves and those curves containing ordinates conditioned on a high intensity segment (Tables 8h,i,j,k,l) are readily apparent (Figure 11). For curves at the same exceedance probability: a curve which was conditioned on the magnitude of a high intensity segment has a steeper rising limb (contains larger rainfall intensities) and a flatter tail. Conversely, if the depth-duration curve is conditioned on the magnitude of an ordinate for a DD longer than the ID, then it has a steeper tail (contains larger total depth) and a flatter rising limb.

Curves contained in Tables 8a to 8l and 9a to 9e obviously do not contain all ordinate combinations which could comprise depth-duration curves. They do, however, represent the most likely curves conditioned on the magnitude of high intensities or total storm depth, whichever is of primary interest.

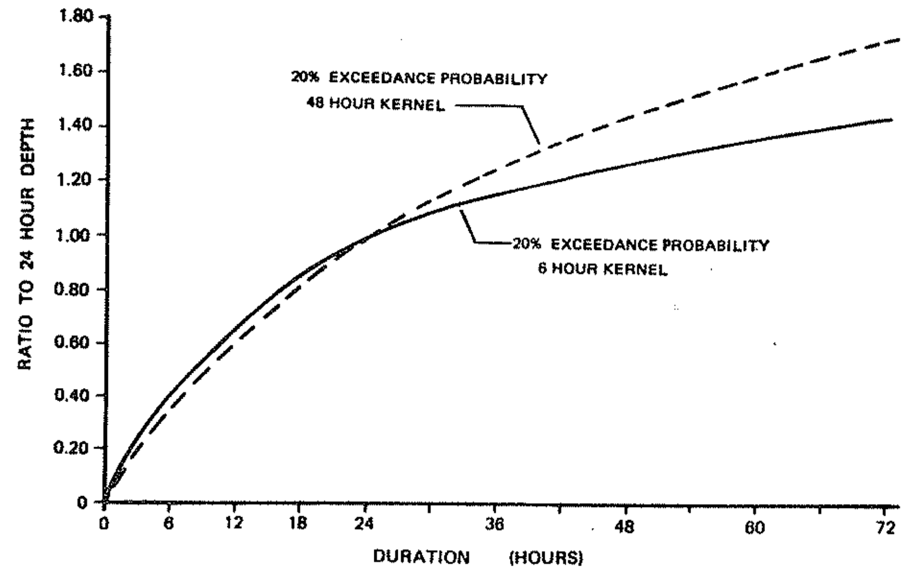

Figure 11. Comparison of Depth-Duration Curves for 24 Hour ID Storms Example - Western Washington Mountains

Table 9a,b Dimensionless Depth-Duration Curves with 48 Hour Kernel Ordinate for 24 Hour Extreme Storms in Eastern Washington

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

24 HOUR EXTREME STORMS - EASTERN WASHINGTON - MOUNTAINS - REGION 1

KERNEL VALUES AT 48.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.081	.129	.212	.279	.453	.586	.709	.892	1.000	1.014	1.022	1.085	1.165
.90	.080	.129	.211	.278	.451	.583	.706	.889	1.000	1.022	1.041	1.105	1.183
.80	.079	.127	.209	.275	.447	.578	.700	.885	1.000	1.040	1.076	1.143	1.219
.67	.077	.125	.206	.272	.442	.570	.692	.878	1.000	1.070	1.125	1.195	1.267
.50	.075	.122	.202	.267	.435	.560	.680	.870	1.000	1.115	1.193	1.268	1.334
.33	.072	.119	.197	.260	.426	.548	.666	.859	1.000	1.155	1.276	1.358	1.417
.20	.069	.115	.192	.254	.416	.534	.650	.847	1.000	1.197	1.367	1.455	1.507
.10	.066	.111	.186	.246	.405	.519	.633	.834	1.000	1.245	1.470	1.566	1.609
.05	.063	.107	.181	.240	.396	.508	.618	.823	1.000	1.285	1.555	1.657	1.693

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

24 HOUR EXTREME STORMS - EASTERN WASHINGTON - CENTRAL BASIN - REGION 2

KERNEL VALUES AT 48.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.102	.165	.251	.325	.510	.653	.779	.909	1.000	1.002	1.004	1.010	1.086
.90	.102	.165	.250	.324	.509	.652	.778	.908	1.000	1.004	1.008	1.015	1.090
.80	.101	.164	.249	.323	.507	.650	.775	.906	1.000	1.008	1.016	1.025	1.100
.67	.101	.163	.247	.321	.504	.646	.771	.903	1.000	1.019	1.033	1.045	1.118
.50	.099	.161	.244	.317	.499	.638	.763	.896	1.000	1.042	1.064	1.082	1.153
.33	.096	.158	.240	.312	.491	.627	.750	.887	1.000	1.062	1.110	1.138	1.206
.20	.093	.154	.234	.305	.481	.613	.734	.875	1.000	1.087	1.169	1.208	1.272
.10	.089	.149	.228	.296	.468	.595	.713	.859	1.000	1.126	1.246	1.301	1.359
.05	.085	.145	.221	.287	.456	.578	.694	.850	1.000	1.166	1.318	1.387	1.440

Table 9c,d Dimensionless Depth-Duration Curves with 48 Hour Kernel Ordinate for 24 Hour Extreme Storms in Western Washington

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

24 HOUR EXTREME STORMS - WESTERN WASHINGTON - PUGET SOUND LOWLANDS - REGION 3

KERNEL VALUES AT 48.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.062	.102	.170	.228	.387	.534	.671	.857	1.000	1.007	1.014	1.038	1.071
.90	.062	.102	.169	.227	.387	.533	.669	.856	1.000	1.013	1.026	1.052	1.086
.80	.062	.101	.169	.227	.385	.531	.666	.853	1.000	1.023	1.045	1.076	1.111
.67	.062	.101	.168	.226	.384	.529	.663	.850	1.000	1.036	1.072	1.108	1.144
.50	.061	.100	.168	.225	.382	.525	.657	.845	1.000	1.063	1.107	1.152	1.190
.33	.061	.100	.166	.223	.380	.521	.651	.839	1.000	1.089	1.153	1.208	1.248
.20	.060	.099	.165	.222	.377	.516	.643	.832	1.000	1.117	1.204	1.271	1.314
.10	.059	.098	.164	.220	.374	.510	.634	.824	1.000	1.151	1.267	1.348	1.394
.05	.059	.097	.162	.218	.371	.504	.626	.816	1.000	1.181	1.324	1.417	1.465

ORDINATE VALUES

DIMENSIONLESS DEPTH-DURATION CURVES

24 HOUR EXTREME STORMS - WESTERN WASHINGTON - MOUNTAINS - REGION 4

KERNEL VALUES AT 48.00 HOURS

EXCEEDANCE PROBABILITY FOR KERNEL	DURATION (hours)												
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.052	.084	.146	.205	.362	.501	.631	.841	1.000	1.021	1.040	1.071	1.108
.90	.051	.084	.146	.205	.361	.499	.629	.839	1.000	1.035	1.069	1.103	1.147
.80	.051	.084	.145	.204	.360	.497	.625	.836	1.000	1.060	1.113	1.163	1.217
.67	.051	.083	.144	.203	.358	.494	.621	.832	1.000	1.100	1.173	1.239	1.305
.50	.050	.082	.143	.201	.356	.490	.614	.826	1.000	1.162	1.252	1.338	1.421
.33	.050	.081	.142	.200	.353	.485	.607	.820	1.000	1.214	1.344	1.455	1.557
.20	.049	.081	.141	.198	.350	.480	.600	.813	1.000	1.267	1.440	1.575	1.697
.10	.048	.080	.140	.197	.348	.474	.591	.805	1.000	1.326	1.544	1.706	1.851
.05	.048	.079	.139	.195	.345	.470	.585	.799	1.000	1.372	1.627	1.811	1.974

n

Table 9e Dimensionless Depth-Duration Curves with 48 Hour Kernel Ordinate for 24 Hour Extreme Storms in Western Washington

EXCEEDANCE PROBABILITY FOR KERNEL	ORDINATE VALUES DIMENSIONLESS DEPTH-DURATION CURVES 24 HOUR EXTREME STORMS - WESTERN WASHINGTON - COASTAL LOWLANDS - REGION 5 KERNEL VALUES AT 48.00 HOURS DURATION (hours)											
	.50	1.00	2.00	3.00	6.00	9.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
.95	.057	.093	.158	.215	.377	.519	.654	.850	1.000	1.019	1.036	1.066	1.103
.90	.056	.093	.158	.215	.376	.518	.652	.848	1.000	1.029	1.057	1.093	1.132
.80	.056	.092	.157	.214	.375	.516	.648	.845	1.000	1.046	1.092	1.137	1.181
.67	.056	.092	.156	.213	.373	.513	.643	.841	1.000	1.078	1.136	1.192	1.242
.50	.055	.091	.155	.212	.371	.509	.638	.835	1.000	1.119	1.193	1.264	1.322
.33	.055	.090	.154	.210	.368	.504	.631	.829	1.000	1.157	1.261	1.349	1.417
.20	.054	.090	.153	.208	.366	.499	.623	.822	1.000	1.197	1.333	1.440	1.518
.10	.053	.089	.152	.207	.363	.493	.615	.815	1.000	1.242	1.416	1.544	1.633
.05	.053	.088	.151	.205	.360	.489	.607	.808	1.000	1.281	1.486	1.632	1.731

VERIFICATION OF VALIDITY OF USING DIMENSIONLESS ORDINATES IN DEPTH-DURATION CURVES

The use of dimensionless depth-duration curves for analysis and design has been a standard technique for decades. An underlying assumption in the use of dimensionless depth-duration curves is that the curve ordinates are independent of scale. This infers that the probabilistic characteristics of the ordinate values are independent of the magnitude of the ID storm. Although dimensionless depth-duration and dimensionless precipitation mass curves are "well accepted", the author is unaware of any detailed theoretical discussion or an investigation of historical data to demonstrate the validity of the scale independence assumption.

An investigation of this assumption can be made by examination of the ordinate values for the kernel DDs relative to the ID storm magnitude. If the independence assumption is valid, then the sample correlation coefficient for the two variables would approach zero and there would be no trend for the ordinate values to increase or decrease with storm magnitude.

The 6 hour ID storm data set for western Washington is one case where there is both a sufficient number of storms and range of storm magnitude to examine the assumption of scale independence. Referring to Figure 12a, it is seen that for the range of 6 hour ID extreme storm data available, the kernel ordinates do not appear to vary with storm magnitude (correlation coefficient = 0.06). Additional analyses were conducted for the 2 hour ID data in eastern and western Washington and the results were similar. In both cases, correlation coefficients had absolute values less than 0.12.

An alternative way to examine the linear scaling assumption is to perform correlation analyses using a logarithmic transform of the original precipitation amounts at various DDs. The logarithm of the precipitation amounts for the ID would be used as the independent variable. In this type of procedure, the scaling is assumed to be a power function (equation 7) and if, in fact the scaling is linear, then the scaling equation simplifies to a linear form. A graphical depiction of this approach is shown in Figure 12b for the 6 hour extreme storm data in western Washington.

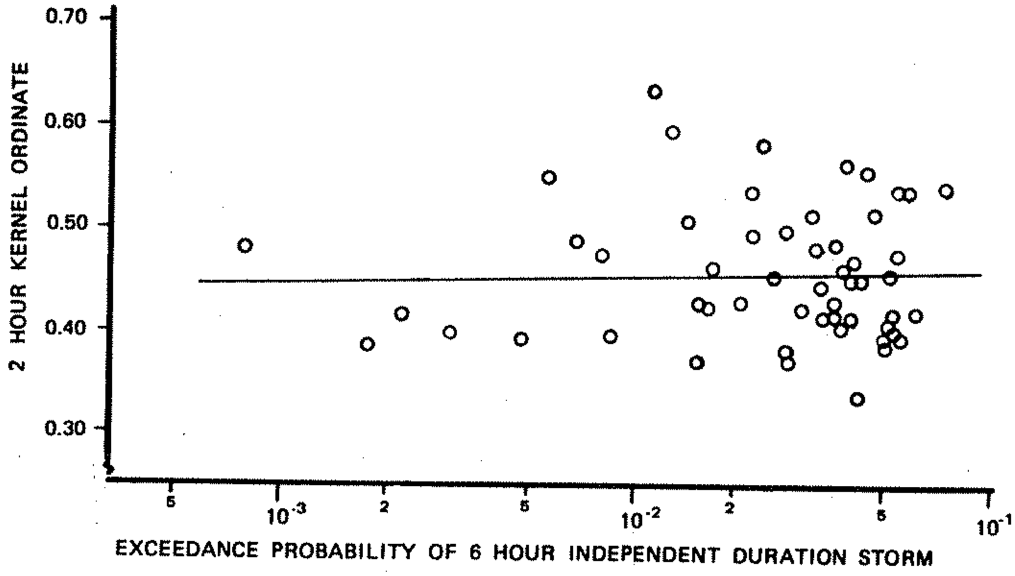

Figure 12a. Variation of Kernel Ordinates with Storm Annual Exceedance Probability
Example - 6 Hour ID Events Western Washington

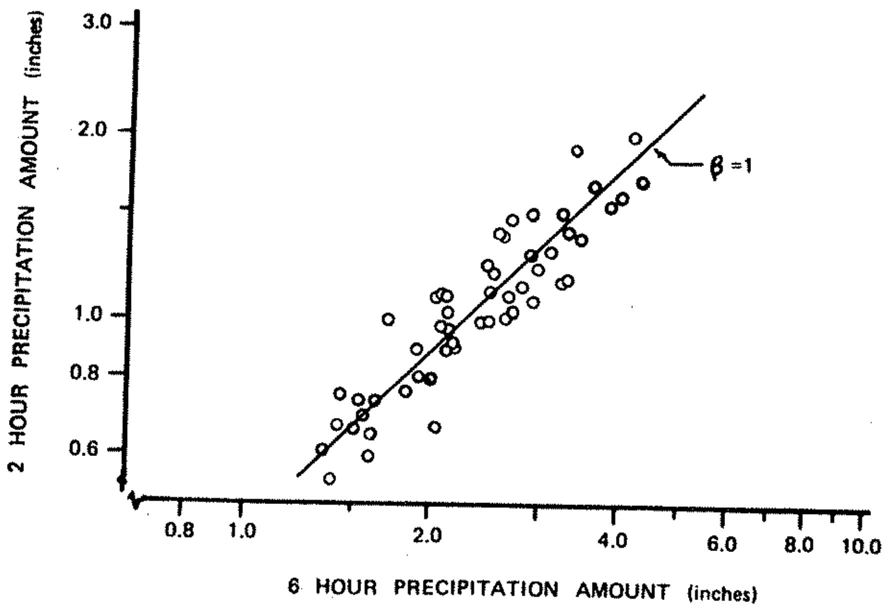

Figure 12b. Relationship of Kernel Duration Precipitation Amounts to Independent Duration Precipitation Amounts
Example - 6 Hour ID Events Western Washington

The scaling relationship for this approach is a simple power function. The solution equation follows directly from the use of log-log correlation and takes the form:

$$P_{dd} = \alpha \, P_{id}^{\ \beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where:

P_{dd} is the precipitation amount for a specified DD
P_{id} is the precipitation amount for the ID
α and β are intercept and slope parameters, respectively

If the linear scaling assumption is applicable, then the slope should have a value of near unity. Rearrangement of equation 7 for a slope of unity results in the equation simplifying to a linear scaling equation. Wherein, the ordinate value (P_{dd}/P_{id}) is equal to the constant α and is not scale (storm magnitude) dependent. If the slope takes on a value other than unity, then the scaling is non-linear and a function of storm magnitude as shown below:

$$\frac{P_{dd}}{P_{id}} = \alpha \, P_{id}^{\ \beta - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Log-log correlation analyses for the western Washington 6 hour extreme storms resulted in slope parameters near unity and ranging from 1.08 to 0.92 for DDs between 1 hour and 18 hours, respectively. Analyses for the short duration 2 hour extreme storm events in both eastern and western Washington produced similar results. Slope values ranged between 1.12 and 0.92 with the larger values generally associated with DDs within the ID and smaller values associated with DDs exterior to the ID.

