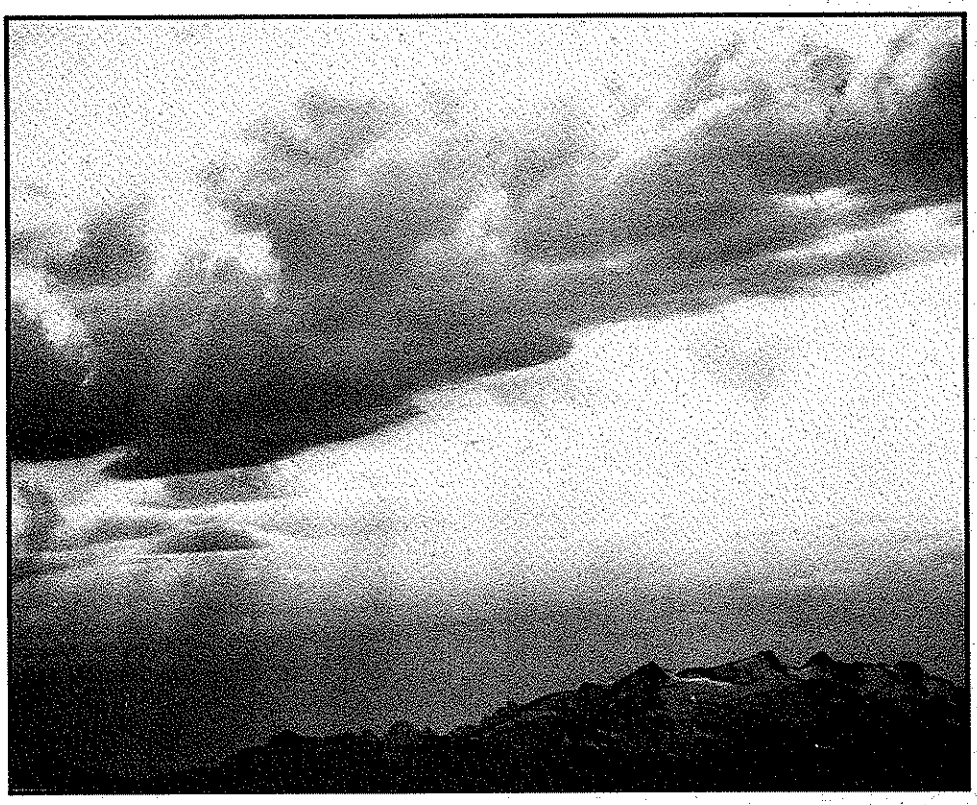
# E.47. Washington

F-912
WDOE
89-51
C. 2

90101366



# Characteristics of Extreme Precipitation Events in Washington State

## Water Resources Program

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

October, 1989
89-51

90101366

PROPERTY OF STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY LIBRARY

Washington State
Department of Ecology
Water Resources Program

# Characteristics of Extreme Precipitation Events in Washington State

By Melvin G. Schaefer
Dam Safety Section

DSS-01

WASHINGTON STATE DEPARTMENT OF ECOLOGY

October 1989
89-51

90101366

# TABLE OF CONTENTS


| | PAGE |
|---|---|
| **INTRODUCTION** | 1 |
| **OVERVIEW** | 2 |
| METHOD OF ANALYSIS | 2 |
| OBJECTIVES AND STUDY CONTENTS | 2 |
| HOMOGENEITY AND REGION DEFINITION | 4 |
| **EXTREME STORM CATALOG** | 9 |
| PROCESS FOR SELECTION OF EXTREME STORMS | 9 |
| **SEASONALITY OF EXTREME STORMS** | 12 |
| **TEMPORAL DISTRIBUTION OF STORMS** | 15 |
| DEFINITIONS - GLOSSARY OF TERMS | 15 |
| MACRO STORM PATTERNS | 19 |
| ANALYSIS OF DEPTH-DURATION CURVES | 25 |
| Methods of Analysis | 26 |
| Stage 1 of Analysis | 27 |
| Stage 2 of Analysis | 35 |
| CONSTRUCTION OF PROBABILISTIC DEPTH-DURATION CURVES | 40 |
| Curves Conditioned on the Total Storm Depth | 49 |
| VERIFICATION OF VALIDITY OF USING DIMENSIONLESS ORDINATES IN DEPTH-DURATION CURVES | 54 |
| TIMING CHARACTERISTICS OF HIGH INTENSITY SEGMENTS | 56 |
| SEQUENCING OF INCREMENTAL PRECIPITATION SEGMENTS | 58 |
| Sequencing of High Intensity Segments Within Storms | 58 |
| Sequencing of 6 Hour Segments Within 24 Hour ID Storms | 59 |