Thus, based on the information available, it appears that the use of the ID precipitation depth to scale up or down a storm of interest, is a reasonable approximation of the meteorologic process.

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TIMING CHARACTERISTICS OF HIGH INTENSITY SEGMENT

The time of occurrence of the high intensity segment within a storm is an important element in the analysis of observed storms and in the development of synthetic storms. The time of occurrence of the high intensity segment within a storm often affects the magnitude of the flood peak which will be generated by the storm. Storms with the high intensity segment near the end of the storm will generally produce larger flood peaks than similar storms where the high intensity segment occurs near the beginning of the storm. This outcome is attributable to both the manner in which runoff collects from the tributary drainage of a watershed, and to the infiltration properties of soils. With regard to the soils, near the end of a storm, the surficial soils are at a wetter state than at the beginning, and thus they have lower infiltration capacity. This results in higher runoff rates and larger flood peaks when the high intensity segment occurs near the end of the storm period. In the design of reservoir projects, the occurrence of the flood peak near the end of the flooding period is often a more stringent design consideration because the reservoir volume allocated to flood control is partially filled prior to the arrival of the flood peak. Information on the observed timing characteristics of the high intensity segment of storms is, therefore, an important and necessary element in the assembly of synthetic storms.

In general, observed storms had only one period of high intensity. This was particularly true for the shorter duration events. In those cases where there were two distinct periods of high intensity, they were usually found in intermittent macro patterns for long duration events and represented the passage of separate fronts during a period of several days. When two periods of high intensity occurred, only the highest intensity segment was included in the data for analysis.

Analysis of the frequency characteristics for the time of occurrence of the high intensity segment was accomplished by fitting the data to the Beta distribution [Benjamin and Cornell, 1970]. The method of moments was used to solve for the distribution parameters for the Beta distribution (equations 2,3) for each of the three IDs in each of the five regions. The lower and upper bounds for the distribution (equation 1) were $\delta_1=0$ and δ_2 equal to the total duration. The results of the analyses are shown in Table 10 and are an expansion of the information contained in Table 4.

The timing data were also examined to determine if the values were related to the magnitude of the kernel ordinates. In simple terms, if a storm exhibited an unusually long (short) timing value, would the magnitude of the kernel ordinate also be more likely to be above (below) average? Alternatively, are the two values unrelated? Correlation analyses of the two variables were performed for each of the three IDs and various region combinations. All correlation coefficients had absolute values less than 0.10 and it was concluded that the correlation coefficients were not significantly different from zero. Therefore, during the assembly of a synthetic storm, the kernel ordinate and the time of occurrence of the high intensity segment can be selected independent of each other.

Table 10. Frequency Characteristics for Time of Occurrence of High Intensity Segment of Extreme Storms

REGIONS	INDEPENDENT DURATION (hours)	TIME OF HIGHEST INTENSITY - HOURS									
		MEAN (hours)	EXCEEDANCE PROBABILITY								
			0.95	0.90	0.80	0.67	0.50	0.33	0.20	0.10	0.05
1 & 2	2	0.70	0.03	0.06	0.12	0.25	0.50	0.80	1.20	1.70	2.15
3 & 4 & 5	2	0.90	0.15	0.23	0.37	0.55	0.80	1.05	1.35	1.75	2.05
1 & 2	6	6.3	1.1	1.7	2.8	4.1	5.9	7.8	9.6	11.6	13.1
3 & 4 & 5	6	9.2	2.2	3.3	5.0	7.0	9.2	11.5	13.4	15.1	16.1
1	24	23.7	1.9	3.8	7.6	13.0	20.8	30.2	39.2	48.5	55.2
2	24	15.6	0.7	1.5	3.5	6.7	12.0	19.0	26.7	35.7	43.0
3	24	25.5	5.0	7.7	12.2	17.3	24.0	31.3	38.3	45.7	51.3
4	24	33.6	10.4	14.3	20.1	26.1	33.3	40.6	47.0	53.4	57.8
5	24	30.6	8.4	11.9	17.2	22.9	29.9	37.1	43.7	50.4	55.3

SEQUENCING OF INCREMENTAL PRECIPITATION SEGMENTS

The sequencing (arrangement) of incremental precipitation amounts surrounding the high intensity segment is another element of an extreme storm which can have an affect on the magnitude of the flood peak discharge. Those sequences which have the high intensity segment near the end of the sequence generally produce larger flood peaks. This applies to both the high intensity sequences immediately surrounding the high intensity segment, and to trisector sequences which describe the storm macro pattern. This phenomenon occurs as a result of the hydraulic response of watersheds and the runoff properties of surficial soils which were discussed in the previous section.

The sequencing characteristics of the incremental precipitation segments within storms can be seen as a companion element to the timing characteristics. Probabilistic information on observed sequences is, therefore, needed to allow realistic development of synthetic storm hyetographs.

Sequencing of High Intensity Segments Within Storms

To investigate the sequencing characteristics of the high intensity segments, each storm was examined to identify the incremental precipitation amounts during the time intervals surrounding the occurrence of the highest intensity. The time increments that were used in this phase of the analysis for each of the three IDs are shown in Table 7. Consideration of the three largest incremental precipitation amounts in a storm resulted in six possible sequences: 123; 132; 213; 312; 231; 321 (see definitions section).

Table 11 contains the results of the analysis on the frequency of occurrence of the six sequences. It should be noted that those sequences, 132 and 231, which separate the two largest increments are fairly rare at all three IDs. In eastern Washington at the 2 hour ID, the sequence 123 occurred most frequently. In all other regions and durations, those sequences, 213 and 312, which sandwich the highest intensity segment in the middle were the most common and should be preferred in the development of synthetic storms.

No trends were identified which would indicate that the sequencing characteristics are statistically dependent on either the kernel ordinate or on the time of occurrence of the high intensity segment.

Table 11. Sequencing Characteristics of High Intensity Segments

REGIONS	INDEPENDENT DURATION (hours)	NUMBER OF EVENTS	HIGH INTENSITY SEGMENTS					
			FIRST BLOCK SEQUENCES		SECOND BLOCK SEQUENCES		THIRD BLOCK SEQUENCES	
			1 2 3	1 3 2	2 1 3	3 1 2	2 3 1	3 2 1
1 & 2	2	32	11	1	7	6	3	4
			38%		41%		21%	
3 & 4 & 5	2	22	5	0	9	8	0	0
			23%		77%		0%	
1 & 2	6	23	5	2	4	8	1	3
			30%		52%		18%	
3 & 4 & 5	6	56	13	2	12	18	4	7
			27%		54%		19%	
1 & 2	24	28	3	1	9	13	0	2
			14%		79%		7%	
3 & 4 & 5	24	49	3	3	13	19	3	8
			12%		65%		22%	

Sequencing of 6 Hour Segments Within 24 Hour ID Storms

At the 2 hour and 6 hour IDs, information on time of occurrence and sequencing of the high intensity segments, in combination with information on macro storm patterns, is usually adequate to describe a storm hyetograph. Additional information, however, is needed to describe a hyetograph for the longer duration 24 hour ID events. To describe the longer duration storm, the 24 hour ID was broken into four time segments with each segment being 6 hours in duration. As before, the sequence 1234 would represent the first, second, third and fourth largest incremental precipitation segments, respectively. With four segments, there are 24 separate sequences which can occur. Unfortunately, there were an insufficient number of extreme storms in any region to properly investigate the frequency characteristics. Nonetheless, there was sufficient data to identify some of the more common sequences. Referring to Table 12, it can be seen that the first and second largest precipitation segments occur adjacent to each other in about 80% of the cases. Therefore, regardless of the final sequence selected for use in a synthetic storm, it would be appropriate to keep the two largest 6 hour segments adjacent to each other.

Table 12. Frequency that the First and Second Largest 6 Hour Precipitation Segments Occur Adjacent to Each Other Within 24 Hour ID Extreme Storms

REGION	NUMBER OF EVENTS	SEQUENCE 12.. 21..	SEQUENCE .12. .21.	SEQUENCE ..12 ..21	TOTAL
1	21	24%	14%	33%	71%
2	7	43%	14%	29%	86%
3	16	13%	44%	31%	88%
4	22	18%	36%	32%	86%
5	11	27%	55%	9%	91%

Another sequencing characteristic was investigated by examining the sequence location of the largest 6 hour precipitation segment within the 24 hour ID storms. The frequency of occurrence of the sequence location of the largest segment can be seen in Table 13. There was a general tendency for the largest 6 hour segment to be located in the middle of the 24 hour ID.

Table 13. Sequencing Characteristics of the Largest 6 Hour Precipitation Segment Within 24 Hour ID Extreme Storms

REGION	NUMBER OF EVENTS	SEQUENCE 1...	SEQUENCE .1..	SEQUENCE ..1.	SEQUENCE ...1
1	21	14%	48%	0%	38%
2	7	29%	43%	14%	14%
3	16	0%	50%	31%	19%
4	22	9%	32%	45%	14%
5	11	9%	55%	36%	0%

In each region, several sequences were observed to occur frequently. Those sequences (Table 14) exhibited the tendencies identified in Tables 12 and 13 and are logical choices for use in constructing synthetic storms. The more commonly occurring sequences are ordered from left to right in the table, but the ranking is not necessarily significant. Any of the sequences shown, or minor variations thereof, should be acceptable.

Table 14 Commonly Occurring Sequences for 6 Hour Precipitation Segments Within 24 Hour ID Extreme Storms

REGION	COMMONLY OCCURRING SEQUENCES		
1	4321	3124	2134
2	3124	4321	2134
3	4123	4312	4213
4	4312	4213	4123
5	4123	4312	4213

ANTECEDENT STORMS

The meteorological conditions in the days and weeks prior to the occurrence of an extreme storm predetermine the hydrologic conditions which will prevail in a watershed when the extreme storm occurs. Initial streamflow, antecedent soil moisture conditions and initial reservoir levels are all dependent on prior meteorological conditions. The runoff volume and flood peak discharge produced by an extreme storm are in turn affected by the antecedent hydrologic conditions. Thus, information on antecedent conditions is necessary for proper rainfall-runoff modeling.

An investigation was conducted to examine the precipitation events which occurred antecedent to the extreme storm. Specifically, the 14 day period prior to each extreme storm was examined. The largest precipitation amount for any 24 hour period was recorded along with the number of days elapsed between antecedent and extreme events. Sample statistics were computed for the recorded data and the results are shown in Table 15.

A review of the contents of Table 15 reveals that, typically, extreme storms are <u>not</u> preceded by an unusual storm. In the case of the 2 hour ID storms, which occur predominately in the warm season, the antecedent storms are of a magnitude which occur from 10 to 20 times during any given year. Likewise, for the 6 hour and 24 hour ID storms, which are cool season events, antecedent storms are of a magnitude which occur numerous times during a given year.

In the particular case of the 24 hour ID extreme storms, a plot was made (Figure 13) depicting the relationship between the return period for a given 24 hour ID event and its associated antecedent storm. Partial duration return periods were used in lieu of annual return periods to allow a more direct interpretation of the frequency characteristics of the antecedent storms. Estimates of the return periods of the antecedent storms were based on climatic and precipitation-frequency information contained in publications prepared by Phillips [1964-1970] for Washington State precipitation stations.

Table 15. Characteristics of Storms Antecedent to Extreme Storms

REGION	INDEPENDENT DURATION (hours)	NUMBER OF EVENTS	ANTECEDENT STORM	
			AVERAGE 24 HOUR DEPTH (inches)	AVERAGE # DAYS PRIOR
1	2	32	0.35	8.5
2	2	15	0.45	7.5
3	2	18	0.60	7.5
4	2	17	0.70	6.5
5	2	5	0.65	6.0
1	6	17	0.45	7.5
2	6	6	0.40	7.0
3	6	17	0.80	8.5
4	6	25	1.70	5.5
5	6	11	2.40	4.5
1	24	21	0.60	8.0
2	24	9	0.25	10.0
3	24	16	1.05	8.0
4	24	22	1.60	7.0
5	24	11	1.25	8.5

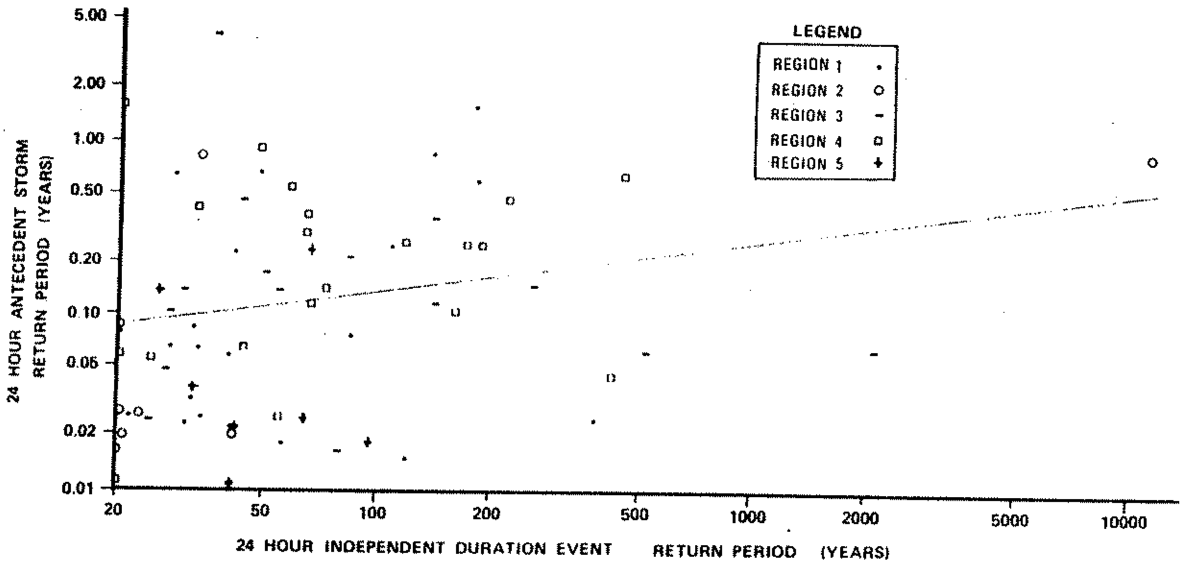

Figure 13. Relationship of Antecedent 24 Hour Duration Storms to 24 Hour ID Extreme Storms

A review of the data in Figure 13 reveals the antecedent storms to be highly variable and nearly independent of the associated extreme storm. The weak trend line depicted on the graph (correlation coefficient 0.24) indicates that for the 24 hour ID storms, there is some small tendency for the rare events to have slightly larger antecedent storms. However, even for extraordinarily rare events, the antecedent storms would not be expected to have a significant magnitude.

The average antecedent storm contained in Figure 13 corresponds to a partial duration return period of 0.11 years (occurs an average of 9 times per year.). This result roughly corresponds to storm magnitudes to be expected during any 14 day period during the cool season. As a practical matter, it would appear reasonable to conclude that the time period preceding a given extreme storm is not significantly different than that same (calendar) time period during any given year.

Based on the foregoing, selection of antecedent conditions, such as individual storm amounts, soil moisture conditions, streamflow, snowpack, initial reservoir levels, etc., can be reasonably made by consideration of the seasonality of the extreme storm and a review of the historical record on the desired items. Selection of a more or less conservative value can then be made on a probabilistic basis when considering each item.

For example, while the antecedent storms for the 24 hour ID storms in western Washington were not large, it was quite common to have extreme storms preceded by a series of small precipitation events. These events undoubtedly produced elevated streamflows and wet soils. These conditions are typical of the winter months and would be expected from a simple review of the historic meteorologic and hydrologic data for the winter months.

SPATIAL CHARACTERISTICS

Investigation of the spatial characteristics of extreme storms was not a major element in this study. This decision was made because the principal applications for the results of this study are on small watersheds. Small as used herein refers to watersheds with a drainage area less than 50 square miles with most applications on watersheds having areas less than 10 square miles. Small also is appropriate as a relative term for the size of the watersheds of interest compared to the extensive areal coverage of extreme storms at the 6 hour and 24 hour ID. Thus, for the longer duration storms, more detailed depth-area and other spatial information was not of great importance. For completeness, conventional depth-area duration curves have been obtained from other sources [NWS Hydrometeorological Report 43, 1966], [NOAA Atlas 2, Miller et al, 1973] and are presented later.

The main objective of this element of the study was to investigate the spatial characteristics of the short duration, warm season, convective events, in eastern Washington. These events are usually localized but may be associated with an organized weather system which can be identified at the synoptic scale. Thunder, lightning and hail often accompanied these storms and the storms have been given the generic label of "thunderstorm" to avoid problems associated with categorizing the causative storm type.

There has been controversy among meteorologists and hydrologists for many years on the typical and potential maximum areal coverage of thunderstorms in eastern Washington. The thunderstorms which are large enough to attract public and news media attention, often have areal coverages of less than 20 square miles. In contrast, the NWS [1966] has estimated an areal coverage of about 500 square miles to be used in association with thunderstorm Probable Maximum Precipitation (PMP) events. Thus, there was a need to investigate the probabilistic characteristics of thunderstorm areal coverage.

THUNDERSTORM CHARACTERISTICS - EASTERN WASHINGTON

The scarcity of recording precipitation gauges in eastern Washington restricted the ability to make detailed analyses of thunderstorm characteristics. It was not possible to examine more complex characteristics, such as the spatial correlation structure of precipitation amounts or the depth-area relations. The study was restricted by data limitations to: investigation of the areal coverage of observed extreme storms; the direction of storm movement; and the general physical shape of the areal distribution. Those elements will be presented in the following sections.

Thunderstorm Areal Coverage

The areal coverage characteristics of eastern Washington thunderstorms were investigated by reviewing the storm catalog and selecting those events for which additional storm information was available. Outside sources which were used to estimate the limits of precipitation included:

- observers notes at precipitation stations
- newspaper accounts
- crop damage reports
- county highway department damage surveys
- U.S. Geological Survey (USGS), continuous recording streamflow records and miscellaneous streamflow measurements
- published accounts of storm events (NWS & USGS)

The areal coverage of a given storm was determined by defining the outer boundary of the storm to be the precipitation amount corresponding to approximately 10% of the maximum observed point rainfall amount. Using the information sources discussed above, considerable judgment was applied in delineating the storm boundary. The delineated area was then measured and the results are listed in Table 16 and displayed in Figure 14. While the accuracy of any individual areal estimate is questionable, it can still be seen that there is considerable variability in the areal coverage of the storms that have occurred.

Based on these results, it appears that thunderstorm areal coverage on the order of the NWS [1966] estimate of 500 square miles is indeed possible. Also, it appears that little correlation exists between maximum point rainfall and areal coverage. Consideration of meteorological physics would suggest that a larger point rainfall is likely produced by a larger, more organized, more intensive convective cell or cells. This infers that there should be a tendency for storms with greater point rainfall to produce larger areal coverage. However, there is insufficient data to either confirm or refute this trend.

Table 16. Database of Selected Pacific Northwest Thunderstorms

STORM LOCATION	DATE	MAXIMUM MEASURED POINT RAINFALL (inches) *	MAXIMUM REPORTED/ESTIMATED POINT RAINFALL (inches) *	EFFECTIVE DURATION (minutes)	AREAL COVERAGE (sq miles)	DIRECTION OF STORM MOVEMENT (from)
near Sunnyside, WA	6/07/1947	1.62	-	25	35	SW
near Waterville WA	6/10/1948	1.76	4.00±	45	-	SW
near Pomeroy WA	6/17/1950	2.50	-	60	-	SW
near Selah WA	8/10/1952	2.75	4.00±	90	440	W
near Pullman WA	8/10/1952	2.45	-	180	255	W
near Connell WA	5/10/1956	2.00	-	60	330	NE
near Mitchell OR	7/13/1956	3.50	-	30	55	-
near Wenatchee WA	8/25/1956	1.38	-	180	275	SW
near Walla Walla WA	5/08/1957	1.15	-	120	100	-
near Walla Walla WA	5/24/1958	1.62	-	100	200	SW
near Morgan UT	8/16/1958	7.00	7.00	60	200	-
near Pullman WA	6/13/1963	1.47	3.40	60	100	SW
near Pomeroy WA	9/13/1966	1.21	2.25±	45	500	NW
near Walla Walla WA	5/26/1971	1.75	3.36	60	280	SSW
near Clarkston WA	8/03/1976	-	3.00±	45	-	SW
near Dayton WA	7/07/1978	1.20	2.00±	60	125	-
near Cowiche WA	4/21/1988	-	2.25	45	-	SSE

* Duration of rainfall 2 hours or less

Thunderstorms - Direction of Movement

Although there were only 13 events for which the direction of storm movement could be determined, the storm vectors occupied a relatively small sector of the wind rose. Review of Table 16 reveals that nearly all the storms originated from the southwest or west.

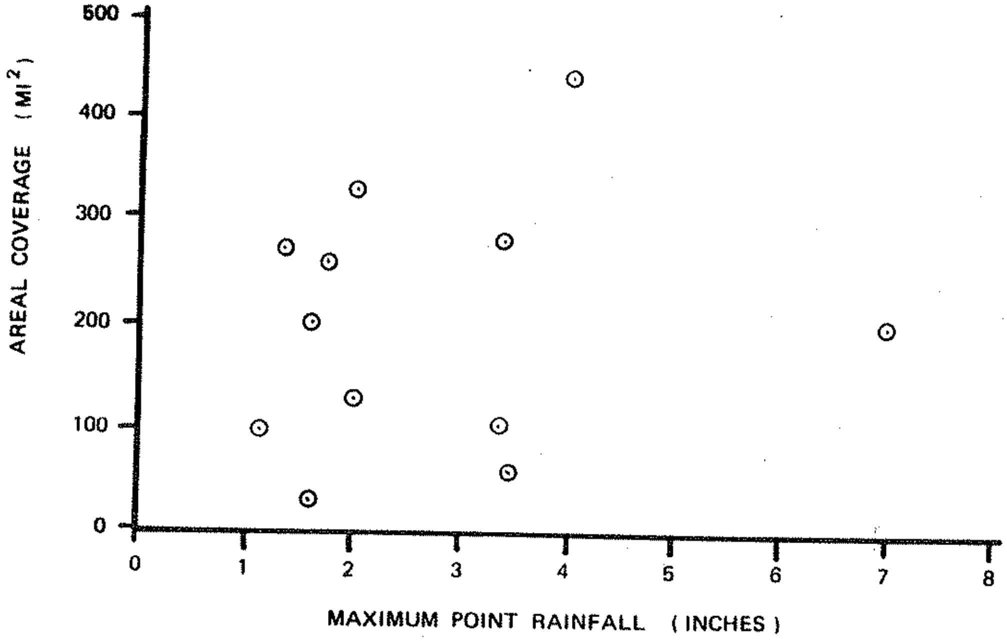

Figure 14. Variation of Areal Coverage with Maximum Point Rainfall for 2 Hour ID Pacific Northwest Thunderstorms

Thunderstorm - Storm Shape

The inability to accurately define the outer boundaries of precipitation (ground print) resulted in "smoothed" storm shapes. Nearly all shapes were ovals with the majority being elongated ovals. Based on newspaper accounts, many of the elongated ovals resulted from storm movement across the area. Measurement of the lengths of the major and minor axes of the ovals produced an average ratio of 2.45:1. The axes ratios ranged from a minimum of 1.15 to 3.33. Based on these results, an elliptical isohyetal pattern with an axes ratio of 2.5:1 would appear to be a reasonable approximation of the storm ground print. Information on storm shape and direction of movement could be important considerations for watersheds which are oriented in such a manner where only partial storm coverage of the basin is likely. This information should be taken into account when applying the depth-area curves discussed in the next section.

DEPTH-AREA RELATIONSHIPS

As discussed previously, the results of this study are intended for use primarily on small watersheds. Therefore, minimal efforts were made to conduct a probabilistic study of the spatial characteristics of extreme storms. In those cases where spatial information is needed for application on large watersheds, conventional depth-area-duration curves can be used to estimate the spatial and temporal distribution of the storm amounts.

The depth-area curves (Figure 15) recommended for use with the 6 hour and 24 hour ID storms were obtained from procedures contained in NWS Hydrometeorological Report 43 [1966] and are similar to curves contained in NOAA Atlas 2 [Miller et al, 1973]. Use of these curves are for watersheds larger than 10 square miles, because at-site precipitation depths are taken to represent an area of 10 square miles for the 6 hour and 24 hour ID cool season extreme storms.

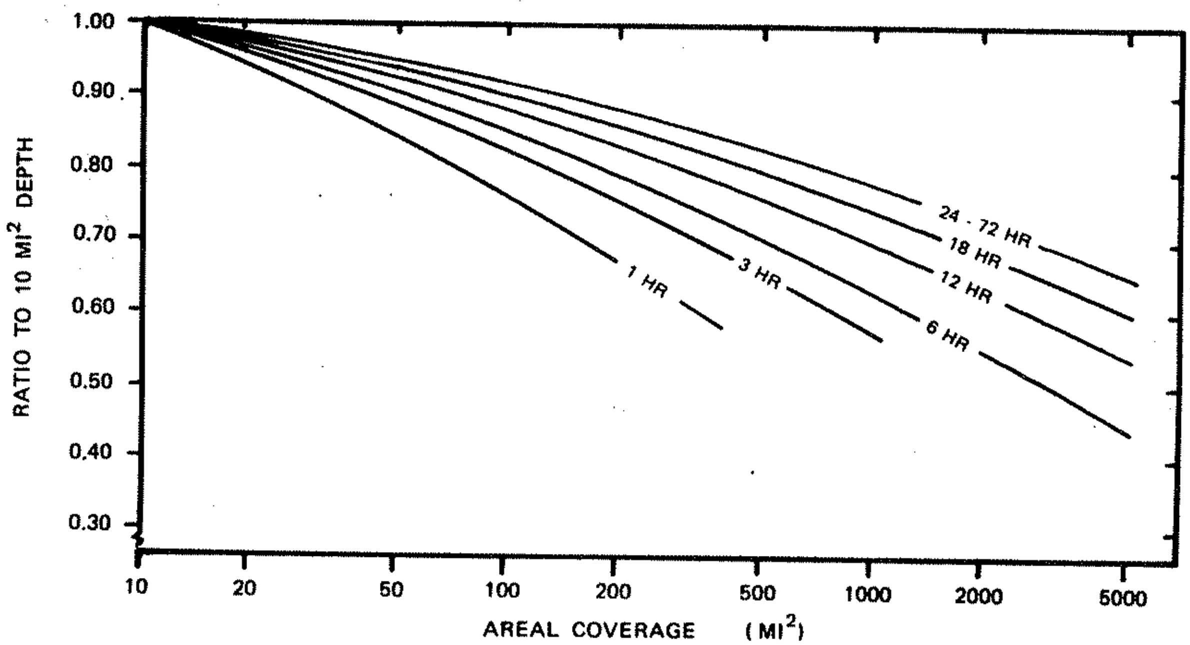

Figure 15. Depth-Area Curves for 6 Hour and 24 Hour ID Storms

The depth-area curves (Figure 16) for use with the 2 hour ID storms in eastern Washington were taken from NWS Hydrometeorological Reports 49 and 55 [1977, 1984]. The original curves were modified for use in Washington and reflect a reduced areal coverage for a nominal 250 square mile coverage versus the 500 square mile coverage of the original. This reduction was based on the finding that the areal coverage of the 2 hour ID storms were typically about 250 square miles. At-site precipitation depths are taken to represent an area of 1 square mile for the 2 hour ID warm season extreme storms.