**ANTECEDENT STORMS** 62

**SPATIAL CHARACTERISTICS** 65

THUNDERSTORM CHARACTERISTICS - EASTERN WASHINGTON 66

Thunderstorm Areal Coverage 66

Thunderstorms - Direction of Movement 67

Thunderstorm - Storm Shape 68

DEPTH-AREA RELATIONSHIPS 69

**ASSEMBLY OF SYNTHETIC STORMS** 72

METHODOLOGY FOR ASSEMBLY OF SYNTHETIC STORMS 73

**SUMMARY AND CONCLUSIONS** 87

**ACKNOWLEDGMENTS** 91

**REFERENCES** 92

**APPENDICES 1A to 1E - EXTREME STORM CATALOG** 94

**APPENDIX 2 - CONSTRUCTION OF DEPTH-DURATION CURVES** 102

**APPENDIX 3 - WORKSHEETS FOR ASSEMBLY OF SYNTHETIC STORMS** 105

## A B S T R A C T

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.

# LIST OF FIGURES


| | | PAGE |
|---|---|---|
| Figure 1a. | Washington State Precipitation Gaging Network | 7 |
| Figure 1b. | Mean Annual Precipitation in Washington State and Delineation of Climatic Regions | 8 |
| Figure 2a-2f. | Frequency Histograms for Seasonality of Extreme Storms in Washington State | 13 |
| Figure 3. | Frequency Histogram for Occurrence of 2 Hour Extreme Storms Versus Time of Day | 14 |
| Figure 4. | Example of Relationships Between Independent Duration, Total Duration and Trisectors | 19 |
| Figure 5. | Generalized Macro Storm Patterns for Categorization of Extreme Storms | 21 |
| Figure 6a-6f. | Frequency Histograms for Macro Patterns of Extreme Storms in Washington State | 22 |
| Figure 7. | Depth-Duration Curve for 2 Hour ID Extreme Storm Depicting Typical Characteristics and Physical Boundaries | 28 |
| Figure 8a-8f. | Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves | 29 |
| Figure 9. | Smoothing Functions for Improved Regression Parameters Example - 24 Hour ID Storms for Puget Sound Lowlands | 39 |
| Figure 10. | Typical Shape Characteristics of Depth-Duration Curves Example - 2 Hour ID Storms for Eastern Washington | 41 |
| Figure 11. | Comparison of Depth-Duration Curves for 24 Hour ID Storms Example - Western Washington Mountains | 50 |

Figure 12a. Variation of Kernel Ordinates with Storm Annual Exceedance Probability Example - 6 Hour ID Events in Western Washington 55

Figure 12b. Relationship of Kernel Duration Precipitation Amounts to Independent Duration Precipitation Amounts Example - 6 Hour ID Events in Western Washington 55

Figure 13. Relationship of Antecedent 24 Hour Duration Storms to 24 Hour ID Extreme Storms 63

Figure 14. Variation of Areal Coverage with Maximum Point Rainfall for 2 Hour ID Pacific Northwest Thunderstorms 68

Figure 15. Depth-Area Curves for 6 Hour and 24 Hour ID Storms 69

Figure 16. Depth-Area Curves for 2 Hour ID storms 70

Figure 17. Synthetic Mass Hyetograph for 2 Hour ID Extreme Storm for a 1 Square Mile Watershed near Olympia, WA. 78

Figure 18. Synthetic Mass Hyetograph for 6 Hour ID Extreme Storm for a 5 Square Mile Watershed near Olympia, WA. 80

Figure 19. Synthetic Mass Hyetograph for 24 Hour ID Extreme Storm for a 100 Square Mile Watershed near Olympia, WA. 85

Figure 20. Comparison of Depth-Duration and Observed Mass Curves for Extreme Storm of October 14, 1945 near Snoqualmie Pass, WA. 104