In western Washington, no specific studies were conducted for the areal coverage of 2 hour ID storms. It is anticipated that the primary application of 2 hour ID storms will be on very small urban watersheds where the depth-area characteristics will not be of great importance. Figure 16 values are recommended for interim usage in western Washington until detailed information becomes available.

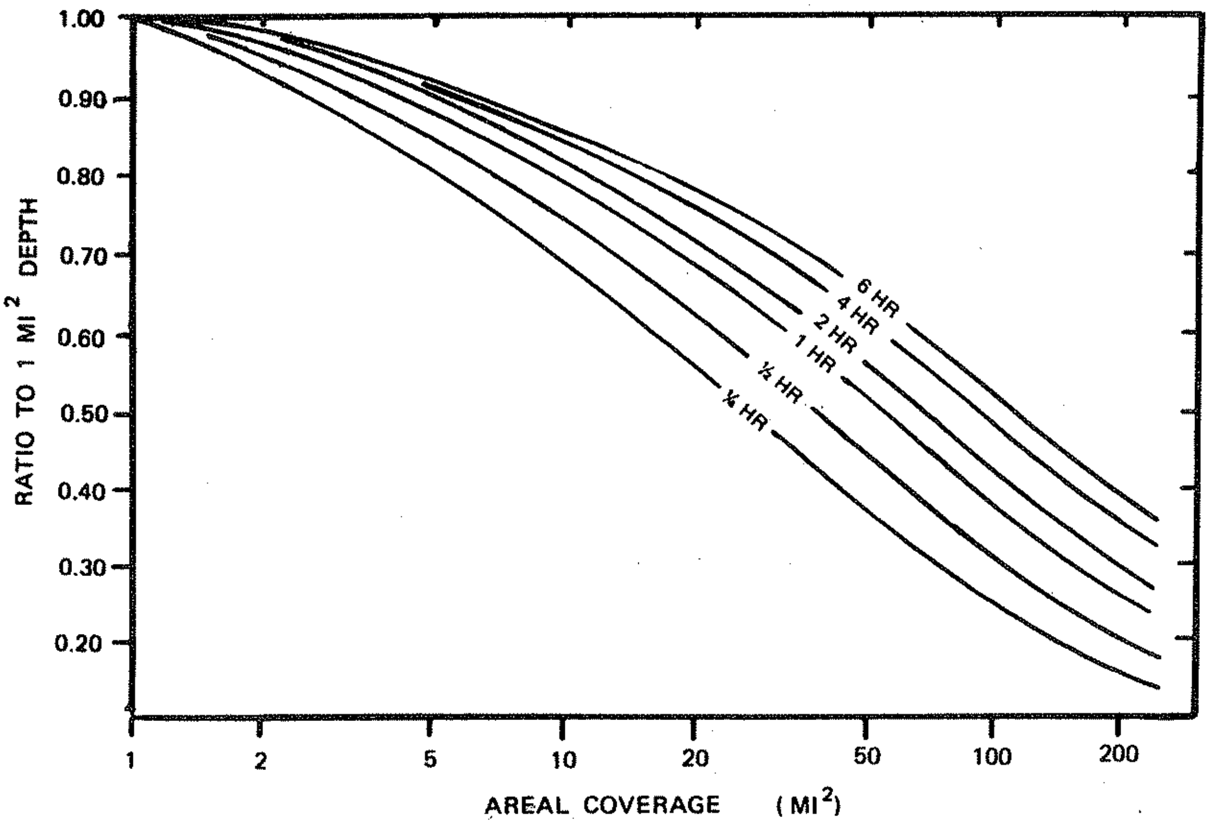

Figure 16. Depth-Area Curves for 2 Hour ID Storms

The following procedures would be employed to apply the depth-area curves to produce a basin-average depth-duration curve for a given ID storm magnitude on a specific watershed:

- Prepare a grid network and overlay the grid on the watershed. Estimate an at-site precipitation depth for the chosen ID and specified exceedance probability for each node point on the grid network of points.

- Compute an average precipitation depth for the watershed from the collection of at-site values for the grid nodes.

- Use the average precipitation depth computed above, in combination with the chosen dimensionless depth-duration curve, to scale the dimensionless ordinates to the desired storm magnitude.

- Compute the basin-average depth-duration curve by using the areal reduction factors from Figure 15 or 16 to adjust the curve computed above for the effects of storm spatial distribution.

In using data from both Figures 15 and 16, it should be recognized that these values represent the average spatial characteristics from a limited pool of data. At the present time, the author is unaware of any published regionalized information or study which addresses the stochastic nature of the spatial characteristics of extreme storms in the Northwest. Until further information is available, these depth-area curves represent the only practical approach to account for the spatial distribution of extreme storm precipitation.

ASSEMBLY OF SYNTHETIC STORMS

The primary objective of this study was to collect sufficient information on the characteristics of extreme storms to allow development of synthetic storm hyetographs for use in rainfall-runoff modeling. In this section, a methodology is presented for the assembly of synthetic storms which incorporates the probabilistic information on storm elements developed in the previous sections.

Assembly of a synthetic storm hyetograph can be viewed as a reversal of the depth-duration analysis process. The incremental precipitation amounts from a depth-duration curve are rearranged to produce a storm mass hyetograph. An important component in the assembly of synthetic storms is that conscious decisions must be made on the level of conservatism to be applied in the selection of the various storm elements. Every storm element discussed previously has been described in probabilistic terms and thus it is possible to reasonably predetermine the likelihood of occurrence of each element being built into the storm. This affords the opportunity to construct storms suited to site specific or commonly encountered types of applications.

In some applications, the selection of individual storm elements representing typical or mean values is appropriate. This is usually the case when attempting to synthetically generate a flood frequency curve of flood peak discharges. Typical storm elements would also be used in the calibration of soil or watershed response parameters in flood modeling when attempting to recreate a flood frequency curve obtained from other sources. In applications involving the design of hydraulic structures, somewhat more conservative values may be desirable.

The term conservative, as used here, refers to the procedure of selecting a more unusual magnitude or sequence of a storm element in order to produce a larger flood. This acts as a hedge against underestimation of the design flood when faced with the ever present uncertainty of obtaining the "correct" flood magnitude for the desired flood frequency. Although this procedure does provide protection from underdesign, it often results in more expensive construction to accommodate the larger flood. Ultimately, the selection of an acceptable level of conservatism resides with the project manager or the responsible regulatory agency.

In general, the selections of the exceedance probability for the depth-duration curve and the time of occurrence of the high intensity segment have the greatest influence on the resultant flood peak discharge. Variations of sequences for the high intensity segment or for the four 6 hour segments in the 24 hour ID event are of lesser importance. Where appropriate, sensitivity analyses may be used to examine the effects that alternative decisions on the selection of storm elements would have on the resultant flood.

METHODOLOGY FOR ASSEMBLY OF SYNTHETIC STORMS

The assembly of a synthetic storm mass hyetograph begins with the selection of a specific depth-duration curve, the time of occurrence of the high intensity segment and sequences for storm segments. Incremental precipitation amounts from the specified depth-duration curve are then arranged in a manner consistent with the chosen storm characteristics and macro storm pattern.
The following list describes the general methodology to be used in storm assembly:

Step 1. Estimate the at-site precipitation depth for the desired Annual Exceedance Probability (AEP) and Independent Duration (ID) of the extreme storm. This can be accomplished using information contained in either NOAA Atlas 2 [Miller et al, 1973] or Schaefer [1989].

Step 1a. If the watershed of interest is larger than 1 square mile at the 2 hour ID, or larger than 10 square miles at the 6 hour or 24 hour IDs, then computation of an average precipitation depth for the watershed is necessary. The average depth can be computed using the grid network procedures presented in the section on depth-area relationships.

Step 2. Select a dimensionless depth-duration curve from Tables 8a-8l or Tables 9a-9e for the desired level of exceedance probability and appropriate climatic region. Scale the dimensionless depth-duration ordinates to the desired storm magnitude by multiplying the ordinates by the precipitation depth from Step 1 or 1a.

Step 3. Select the time of occurrence of the high intensity segment using information contained in Table 10.

Step 4. Select the sequence for the three high intensity storm segments using information contained in Table 11. The time interval associated with each of the three segments is listed in Table 7.

Step 5. If the extreme storm is a 24 hour ID event, then select the sequence for the four 6 hour storm segments within the ID. Necessary information is contained in Tables 13 and 14.

Step 6. Select a macro storm pattern from Figures 6a-6f which is consistent with the timing and sequencing selections made previously. Choose a six segment macro sequence. Note: The choice of the number of segments for the macro pattern sequence is arbitrary. The macro patterns in Figure 5 are shown using trisector sequences comprised of three segments. However, this was done to simplify the categorization of observed storms. It is recommended that macro patterns and associated sequences with six segments be used for storm assembly. This is consistent with the time intervals (Table 7) used in the original development of the depth-duration curves and will simplify construction.

Step 7. If Step 1a is utilized above, then the watershed is sufficiently large that the spatial characteristics of the storm must be incorporated. The basin-average depth-duration curve can be computed using the areal reduction factors from Figures 15 or 16 as described in the section on depth-area relationships.

The storm can now be assembled in a manner which incorporates the storm elements chosen in Steps 2 - 6. Worksheets are provided in Appendix 3 which should aid in the bookkeeping aspects of storm assembly. While the methodology for storm assembly appears straightfoward, actual applications will reveal subtleties and possible permutations which may raise questions regarding appropriate procedures. Therefore, a series of examples are provided to demonstrate the assembly of a few synthetic storm mass hyetographs. As mentioned above, there is room for reasonable latitude in determining the manner in which a hyetograph incorporates the various storm characteristics. Minor variations in the completed hyetograph may be expected from separate practitioners even though the same values for the storm elements are employed. In general, these minor variations of the hyetograph would not be anticipated to have significant effects on the resultant flood. Where deemed appropriate, sensitivity analyses may be used to explore the differences in the floods produced by the various hyetographs.

The following examples are presented to clarify the methodology that is used to assemble synthetic storm hyetographs.

Example 1. Development of a typical mass hyetograph for a 2 hour ID event, with an Annual Exceedance Probability (AEP) of 0.01 for a 1 square mile watershed near Olympia, WA in the Puget Sound lowlands.

Given: For a 100 year recurrence interval event (AEP=0.01), the precipitation depth from NOAA Atlas 2 is 1.30 inches. Interpret **typical** event to be median or mean values for all storm elements.

Step 1:

The 2 hour ID precipitation depth is 1.30 inches.

Step 2:

Use the dimensionless depth-duration ordinate values for the 50% exceedance probability (median value) from Table 8b. Multiply the dimensionless ordinates by the 2 hour ID depth to scale the storm to the proper magnitude.

Step 3:

Select the mean value (0.9 hours, 54 minutes) from Table 10 for the time of occurrence of the high intensity segment.

Step 4:

Select the most likely sequence for the three high intensity segments of the storm. Referring to Table 11, this corresponds to either sequence 213 or 312. Choose sequence 213 at 15 minute increments per Tables 7 and 11.

During storm assembly, the incremental precipitation amounts corresponding to this sequence are inserted into the storm mass curve so the largest segment spans the time increment from 45 to 60 minutes of elapsed time (per Step 3).

It should be noted that Table 8b also contains ordinate values for precipitation amounts for three 5 minute segments. These segments are internal to the largest 15 minute high intensity segment and should be inserted within the largest 15 minute increment.

A sequence of 213 may also be used for these segments.

Step 5:

Not applicable.

Step 6:

Select macro pattern Type I based on Figure 6a and selections in Steps 3 and 4. Choose sequence 123456 for the six 1 hour segments.

Step 7:

No corrections for areal coverage are required since the watershed is not larger than 1 square mile.

Examination of the resultant synthetic storm (Table 17, Figure 17) reveals that it contains all of the storm elements described above.

Table 17. Assembly of Synthetic Mass Hyetograph for 2 Hour ID Extreme Storm for 1 Square Mile Watershed near Olympia, WA.

DEPTH-DURATION ORDINATES

DEPENDENT DURATION (hours)	ORDINATE VALUES: TABULAR	SCALED	AREAL REDUCTION	FINAL	TIME INCREMENT (hours)	INCREMENTAL PRECIPITATION AMOUNT (inches)	SEQUENCE NUMBER
0.00	0.000	0.00	----	0.00			
0.08	0.139	0.18	1.00	0.18	0.08	0.18	within
0.17	0.267	0.35	1.00	0.35	0.08	0.17	.25 hour
0.25	0.386	0.50	1.00	0.50	0.08	0.15	hi
0.00	0.000	0.00	----	0.00			
0.25	0.386	0.50	1.00	0.50	0.25	0.50	1 hi
0.50	0.586	0.76	1.00	0.76	0.25	0.26	2 hi
0.75	0.712	0.93	1.00	0.93	0.25	0.17	3 hi
1.00	0.814	1.06	1.00	1.06	0.25	0.13	1 macro
1.25	0.888	1.15	1.00	1.15	0.25	0.09	
1.50	0.931	1.21	1.00	1.21	0.25	0.06	2 macro
2.00	1.000	1.30	1.00	1.30	0.50	0.09	
3.00	1.097	1.43	1.00	1.43	1.00	0.13	3 macro
4.00	1.149	1.49	1.00	1.49	1.00	0.06	4 macro
5.00	1.193	1.55	1.00	1.55	1.00	0.06	5 macro
6.00	1.226	1.59	1.00	1.59	1.00	0.04	6 macro

SYNTHETIC STORM MASS HYETOGRAPH

TIME (hours)	SEQUENCE NUMBER	INCREMENTAL AMOUNT (inches)	MASS ORDINATE VALUE (inches)
0.00			0.00
0.25	part of 2 macro	0.06	0.06
0.50	part 1 macro	0.13	0.19
0.75	2 hi	0.26	0.45
0.83	within 1 hi	0.17	0.62
0.92	within 1 hi	0.18	0.80
1.00	within 1 hi	0.15	0.95
1.25	3 hi	0.17	1.12
1.50	part of 2 macro	0.09	1.21
2.00		0.09	1.30
3.00	3 macro	0.13	1.43
4.00	4 macro	0.06	1.49
5.00	5 macro	0.06	1.55
6.00	6 macro	0.04	1.59

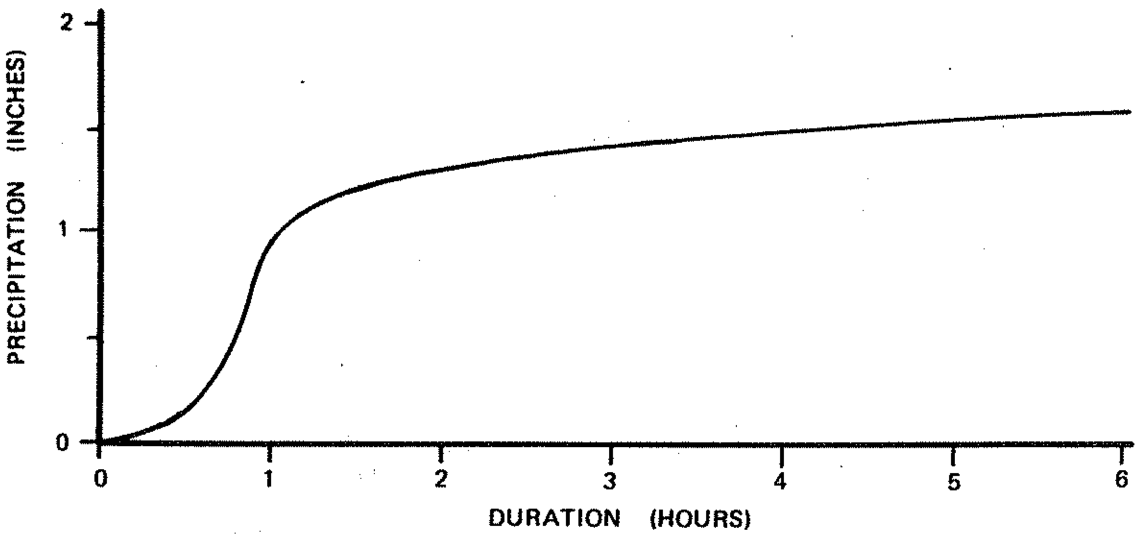

Figure 17. Synthetic Mass Hyetograph for 2 Hour ID Extreme Storm for a 1 Square Mile Watershed near Olympia, WA.

Example 2. Development of a conservative mass hyetograph for a 6 hour ID event, with an AEP of 0.01 for a 5 square mile watershed near Olympia, WA in the Puget Sound lowlands.

Given: For a 100 year recurrence interval event (AEP=0.01), the precipitation depth from NOAA Atlas 2 is 2.40 inches. Interpretation of a **conservative** temporal distribution is taken to mean storm elements having exceedance probabilities of 0.20 - one chance in five of being exceeded:

Step 1:

The precipitation depth is 2.40 inches.

Step 2:

Use the dimensionless depth-duration ordinate values for the 20% exceedance probability (conservative occurrence) from Table 8e. Multiply the dimensionless ordinates by the 6 hour ID depth to scale the storm to the proper magnitude.

Step 3:

Select the 20% exceedance probability value (13.4 hours) from Table 10 for the time of occurrence for the high intensity segment. Remember that the occurrence of the high intensity segment nearer the end of the storm generally produces a larger flood peak discharge. Thus, a longer timing value is conservative relative to a value nearer the start of the storm.

Step 4:

Select a conservative sequence for the three high intensity segments of the storm. The sequence chosen should be one with the larger precipitation segments nearer the end of the sequence.

In consideration of the above, choose sequence 312 at 60 minute increments per Tables 7 and 11. The incremental precipitation amounts corresponding to this sequence are inserted into the storm so the largest amount spans the time increment from 13 to 14 hours of elapsed time (per Step 3). Table 8e also contains high intensity ordinates for two 15 minute segments and one 30 minute segment. These segments should be inserted within the largest 60 minute segment to have the greatest intensity occurring around 13.4 hours.

Step 5:

Not applicable.

Step 6:

Select macro pattern Type IX based on selections in Steps 3,4 and Figure 6c. Use of a six segment sequence for the macro pattern (3 hour time intervals) does allows some latitude in the selection of a sequence which incorporates the previously chosen timing and sequencing elements. Logical choices would include: 654213 and 654312. Choose macro pattern sequence 654213 based on the timing of the high intensity segment at 13.4 hours which is near the boundary between macro segments 4 and 5 (boundary at 12 hours).

Step 7:

No corrections for areal coverage are necessary since the watershed is less than 10 square miles.

The resultant synthetic storm is shown in Figure 18 and the supporting computations for storm assembly are contained in Table 18.

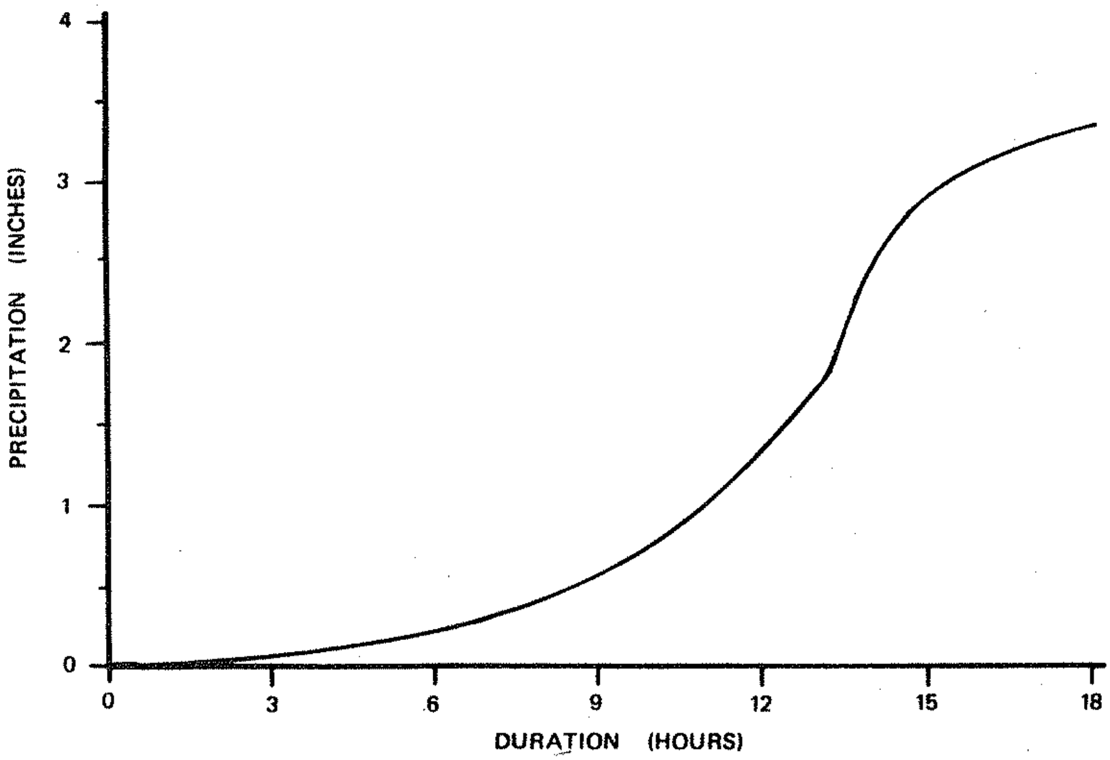

Figure 18. Synthetic Mass Hyetograph for 6 Hour ID Extreme Storm for 5 Square Mile Watershed near Olympia, WA.

Table 18. Assembly of Synthetic Mass Hyetograph for 6 Hour ID Extreme Storm for 5 Square Mile Watershed near Olympia, WA.

DEPTH-DURATION ORDINATES

DEPENDENT DURATION (hours)	ORDINATE VALUES: TABULAR	ORDINATE VALUES: SCALED	ORDINATE VALUES: AREAL REDUCTION	ORDINATE VALUES: FINAL	TIME INCREMENT (hours)	INCREMENTAL PRECIPITATION AMOUNT (inches)	SEQUENCE NUMBER
0.00	0.000	0.00	----	0.00			
0.25	0.139	0.33	1.00	0.33	0.25	0.33	within
0.50	0.202	0.48	1.00	0.48	0.25	0.15	1 hour
1.00	0.314	0.75	1.00	0.75	0.50	0.27	hi
0.00	0.000	0.00	----	0.00			
1.00	0.314	0.75	1.00	0.75	1.00	0.75	1 hi
2.00	0.515	1.24	1.00	1.24	1.00	0.49	2 hi 1 macro
3.00	0.664	1.59	1.00	1.59	1.00	0.35	3 hi
6.00	1.000	2.40	1.00	2.40	3.00	0.81	2 macro
9.00	1.171	2.81	1.00	2.81	3.00	0.41	3 macro
12.00	1.272	3.05	1.00	3.05	3.00	0.24	4 macro
15.00	1.344	3.23	1.00	3.23	3.00	0.18	5 macro
18.00	1.385	3.32	1.00	3.32	3.00	0.09	6 macro

SYNTHETIC STORM MASS HYETOGRAPH

TIME (hours)	SEQUENCE NUMBER	INCREMENTAL AMOUNT (inches)	MASS ORDINATE VALUE (inches)
0.00			0.00
	6 macro	0.09	
3.00			0.09
	5 macro	0.18	
6.00			0.27
	4 macro	0.24	
9.00			0.51
	2 macro	0.81	
12.00			1.32
	3 hi	0.35	
13.00			1.67
	within 1 hi	0.15	
13.25			1.82
	within 1 hi	0.33	
13.50			2.15
	within 1 hi	0.27	
14.00			2.42
	2 hi	0.49	
15.00			2.91
	3 macro	0.41	
18.00			3.32

Example 3. Development of a very conservative mass hyetograph for a 24 hour ID event, with an AEP=0.01 for a 100 square mile watershed near Olympia, WA. in the Puget Sound lowlands.

Given: For a 100 year recurrence interval event (AEP=0.01), the average precipitation depth for the watershed was computed using the collection of at-site values from NOAA Atlas 2 at nodes on a rectangular grid which encompassed the watershed. The average depth was computed to be 5.40 inches.
Interpretation of a **very conservative** temporal distribution is taken to mean storm elements having exceedance probabilities of 0.05 - one chance in twenty of being exceeded. For purposes of this example, assume flood peak discharge is the primary concern, rather than flood volume. Therefore, use a depth-duration curve developed from a 6 hour kernel.

<u>Step 1a:</u>
The 24 hour average precipitation depth for the watershed was determined to be 5.40 inches.

<u>Step 2:</u>
Use the dimensionless depth-duration ordinate values for the 5% exceedance probability from Table 8j. Multiply the dimensionless ordinates by the 24 hour ID average depth to scale the storm to the proper magnitude.

<u>Step 3:</u>
Select the 5% exceedance probability value (51.3 hours) from Table 10 for the time of occurrence for the high intensity segment.

<u>Step 4:</u>
Select a sequence for the three high intensity segments of the storm. As discussed previously, a more conservative sequence would have the larger precipitation amounts nearer the end of the sequence. In consideration of the above, a very conservative sequence would be represented by sequence 321 at 60 minute increments per Tables 7 and 11.

The incremental precipitation amounts corresponding to this sequence are inserted into the storm so the largest amount spans the time increment from 51 to 52 hours of elapsed time. Table 8j also contains ordinate values for precipitation amounts for two 30 minute high intensity segments. These segments should be inserted within the largest 60 minute segment.

Step 5:

Select a sequence for the four 6 hour segments within the 24 hour ID. As before, a conservative sequence should have the larger precipitation amounts nearer the end of the sequence. Chose sequence 4312 based on information in Tables 13 and 14. The largest 6 hour precipitation amount should include and be centered around the 1 hour high intensity segment at 51.3 hours. This results in the 24 hour ID occurring between 36 and 60 hours of elapsed time.

Step 6:

Select macro pattern Type IX based on selections in Steps 3,4 and 5. Choose macro pattern sequence 654213 for the six segment macro pattern sequence (12 hour time intervals) based on previous selections in Steps 3,4 and 5.

Step 7:

Multiply the scaled ordinate values from Step 2 by the appropriate areal reduction factors in Figure 15 to produce the final ordinates for the basin-average depth-duration curve.

The resultant synthetic storm is shown in Figure 19 and the supporting computations are contained in Table 19. For comparison purposes, a second storm mass hyetograph was computed (computations not shown) using a 48 hour DD kernel (Table 9c) in conjunction with the same characteristics used in Example 3. It can be seen in Figure 19 that the storms have similar mass curves. The primary differences being that the storm generated from the 6 hour DD kernel contains higher intensities and the storm generated from the 48 hour DD kernel has significantly larger total depth. The selection of the appropriate storm for the design of a specific hydraulic structure would depend on whether flood volume or flood peak discharge was the critical consideration.

Table 19. Assembly of Synthetic Mass Hyetograph for 24 Hour ID Extreme Storm for 100 square Mile Watershed near Olympia, WA.