# LIST OF TABLES


| | | PAGE |
|---|---|---|
| Table 1. | Formulation for Region Definition | 5 |
| Table 2. | General Guideline for Selection of the Duration Most Representative of a Given Storm Event | 11 |
| Table 3. | Percentage of Extreme Storms which had Continuous or Intermittent Precipitation | 20 |
| Table 4. | Typical Macro Pattern Characteristics for Extreme Storms | 23 |
| Table 5. | Corrections Applied to Dimensionless Ordinates in Depth-Duration Curves | 27 |
| Table 6a-6c. | Cross-Correlation Matrices for Dependent Duration Ordinates | 36 |
| Table 7. | Time Increments used in Various Elements of the Study of the Temporal Distribution of Extreme Storms | 38 |
| Table 8a-81. | Dimensionless Depth-Duration Curves | 42 |
| Table 9a-9e. | Dimensionless Depth-Duration Curves with 48 Hour Kernel Ordinate for 24 Hour Extreme Storms | 51 |
| Table 10. | Frequency Characteristics for Time of Occurrence of High Intensity Segment of Extreme Storms | 57 |
| Table 11. | Sequencing Characteristics of High Intensity Segments | 59 |
| Table 12. | Frequency that the First and Second Largest 6 Hour Precipitation Segments Occur Adjacent to Each Other Within 24 Hour ID Extreme Storms | 60 |

Table 13. Sequencing Characteristics of the Largest 6 Hour Precipitation Segment Within 24 Hour ID Extreme Storms 61

Table 14. Commonly Occurring Sequences for 6 Hour Precipitation Segments Within 24 Hour ID Extreme Storms 61

Table 15. Characteristics of Storms Antecedent to Extreme Storms 63

Table 16. Database of Selected Pacific Northwest Thunderstorms 67

Table 17. Assembly of Synthetic Mass Hyetograph for 2 Hour ID Extreme Storm for 1 Square Mile Watershed near Olympia, WA. 77

Table 18. Assembly of Synthetic Mass Hyetograph for 6 Hour ID Extreme Storm for 5 Square Mile Watershed near Olympia, WA. 81

Table 19. Assembly of Synthetic Mass Hyetograph for 24 Hour ID Extreme Storm for 100 Square Mile Watershed near Olympia, WA. 84

Table 20. Development of Depth-Duration Curve for Observed 6 Hour ID Extreme Storm of October 14, 1945 at Snoqualmie Pass, WA. 104

# 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.

# O V E R V I E W

## 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<br>Convergence |
| 1 | 15 - 70 | 23.5 | 1 | EASTERN WASHINGTON - MOUNTAINS<br>Convergence and Orographic |
| 3 | 20 - 70 | 42.0 | 3 partial region | WESTERN WASHINGTON - PUGET SOUND LOWLANDS<br>Convergence |
| 4 | 50 - 200 | 86.5 | 4 | WESTERN WASHINGTON - MOUNTAINS<br>Convergence and Orographic |
| 5 | 70 - 120 | 89.0 | 3 partial region | WESTERN WASHINGTON - COASTAL LOWLANDS<br>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.