DEPTH-DURATION ORDINATES

DEPENDENT DURATION (hours)	ORDINATE VALUES: TABULAR	SCALED	AREAL REDUCTION	FINAL	TIME INCREMENT (hours)	INCREMENTAL PRECIPITATION AMOUNT (inches)	SEQUENCE NUMBER
0.00	0.000	0.00	----	0.00			within
					0.50	0.31	
0.50	0.083	0.45	0.70	0.31			1 hour
					0.50	0.22	
1.00	0.130	0.70	0.76	0.53			hi
0.00	0.000	0.00	----	0.00			
					1.00	0.53	1 hi
1.00	0.130	0.70	0.76	0.53			
					1.00	0.38	2 hi
2.00	0.209	1.13	0.80	0.91			
					1.00	0.33	3 hi
3.00	0.279	1.51	0.82	1.24			1..6 hr
					3.00	0.94	
6.00	0.475	2.57	0.85	2.18			
					3.00	0.74	2..6 hr
9.00	0.629	3.40	0.86	2.92			
					3.00	0.64	
12.00	0.758	4.09	0.87	3.56			3..6 hr
					6.00	0.75	
18.00	0.886	4.78	0.90	4.31			2 macro
					6.00	0.66	4..6 hr
24.00	1.000	5.40	0.92	4.97			
					12.00	0.27	3 macro
36.00	1.055	5.70	0.92	5.24			
					12.00	0.21	4 macro
48.00	1.097	5.92	0.92	5.45			
					12.00	0.21	5 macro
60.00	1.139	6.15	0.92	5.66			
					12.00	0.18	6 macro
72.00	1.175	6.35	0.92	5.84			

SYNTHETIC STORM MASS HYETOGRAPH

TIME (hours)	SEQUENCE NUMBER	INCREMENTAL AMOUNT (inches)	MASS ORDINATE VALUE (inches)
0.0			0.00
	6 macro	0.18	
12.0			0.18
	5 macro	0.21	
24.0			0.39
	4 macro	0.21	
36.0			0.60
	4....6 hr	0.66	
42.0			1.26
	3....6 hr	0.75	
48.0			2.01
	1/3 of .94	0.31	
49.0			2.32
	3 hi	0.33	
50.0			2.65
	2 hi	0.38	
51.0			3.03
	within 1 hi	0.31	
51.5			3.35
	within 1 hi	0.22	
52.0			3.56
	2/3 of .94	0.63	
54.0			4.19
	2....6 hr	0.74	
57.0			4.93
		0.64	
60.0			5.57
	3 macro	0.27	
72.0			5.84

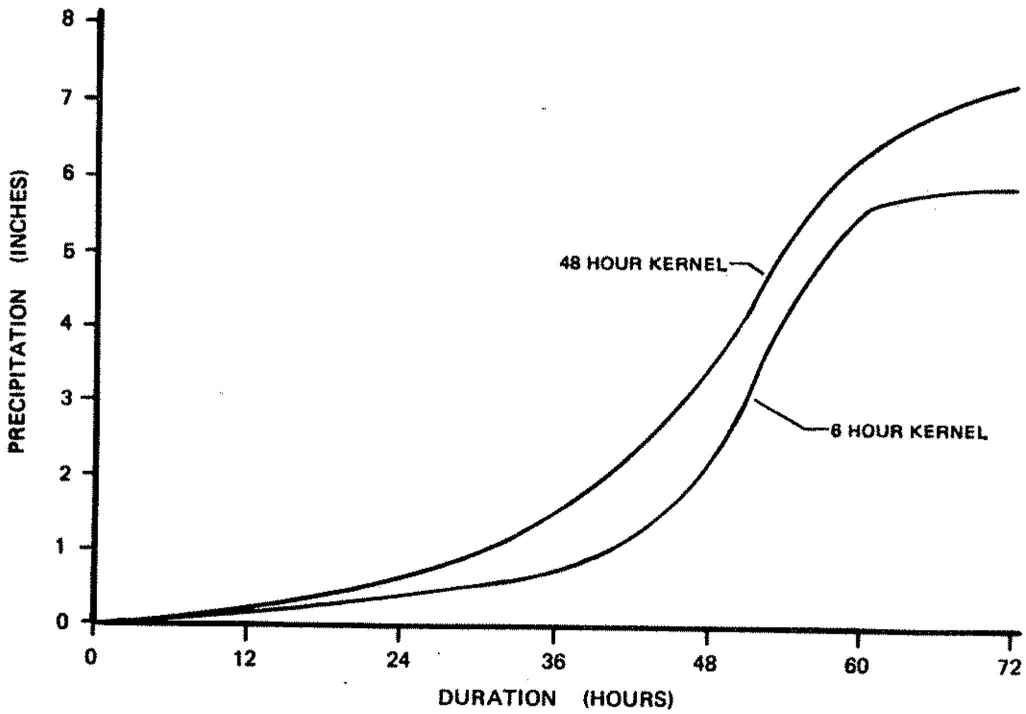

Figure 19. Synthetic Mass Hyetographs for 24 Hour ID Extreme Storms for 100 Square Mile Watershed near Olympia, WA.

One of the findings identified earlier in this study was the general relationship between storm seasonality, precipitation intensity and duration. To reiterate, short duration 2 hour ID extreme storms occur predominately in the warm season and typically contain high intensities but relatively small total depth. By comparison, the long duration 24 hour ID extreme storms are cool season events which contain relatively moderate and uniform intensities and a much larger total depth. The 6 hour ID extreme storms exhibit characteristics intermediate between the two. The general relationship between storm duration and the magnitude of the high intensities contained within the storm can be seen by reviewing the results from the three examples. The highest intensities in the example storms, for the 15 minute DD and no areal reduction, are 2.00 in/hr, 1.32 in/hr and 0.90 in/hr for the

2 hour ID, 6 hour ID and 24 hour ID storms respectively. **This complexity between storm magnitude, duration and the magnitude of the high intensity segments warrants that several synthetic storms be developed at each duration when investigating the flood characteristics of a specific watershed.** This will allow a proper determination of the storm duration and temporal components which have the characteristics to generate the flood which will govern the design of a given hydraulic structure.

SUMMARY AND CONCLUSIONS

Analyses were conducted to describe the probabilistic characteristics of extreme storms in Washington State. An extreme storm was defined as being a precipitation event whose depth for a specified duration, the Independent Duration (ID), represented a return period of 20 years or greater. For purposes of the study, a catalog of extreme storms was developed for three specific IDs, 2 hours, 6 hours and 24 hours, for each of five reasonably homogeneous climatic regions. Storms which exceeded the extreme storm threshold had to meet certain selection criteria to be included in the catalog. For each region, a specific storm (date) could appear at only one of the three IDs. In addition, only the recording station where the storm amount was the rarest was retained in the catalog.

The catalog created by the storm selection process formed the database for the probabilistic analyses. As a result of those analyses, the following observations and conclusions were made:

Seasonality

The season of occurrence of the extreme storms was strongly related to storm duration. The 2 hour ID events, in both eastern and western Washington, were found to occur primarily in the warm season; typically May through September. The influence of solar heating in initiating these convective events is evidenced by the fact that the vast majority of storms occurred between noon and early evening.

The 6 hour and 24 hour ID storms in western Washington were found to occur almost exclusively in the cool season; typically October through February. These storms were characterized by relatively moderate and uniform intensities. The high intensity segments of these storms rarely contained intensities as large as those found in the shorter duration 2 hour ID events.

The 24 hour ID storms in eastern Washington were found to occur primarily in the cool season; typically September through February.

The seasonality of occurrence of the 6 hour ID storms in eastern Washington had a bimodal distribution. Common seasons of occurrence were in spring and in late fall and winter.

Temporal Storm Characteristics

Twelve generalized macro storm patterns (incremental precipitation histograms) were created and used to categorize extreme storms. Six patterns were for storms which contained continuous precipitation and six patterns were for intermittent storms. Continuous patterns were always in the majority, although the percentage of intermittent storms tended to increase with storm duration. Likewise, a greater variety of macro patterns were observed as the ID of the storm increased.

The short duration 2 hour ID storms, in both eastern and western Washington, exhibited predominately Type I macro patterns. This pattern has the high intensity segment near the beginning of the storm.

In eastern Washington, the 6 hour and 24 hour ID storms typically exhibited a Type I macro pattern. In western Washington, the 6 hour and 24 hour ID storms typically occurred with a macro pattern where the high intensity segment was near the middle of the storm.

Probabilistic dimensionless depth-duration curves were developed for each of the three durations and five climatic regions. The depth-duration curves were found to be essentially independent of storm magnitude. Thus, selection of a design storm magnitude and a depth-duration curve are to be considered as independent decisions in the development of synthetic storms for rainfall-runoff modeling.

The cross-correlation structure of the dependent duration (DD) ordinates within the depth-duration curves was investigated for the three IDs in each region. In all cases, a definitive decay structure was observed, wherein, the magnitudes of the cross-correlation coefficients decreased as the time between DD pairs increased in magnitude. The cross-correlation structure resulted in probabilistic dimensionless depth-duration curves having certain characteristic shapes. For all three durations, dimensionless curves with steeper than average rising limbs had flatter than average upper tails. Conversely, curves having steeper than average upper tails had flatter than average rising limbs. Thus, it was quite rare to see a storm whose dimensionless depth-duration curve ordinates exhibited significantly higher than average values at the high intensity segment of the storm and which exhibited unusually large ordinate values at the total duration.

Probabilistic information was developed on the sequencing (arrangement) characteristics of the incremental precipitation amounts within storms and on the time of occurrence of the high intensity storm segment for each of the three IDs and five regions. The sequencing characteristics were found to occur in a wide variety of possible combinations. Likewise, the timing characteristics of the high intensity segment were highly variable.

Antecedent Storms

Investigations were conducted to examine the largest antecedent precipitation events which occurred in the 14 day period prior to the extreme storms. For all three IDs, it was found that extreme storms are not preceded by an unusual storm.
In particular, antecedent storms are typically of a magnitude which occur numerous times during a given year.

Spatial Characteristics

The areal coverage characteristics of the 2 hour ID "thunderstorms" in eastern Washington were examined. Observed areal coverages were found to be highly variable, ranging from 35 to 500 square miles, and were nearly independent of the storm magnitude. The majority of storms originated out of the southwest or west. Storm movement resulted in areal coverages having an elliptical shape with an average major to minor axis ratio of about 2.5:1.

Assembly of Synthetic Storms

A methodology was presented for assembly of synthetic storms for each of the three IDs and five regions. The assembly methodology contained procedures which allowed decisions to be made regarding the manner in which the observed statistical characteristics could be incorporated in a synthetic storm.

In conclusion, it is intended that the findings from this study will allow engineers, hydrologists, meteorologists and other practitioners of rainfall-runoff modeling to make informed decisions in the selection and development of synthetic storms. Ultimately, it is hoped that this study will result in improved estimates of floods in Washington State.

ACKNOWLEDGMENTS

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Cover Photo by Dan Kruger:
Autumn Storm over the Cascade Mountains near Mt. Daniel

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APPENDIX 1A

EXTREME STORM CATALOG

REGION 1 - EASTERN WASHINGTON - MOUNTAIN AREAS

2 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
REPUBLIC RANGER STN	08/23/41	1.43	.01240	I	X	X	
DAYTON 1WSW	07/08/46	0.79	.04629	I	X		
OROVILLE	06/16/47	1.25	.00656	I	X	X	
CENTERVILLE	06/07/47	0.80	.03757	I	X		
METHOW	08/10/48	1.08	.01854	I	X		
METHOW	06/17/50	0.89	.04020	I	X		
COLVILLE	07/19/50	1.00	.01879	I	X		
PULLMAN 2NW	08/10/52	1.77	.00195	VI	X	X	X
WENATCHEE EXP. STN	08/10/52	1.29	.01177	I	X		
COLVILLE	07/06/56	0.82	.04411	I	X		
WENATCHEE EXP. STN	08/25/56	1.38	.00895	I	X	X	
ICE HARBOR DAM	06/05/57	1.67	.00250	I	X		
WALLA WALLA WSO	05/24/58	1.60	.00837	I	X	X	
REPUBLIC RANGER STN	07/05/58	1.10	.03855	I	X		
PLUMMER	07/07/58	0.87	.04089		X		
METHOW	07/08/58	1.33	.00774	I	X	X	
REPUBLIC RANGER STN	08/09/62	1.26	.02166	I	X	X	
BONNERS FERRY 1SW	09/10/62	0.99	.01279		X	X	
PULLMAN 2NW	06/16/63	1.47	.00496	I	X	X	
WENATCHEE EXP.	08/23/65	0.96	.03721	I	X		
POMEROY	09/13/66	1.12	.03500	I	X		
MAZAMA	01/17/71	0.90	.04851	VI	X		
WALLA WALLA WSO	05/26/71	1.75	.00557	I	X	X	X
WENATCHEE EXP.	06/09/72	1.05	.02647	I	X	X	
SPOKANE WSO	06/07/77	0.96	.02712	I	X		
WHITMAN MISSION	08/05/77	0.94	.01971	I	X		
DAYTON 1WSW	07/07/78	1.20	.00669	VI	X	X	
MT ADAMS RNGR STN	01/12/80	1.30	.01848	I	X		
BOUNDARY SWITCHYARD	05/21/81	1.10	.01111	I	X	X	
CHEWELAH	07/20/83	1.00	.02210	I	X		
REPUBLIC RANGER STN	08/10/83	1.50	.01363	I	X	X	X
EASTON	08/26/83	1.80	.00029	I	X		
LAKE WENATCHEE	02/11/85	1.10	.03711	I	X		
MAZAMA	07/16/85	1.10	.01999	I	X		

APPENDIX 1A

EXTREME STORM CATALOG

REGION 1 - EASTERN WASHINGTON - MOUNTAIN AREAS

6 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
EASTON	10/31/42	2.13	.02699	V		X	
PLUMMER 3WSW	06/06/47	1.46	.01489	I		X	
MAZAMA	07/16/55	1.83	.01282	I	X	X	
COLVILLE AP	05/13/57	1.45	.00887	VII	X	X	X
BONNERS FERRY 1SW	06/09/58	1.32	.02077	I		X	
COEUR D'ALENE	06/08/64	1.28	.04211			X	
PLUMMER 3WSW	06/17/65	1.42	.01836			X	
LUCERNE 2NNW	12/08/71	1.45	.02683	VI		X	
MAZAMA	01/11/72	2.20	.00396	VI		X	
WENATCHEE EXP STN	10/31/73	1.49	.06729	I		X	
LAKE WENATCHEE	01/17/75	2.10	.01892	VI	X	X	
WENATCHEE EXP STN	08/18/75	1.38	.03884	VI		X	X
GLENWOOD	12/01/77	1.65	.01468	VI		X	
TEKOA	07/04/78	1.30	.05184	I		X	X
PESHASTIN TELMTRY	02/06/79	1.60	.01466	VI		X	X
SATUS PASS 2SW	01/12/80	2.10	.01935	I		X	
WALLA WALLA WSO	10/13/80	1.97	.00801	I	X	X	
LUCERNE 2NNW	01/23/82	1.58	.01402	VI		X	
MAZAMA	12/03/82	2.10	.00538	VI		X	X
REPUBLIC RNGR STN	08/10/83	2.10	.00276	I		X	X

24 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	2 hr	6 hr	24 hr
SPRAGUE	09/21/45	1.55	.06002	XII			X
BONNERS FERRY 1SW	11/18/46	2.78	.00858	VI			X
UNDERWOOD	12/11/46	4.04	.04535	I		X	X
PULLMAN 2NW	09/15/47	2.10	.05404	I			X
HOOD RIVER EXP	01/06/48	3.33	.03638	VI			X
METHOW	05/28/48	2.02	.02430	VIII			X
OROVILLE	11/16/50	1.96	.02917	I			X
CENTERVILLE	01/09/53	2.36	.03548	VI		X	X
SATUS PASS 2SSW	11/24/60	3.12	.03090	VI			X
LUCERNE 2NW	11/19/62	3.05	.03261	I		X	X
DIXIE 4SE	11/23/64	2.70	.03145	I			X
DAYTON 9SE	12/22/64	3.01	.00922	VII			X
DAYTON 9SE	01/02/66	2.53	.03102	I			X
MAZAMA	02/27/72	3.80	.00578	I	X	X	X
SATUS PASS 2SSW	01/15/74	3.60	.01145	I			X
LUCERNE 2NNW	12/02/75	3.17	.02506	XII			X
SATUS PASS 2SSW	12/13/77	3.30	.02102	XII			X
WALLA WALLA WSO	10/14/80	3.08	.00260	V	X	X	X
MAZAMA	01/12/80	3.20	.01832	I			X
STEHEKIN 4NW	01/23/82	5.00	.00560	I		X	X
BOUNDARY SWITCHYARD	02/15/86	3.10	.00723	I			X

APPENDIX 1B

EXTREME STORM CATALOG

REGION 2 - EASTERN WASHINGTON - CENTRAL BASIN

2 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
ELLENSBURG	05/12/43	0.62	.06186	I	X		
WITHROW 4WNW	06/13/44	1.06	.02287	I	X		
YAKIMA	06/19/44	0.90	.02623	I	X		
SUNNYSIDE	06/07/47	1.62	.00161	I	X	X	X
HARRINGTON 4ENE	06/10/48	1.03	.01152	VI	X	X	
WILSON CREEK	06/18/50	1.50	.00261	I	X	X	X
WILSON CREEK	07/24/50	0.80	.03979	I	X		
NACHES 10NW	05/05/57	0.90	.02485	I	X		
CHIEF JOE DAM	06/07/58	0.71	.04654	I	X		
COULEE DAM	04/29/61	0.85	.03374	I	X		
WITHROW 4WNW	08/14/68	0.94	.03615	V	X	X	
WITHROW 4WNW	12/11/69	0.93	.03762	I	X		
YAKIMA	08/18/75	0.98	.01900	V	X	X	
NACHES 10NW	07/07/82	1.20	.00742	I	X		X
NACHES 10NW	08/01/84	0.80	.03979	I	X		

6 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	2 hr	6 hr	24 hr
WILSON CREEK	06/16/48	1.06	.03072	I		X	
ARLINGTON-OREGON	01/08/53	1.02	.04795			X	
MCNARY DAM	10/01/57	1.86	.00058	VIII	X	X	X
CHIEF JOE DAM	08/23/65	1.02	.04979	I		X	
COULEE DAM 1SW	11/12/73	1.19	.02880	I		X	
PASCO	09/13/80	1.30	.01031	VI	X	X	X
NACHES 10 NW	01/23/82	1.00	.06342	V	X	X	X

24 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	2 hr	6 hr	24 hr
LIND 3NE	06/25/42	1.53	.02443	I			X
HARRINGTON 4ENE	09/21/45	1.52	.04749	XII			X
COULEE DAM 1SW	05/28/48	1.66	.03021	I			X
HARRINGTON 4ENE	09/25/48	1.51	.02500	I		X	X
NACHES 10 NW	01/14/56	1.43	.06551	I			X
MCNARY DAM	10/02/57	3.15	.00008	I	X	X	X
ARLINGTON OREGON	12/22/64	3.15	.00689			X	X
ELLENSBURG	12/04/74	1.30	.04410	IV			X

APPENDIX 1C

EXTREME STORM CATALOG

REGION 3 - WESTERN WASHINGTON - PUGET SOUND LOWLANDS

2 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
EVERETT	09/28/44	1.01	.03311	VII	X	X	
MCMILLIN RESERVOIR	07/08/46	1.10	.02178	VIII	X		
CENTRALIA 1W	10/28/49	1.15	.02101	I	X		
SEATTLE WSO	06/29/52	0.96	.04180	I	X		
MCMILLIN RESERVOIR	09/17/57	1.07	.02585	VI	X		
EVERETT	05/31/58	1.14	.01603	I	X		
AUBURN	06/08/59	0.87	.04232	V	X		
MCMILLIN RESERVOIR	08/26/60	1.70	.00176	VII	X	X	
GOBLE 3SW-OREGON	06/30/63	0.87	.03467		X		
LONGVIEW	08/23/63	1.05	.04125	I	X		
SNOQUALMIE FALLS	09/19/64	1.17	.03576	I	X		
BURLINGTON	08/12/65	1.28	.00877	I	X	X	
PORT TOWNSEND	09/10/67	0.84	.03295	X	X		
EVERETT	09/22/72	0.99	.03713	X	X		
CASTLE ROCK	09/20/73	1.46	.00685	V	X	X	
CENTRALIA 1W	07/08/74	1.20	.01638	V	X		
SEATTLE -EMSU	08/26/77	1.64	.00153	I	X	X	
CARNATION 1W	09/20/77	1.20	.00865	I	X		
LANDSBURG	07/09/80	0.90	.05640	I	X		
SEA-TAC	10/06/81	0.85	.04442	II	X		X
CARNATION	06/18/86	1.00	.03000	I	X		

6 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	2 hr	6 hr	24 hr
SEA-TAC (WSO)	01/19/43	1.60	.02674	VI		X	
PORT TOWNSEND	06/14/46	1.35	.01637	I		X	X
SEA-TAC (WSO)	02/16/49	1.50	.04348	X		X	
OLYMPIA	12/09/56	2.13	.02460	IX		X	
YELM	11/20/59	1.44	.05487	VIII		X	
EVERETT	10/23/60	1.39	.05067	I		X	
SNOQUALMIE FALLS	10/21/63	2.08	.04165	I		X	
CARNATION 4NW	12/03/68	1.57	.03335	VI		X	
LANDSBURG	06/23/69	1.64	.04089	VI		X	
PORTLAND ORG -WB	09/17/69	1.82	.02002			X	
BLAINE 1ENE	11/03/71	1.60	.03747	V		X	X
YELM	12/21/72	1.43	.05759	I		X	
PORT ANGELES	11/03/78	1.92	.01514	VI		X	
SNOQUALMIE FALLS	01/23/82	2.00	.05516	IX		X	
SEATTLE EMSU	12/03/82	1.56	.03855	V		X	
MCMILLIN RESRVOIR	08/29/83	1.90	.00822	I		X	
BLAINE 1ENE	12/29/83	1.70	.02345	VIII	X	X	X
BLAINE 1ENE	02/15/86	2.00	.00568	V	X	X	

APPENDIX 1C

EXTREME STORM CATALOG

REGION 3 - WESTERN WASHINGTON - PUGET SOUND LOWLANDS

24 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
SEA-TAC (WSO)	02/06/45	3.00	.05829	I			X
BURLINGTON	10/24/45	4.91	.00049	I		X	X
BURLINGTON	02/15/49	3.42	.01277	I			X
OLYMPIA WB AIRPORT	02/09/51	4.93	.01859	II			X
BLAINE 1ENE	11/03/55	3.63	.01849	I		X	X
AUBURN	11/20/59	3.63	.02312	II	X		X
PORT ANGELES	01/14/61	3.12	.03318	I			X
LONGVIEW	11/19/62	5.41	.00194	I	X	X	X
CASTLE ROCK	11/23/64	4.62	.03649	II			X
SNOQUALMIE FALLS	01/18/67	4.72	.03595	III			X
SNOQUALMIE FALLS	03/05/72	4.90	.02747	I			X
LONGVIEW	12/02/77	4.70	.00710	I		X	X
LANDSBURG	12/16/79	3.40	.05000	VIII			X
SEA-TAC AIRPORT	10/06/81	3.71	.01218	VI	X		X
SEATTLE EMSU	01/18/86	4.48	.00388	XII			X
LONGVIEW	02/23/86	4.70	.00710	VIII	X	X	X

APPENDIX 1D

EXTREME STORM CATALOG

REGION 4 - WESTERN WASHINGTON - MOUNTAINS

2 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
MUD MOUNTAIN DAM	06/10/42	0.99	.05121	I	X		
MUD MOUNTAIN DAM	09/01/43	0.99	.05121	VI	X		
COUGAR 4SW	09/21/44	1.49	.01364	I	X		
SKYKOMISH 1ENE	05/25/45	1.78	.00204	I	X		
MT. BAKER LODGE	06/16/49	1.53	.01349	I	X		
CINEBAR	06/09/53	1.51	.00282	II	X	X	
BONNEVILLE DAM	08/25/56	1.51	.00760		X	X	
RANDLE 1E	08/28/57	1.40	.00422	I	X		
SILVERTON	09/10/67	1.40	.04602	VI	X		
BONNEVILLE DAM	11/20/70	1.40	.01367	I	X		
WHITE RIVER RNGR STA	05/10/75	1.20	.01806	I	X		
CEDAR LAKE	09/20/77	1.40	.05242	I	X		
RANDLE	06/28/78	1.30	.01423	I	X		
MUD MOUNTAIN DAM	07/09/79	1.11	.02402	I	X		
CARSON FISH HATCH	01/12/80	1.40	.01856	I	X		
SILVERTON	09/30/80	1.80	.00542	I	X		
QUILCENE DAM 5SW	11/29/80	1.40	.03717	I	X		

6 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	2 hr	6 hr	24 hr
SNOQUALMIE PASS	12/04/41	2.74	.05860	VI	X	X	
SPIRIT LAKE RNGR STA	10/24/43	3.12	.00177	V	X	X	X
MARBLEMOUNT RNGR STA	01/07/45	2.04	.04324	IX		X	
SILVERTON	02/07/45	2.84	.05340	IX		X	
SNOQUALMIE PASS	10/24/45	3.87	.00299	V	X	X	
SAPHO 8E	02/01/47	3.32	.01265	IX	X	X	
BONNEVILLE DAM	10/19/47	3.60	.00079	I	X	X	X
QUILCENE DAM 5SW	12/01/48	2.55	.07421	VI	X	X	
DARRINGTON RNGR STA	09/27/53	2.20	.06177	V		X	
LESTER	12/09/53	2.15	.03030	X		X	
QUILCENE DAM 5SW	02/07/55	2.64	.05816	IX		X	
SILVERTON	12/09/56	3.30	.01631	IX	X	X	
PALMER 3ESE	09/26/59	2.69	.01417	VIII	X	X	
CAMP GRISDALE	11/19/59	4.14	.02681	VI	X	X	
STAMPEDE PASS	11/22/59	2.94	.01517	VI		X	X
STAMPEDE PASS	11/21/61	2.56	.04583	IX		X	
DIABLO DAM	12/08/71	2.50	.02156	VI	X	X	
WHITE RIVER RNGR STA	11/09/73	2.00	.04035	VI	X	X	
MUD MOUNTAIN DAM	08/18/75	2.13	.00677	I	X	X	X
SNOQUALMIE PASS	12/01/75	2.90	.03867	X	X	X	
GREENWATER	12/02/77	2.70	.00221	V	X	X	
PALMER 3ESE	11/03/83	2.40	.03619	I		X	
GREENWATER	01/03/84	2.10	.02290	I	X	X	X
CEDAR LAKE	01/24/84	2.40	.03284	II		X	
CUSHMAN DAM	01/18/86	4.30	.00476	V	X	X	X

APPENDIX 1D

EXTREME STORM CATALOG

REGION 4 - WESTERN WASHINGTON - MOUNTAINS

24 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
DIABLO DAM	10/24/45	6.42	.01822	VI			X
RAINIER CARBON RIVR	11/17/46	4.30	.04004	V			X
ELECTRON HEADWORKS	12/10/46	4.77	.05000	VII			X
DIABLO DAM	02/16/49	7.57	.00455	XII	X		X
DARRINGTON RNGR STA	11/26/49	4.98	.06920	VIII		X	X
DIABLO DAM	02/09/51	6.47	.01716	V		X	X
QUILCENE DAM 5SW	01/07/59	5.80	.05000	III			X
SKYKOMISH 1ENE	12/14/59	7.70	.01404	VI			X
RAINIER OHANEPECOSH	11/19/62	7.78	.00235	I	X	X	X
PALMER 3ESE	01/28/65	5.14	.04948	VIII			X
GLACIER RNGR STA	03/05/72	4.90	.02150	I			X
STAMPEDE PASS	12/01/75	6.84	.03012	VII			X
CINEBAR	12/02/77	6.80	.00228	I		X	X
GLACIER RNGR STA	12/14/79	5.70	.00522	VI			X
UPPER BAKER DAM	11/21/80	5.80	.05652	XII			X
GREENWATER	01/23/82	5.30	.00583	III	X	X	X
QUILCENE DAM 5SW	10/22/82	7.90	.00627	VII		X	X
SILVERTON	12/03/82	7.70	.01476	VI			X
NOOKSACK HATCHERY	01/10/83	6.30	.01589	XII			X
GREENWATER	01/24/84	4.50	.00284	I	X	X	X
DARRINGTON RNGR STA	01/18/86	6.60	.00850	XI			X
MARBLEMOUNT RNGR STA	02/24/86	6.20	.01586	VII		X	X

APPENDIX 1E

EXTREME STORM CATALOG

REGION 5 - WESTERN WASHINGTON - COASTAL LOWLANDS

2 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	EXCEEDED EXTREME STORM THRESHOLD AT INDEPENDENT DURATIONS 2 hr	6 hr	24 hr
TATOOSH ISLAND	11/03/41	1.41	.03972	IX	X		
TATOOSH ISLAND	10/10/42	1.53	.02249	I	X		
WESTPORT	10/30/50	1.47	.01324	I	X	X	
MOCLIPS	01/02/51	1.30	.05650		X		
WESTPORT	10/18/79	1.20	.05473	V	X		
ABERDEEN 20NNE	05/28/82	2.50	.00217	I	X		

6 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	2 hr	6 hr	24 hr
MOCLIPS	12/11/53	2.47	.04705	VI		X	
ABERDEEN 20NNE	11/02/55	3.47	.05275	V		X	
MONTESANO 3NW	12/22/61	2.46	.05234	VII		X	
FRANCES	11/25/62	2.72	.05101	VI		X	
PT. GRENVILLE	10/29/67	2.98	.03869	VI		X	
QUILLAYUTE	01/25/71	3.21	.02772	V		X	
GRAYS RIVER	11/06/80	3.20	.03226	VI	X	X	
QUINALT RS	02/15/81	4.00	.00863	I	X	X	
FRANCES	12/15/82	2.90	.03137	V	X	X	
WESTPORT 2S	07/01/83	2.20	.05192	VI		X	
GRAYS RIVER	10/26/85	3.10	.04117	VI		X	

24 HOUR INDEPENDENT DURATION STORMS

STATION	DATE	DEPTH (inches)	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY	MACRO STORM PATTERN	2 hr	6 hr	24 hr
CLEARWATER	12/03/43	8.41	.02404	VI			X
TATOOSH ISLAND	10/23/44	5.33	.02426	XII		X	X
ABERDEEN 20NNE	11/03/55	8.39	.06235	I		X	X
GRAYS RIVER	01/14/58	6.64	.05847	IV			X
MONTESANO 3NW	11/18/62	5.40	.02750	I			X
QUILLAYUTE	01/18/68	8.32	.01534	I			X
CLEARWATER	01/25/71	7.90	.03790	IX		X	X
CLEARWATER	07/11/72	8.90	.01549	VI			X
MONTESANO 3NW	02/27/80	5.00	.06522	VI			X
CLEARWATER	02/13/82	9.30	.01081	III			X
FRANCES	01/18/86	5.20	.06500	XI			X

APPENDIX 2

CONSTRUCTION OF DEPTH-DURATION CURVES

The depth-duration curve is an analytical tool developed by meteorologists [Chow, 1964] [WMO, 1969] to allow comparisons to be made between storms of the amount of precipitation which occurred during a given time period. Simply stated, the depth-duration curve is a precipitation mass curve created by rearrangement of the incremental precipitation amounts from an observed storm. The new mass curve is constructed in a manner which contains the largest incremental precipitation amounts at the start of the new mass curve. Slight variations exist in the procedures used by various meteorologists, hydrologists and engineers in the construction of depth-duration curves.