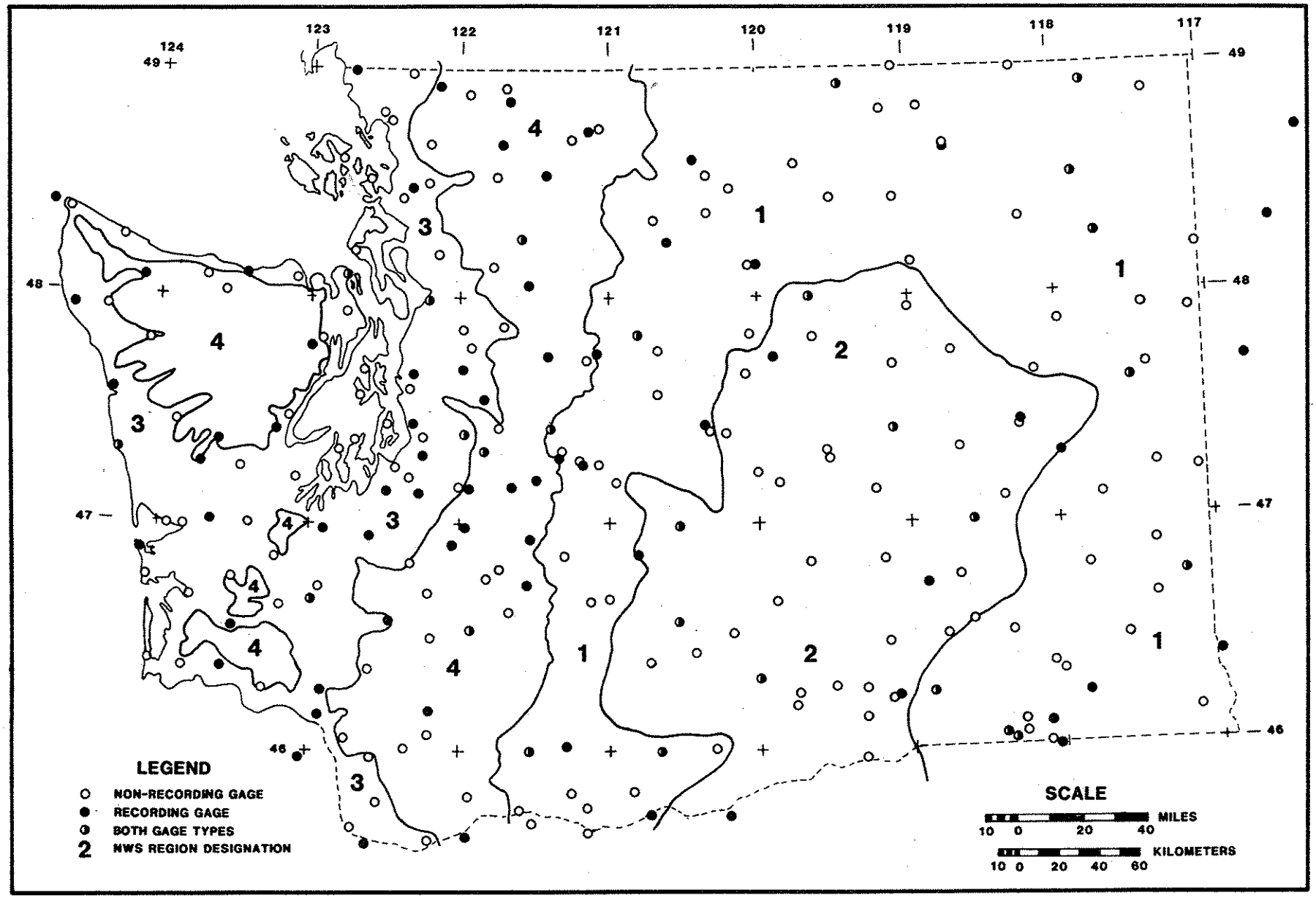



Figure 1a. Washington State Precipitation Gaging Network

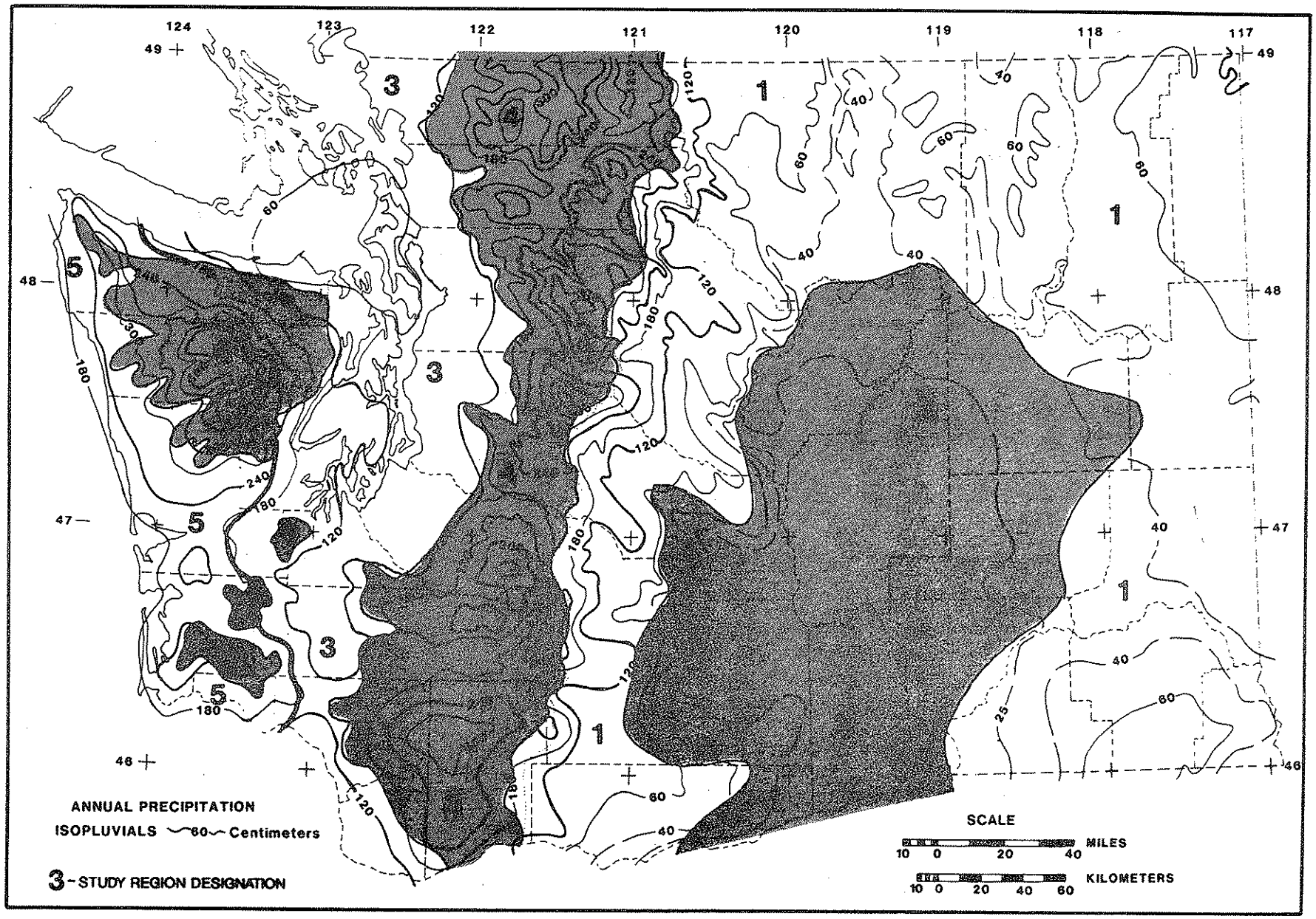



Figure 1b. Mean Annual Precipitation in Washington State and Delineation of Climatic Regions

## 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

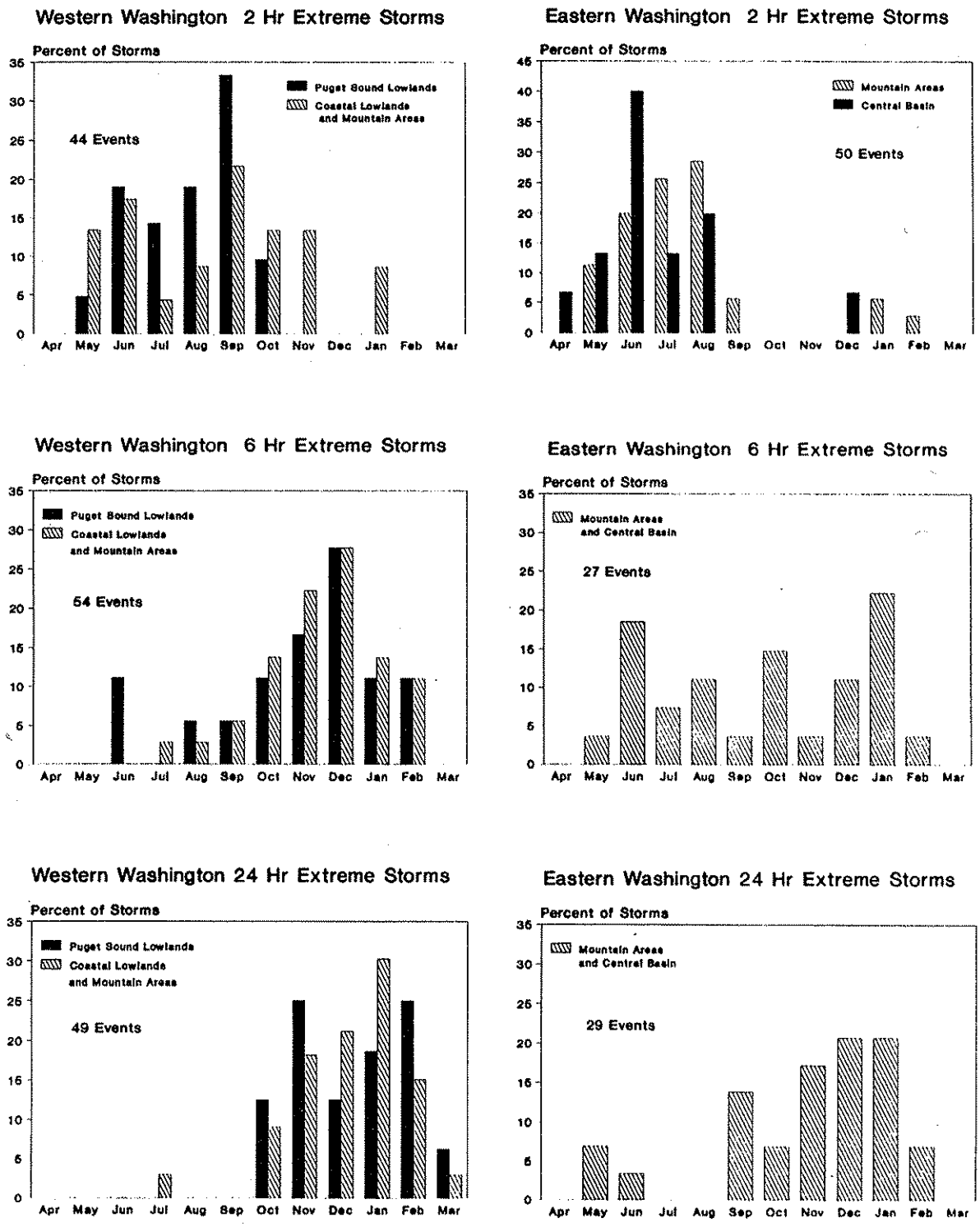
It is common knowledge that the majority of the precipitation that falls annually in the Pacific Northwest occurs in the winter months. However, only limited study [Frederick et al, 1981] has been conducted on the season of occurrence (seasonality) of extreme storms.