Depth-duration curves can be developed for at-site precipitation, representing storm areal coverage for some nominal area such as 1 square mile or 10 square miles, or for a specific area. In the latter case, spatial averaging techniques are first used to define the average temporal distribution of the storm for the given area.

The following list describes procedures for construction of at-site depth-duration curves:

- A time increment for analysis is selected based on the needs of the specific study.

- The precipitation record is examined to determine the largest precipitation amount which occurred in a "window of time" equal to the time increment. This incremental precipitation amount is ranked first and forms the beginning of a new series of reordered amounts from the observed storm.

- The precipitation record is then reexamined to determine the largest precipitation amount which has occurred in a window of time equal to twice the time increment and which includes the initial precipitation amount chosen previously. The precipitation amount which occurred in this second incremental period of time is listed second in the new series being formed. The term "nested" is often applied to the requirement that the duration (time window) being examined must include the entire time period which contained the previously selected amounts.

- The process of expanding the time window by one time increment and selecting the largest nested precipitation amount is continued until the original storm is completely reordered.

- The reordered mass curve is labeled a depth-duration curve.

- A dimensionless depth-duration curve is produced by dividing the ordinates of the curve by the observed precipitation amount corresponding a specic duration of interest.

<u>**EXAMPLE:**</u> Extreme Storm of October 14, 1945 - Snoqualmie Pass, WA.
6 hour Precipitation Depth= 3.87 inches
Independent Duration= 6 hours, Time Increment= 3 hours
Macro Pattern= Type VI

Solution: Use previously discussed steps to reorder observed storm mass curve into dimensionless depth-duration curve. Incremental precipitation amounts are listed and reordered in Table 20 and displayed in Figure 20.

Table 20. Development of Depth-Duration Curve from Observed 6 Hour ID Extreme Storm of October 14, 1945 at Snoqualmie Pass, WA.

ORIGINAL STORM MASS CURVE			DEPTH-DURATION CURVE			
END OF HOUR	MASS CURVE (inches)	INCREMENTAL VALUE (inches)	DURATION (hours)	INCREMENTAL VALUE (inches)	MASS CURVE (inches)	DIMENSIONLESS ORDINATES
1	0.10	0.10	0	0.00	0.00	0.000
2	0.30	0.20	1	0.88	0.88	0.227
3	0.68	0.38	2	0.67	1.55	0.401
4	1.10	0.42	3	0.75	2.30	0.594
5	1.80	0.70	6	1.57	3.87	1.000
6	2.55	0.75*	9	1.06	4.93	1.274
7	3.22	0.67*	12	0.60	5.53	1.429
8	4.10	0.88*	15	0.25	5.78	1.494
9	4.55	0.45	18	0.20	5.98	1.545
10	4.88	0.33				
11	5.23	0.35				
12	5.51	0.28				
13	5.63	0.12				
14	5.73	0.10				
15	5.78	0.05				
16	5.83	0.05				
17	5.91	0.08				
18	5.98	0.07				

- Continuous Storm

Trisector 1 = 2.55"
Trisector 2 = 2.96"
Trisector 3 = 0.47"
Macro Pattern = Type VI

* High Intensity Segment Sequence = 231

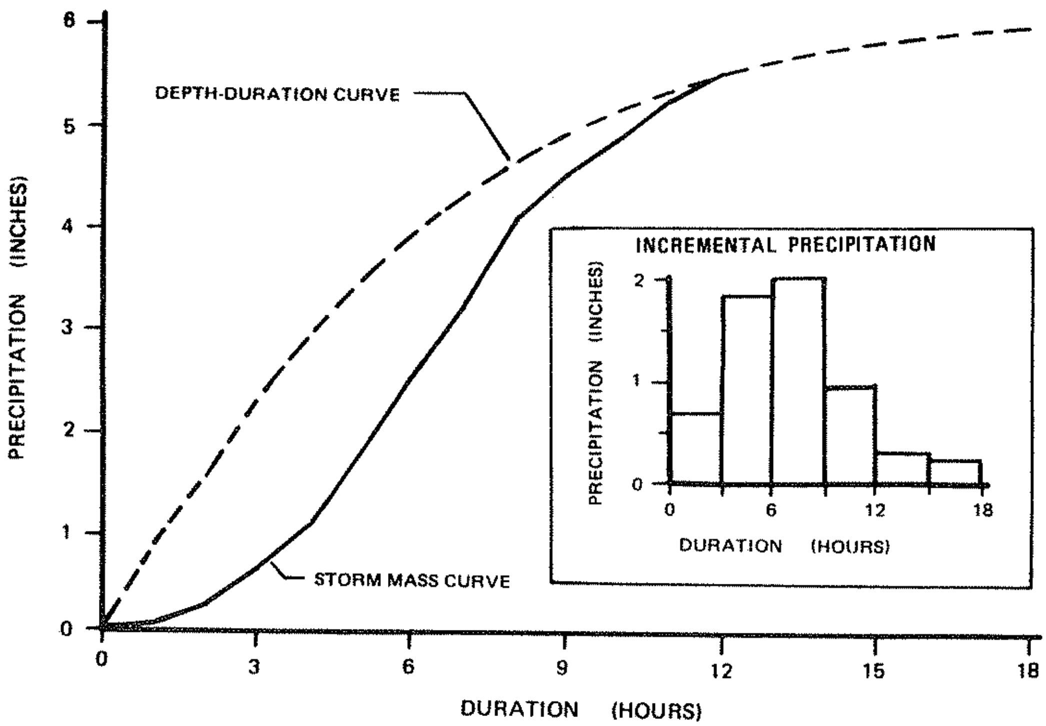

Figure 20. Comparison of Depth-Duration and Observed Mass Curves for Extreme Storm of October 14, 1945 at Snoqualmie Pass, WA.

APPENDIX 3

WORKSHEETS FOR ASSEMBLY OF SYNTHETIC STORMS

WORKSHEET FOR ASSEMBLY OF 2 HOUR ID MASS HYETOGRAPHS

PROJECT__________________ FILE NO.________

LOCATION__________________ NORTH______° WEST______°

WASHINGTON CLIMATIC REGION__________________

WATERSHED DRAINAGE AREA (mi^2)__________

2 HOUR ID EXTREME STORM DEPTH______ Inches KERNEL 0.5 Hours

EXCEEDANCE PROBABILITY OF SELECTED DEPTH-DURATION CURVE _____ %

EXCEEDANCE PROBABILITY OF SELECTED STORM CHARACTERISTICS _____ %

TIME OF OCCURRENCE OF HIGH INTENSITY STORM SEGMENT...AT _____ Hours

HIGH INTENSITY STORM SEQUENCE __ __ __

TIME OF OCCURRENCE OF 2 HOUR ID SEGMENT FROM ____ Hours to ____ Hours

MACRO PATTERN...TYPE _____ MACRO STORM SEQUENCE __ __ __ __ __ __

DEPTH-DURATION ORDINATES							
DEPENDENT DURATION (hours)	ORDINATE VALUES				TIME INCREMENT (hours)	INCREMENTAL PRECIPITATION AMOUNT (inches)	SEQUENCE NUMBER
	TABULAR	SCALED	AREAL REDUCTION	FINAL			
0.00	0.000	0.00	----	0.00			
0.08					0.08		within
0.17					0.08		1 hi
0.25					0.08		
0.00	0.000	0.00	----	0.00			
0.25					0.25		1 hi
0.50					0.25		2 hi
0.75					0.25		3 hi
1.00					0.25		1 macro
1.25					0.25		
1.50					0.25		2 macro
2.00	1.000				0.50		
3.00					1.00		3 macro
4.00					1.00		4 macro
5.00					1.00		5 macro
6.00					1.00		6 macro

SYNTHETIC STORM MASS HYETOGRAPH			
TIME (hours)	SEQUENCE NUMBER	INCREMENTAL AMOUNT (inches)	MASS ORDINATE VALUE (inches)

WORKSHEET FOR ASSEMBLY OF 6 HOUR ID MASS HYETOGRAPHS

PROJECT____________________ FILE NO.________

LOCATION____________________ NORTH______° WEST______°

WASHINGTON CLIMATIC REGION____________________

WATERSHED DRAINAGE AREA (mi^2)__________

6 HOUR ID EXTREME STORM DEPTH______ Inches KERNEL 2.0 Hours

EXCEEDANCE PROBABILITY OF SELECTED DEPTH-DURATION CURVE ______ %

EXCEEDANCE PROBABILITY OF SELECTED STORM CHARACTERISTICS ______ %

TIME OF OCCURRENCE OF HIGH INTENSITY STORM SEGMENT...AT _____ Hours

HIGH INTENSITY STORM SEQUENCE __ __ __

TIME OF OCCURRENCE OF 6 HOUR ID SEGMENT FROM ____ Hours to ____ Hours

MACRO PATTERN...TYPE _____ MACRO STORM SEQUENCE __ __ __ __ __ __

DEPTH-DURATION ORDINATES

DEPENDENT DURATION (hours)	ORDINATE VALUES: TABULAR	SCALED	AREAL REDUCTION	FINAL	TIME INCREMENT (hours)	INCREMENTAL PRECIPITATION AMOUNT (inches)	SEQUENCE NUMBER
0.00	0.000	0.00	----	0.00			
0.25					0.25		within
0.50					0.25		1 hi
1.00					0.50		
0.00	0.000	0.00	----	0.00			
1.00					1.00		1 hi
2.00					1.00		2 hi
3.00					1.00		3 hi
							(1 hi – 3 hi bracketed: 1 macro)
6.00	1.000				3.00		2 macro
9.00					3.00		3 macro
12.00					3.00		4 macro
15.00					3.00		5 macro
18.00					3.00		6 macro

SYNTHETIC STORM MASS HYETOGRAPH

TIME (hours)	SEQUENCE NUMBER	INCREMENTAL AMOUNT (inches)	MASS ORDINATE VALUE (inches)

WORKSHEET FOR ASSEMBLY OF 24 HOUR ID MASS HYETOGRAPHS

PROJECT________________________ FILE NO.________

LOCATION________________ NORTH______° WEST______°

WASHINGTON CLIMATIC REGION________________________

WATERSHED DRAINAGE AREA (mi^2)____________

24 HOUR ID EXTREME STORM DEPTH______ Inches KERNEL____ Hours

EXCEEDANCE PROBABILITY OF SELECTED DEPTH-DURATION CURVE ______ %

EXCEEDANCE PROBABILITY OF SELECTED STORM CHARACTERISTICS ______ %

TIME OF OCCURRENCE OF HIGH INTENSITY STORM SEGMENT...AT _____ Hours

HIGH INTENSITY STORM SEQUENCE __ __ __

TIME OF OCCURRENCE OF 24 HOUR ID SEGMENT FROM ____ Hours to ____ Hours

SEQUENCE OF 6 HOUR SEGMENTS WITHIN 24 HOUR ID __ __ __ __

MACRO PATTERN...TYPE _____ MACRO STORM SEQUENCE __ __ __ __ __ __

DEPTH-DURATION ORDINATES

DEPENDENT DURATION (hours)	ORDINATE VALUES				TIME INCREMENT (hours)	INCREMENTAL PRECIPITATION AMOUNT (inches)	SEQUENCE NUMBER
	TABULAR	SCALED	AREAL REDUCTION	FINAL			
0.00	0.000	0.00	----	0.00			
0.50					0.50		within
1.00					0.50		1 hi
0.00	0.000	0.00	----	0.00			
1.00					1.00		1 hi
2.00					1.00		2 hi
3.00					1.00		3 hi
6.00					3.00		1..6 hr
9.00					3.00		2..6 hr
12.00					3.00		
18.00					6.00		3..6 hr
24.00	1.000				6.00		2 macro 4..6 hr
36.00					12.00		3 macro
48.00					12.00		4 macro
60.00					12.00		5 macro
72.00					12.00		6 macro

SYNTHETIC STORM MASS HYETOGRAPH

TIME (hours)	SEQUENCE NUMBER	INCREMENTAL AMOUNT (inches)	MASS ORDINATE VALUE (inches)

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Mission

The mission of the Department of Ecology is to protect, preserve and enhance Washington's environment and promote the wise management of our air, land and water for the benefit of current and future generations.

12–Point Strategy

To accomplish this mission, the department will:

- Recognize its most valuable asset is its dedicated and committed employees and it will provide necessary support, training and professional development.
- Promote prevention and conservation as the most effective ways to preserve our natural resources and protect the environment.
- Enforce environmental laws and regulations in a fair and firm manner.
- Provide public education programs to promote wise use of our natural resources and encourage environmental protection.
- Offer information, technical and financial assistance to help the public, governments, businesses and industries comply with environmental laws and regulations.
- Promote the recognition that compliance with environmental laws and regulations is compatible with a sound economy.
- Provide meaningful public involvement in the development of rules, regulations and new initiatives.
- Provide leadership in addressing emerging problems and strive to bring public agencies and diverse interest groups together to address environmental issues.
- Use an integrated approach to resolve environmental issues.
- Place special emphasis on educating and working with youth to create a strong environmental ethic.
- Help state agencies set an example in environmental protection.
- Work with the executive and legislative branches to promote sound environmental policy.