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.

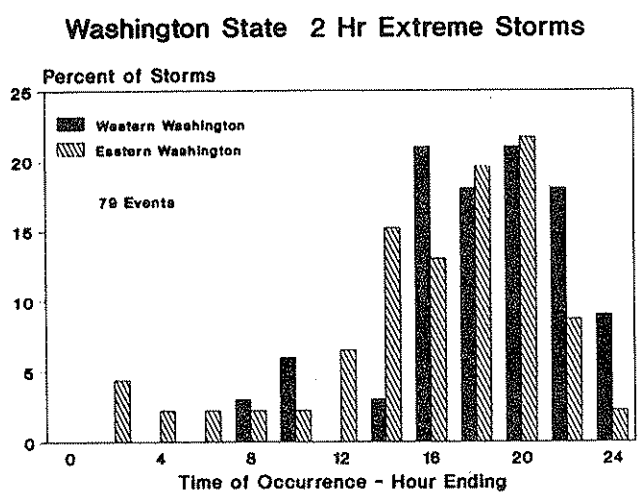



Figure 3. Frequency Histogram for Occurrence of 2 Hour Extreme Storms versus Time of Day

## 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).

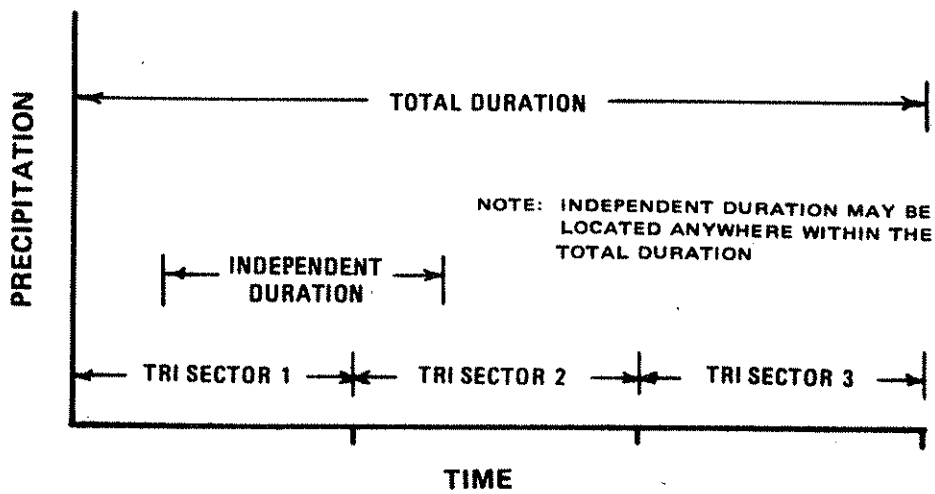



Figure 4 Example of Relationships between Independent Duration, Total Duration and Trisectors

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 |

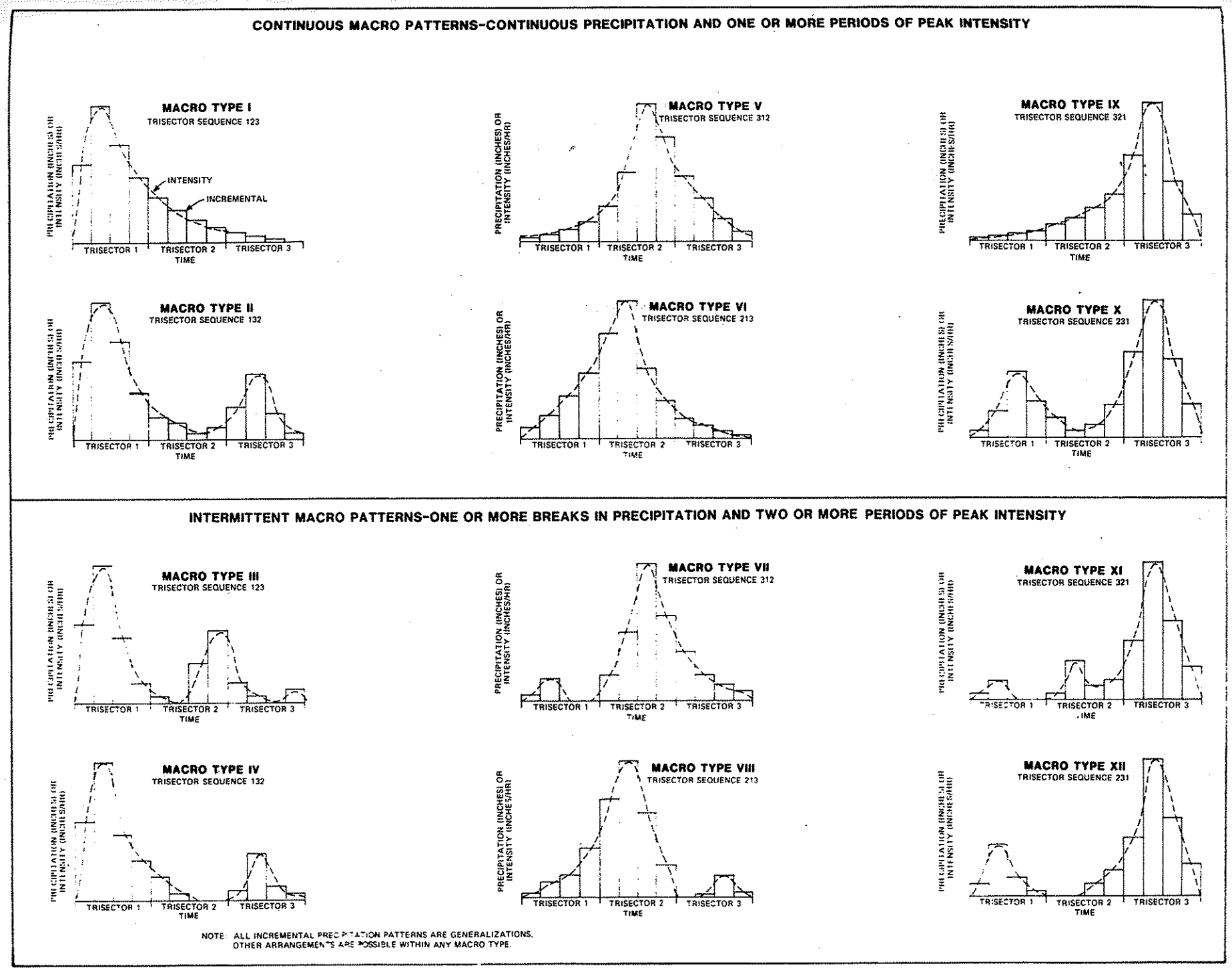
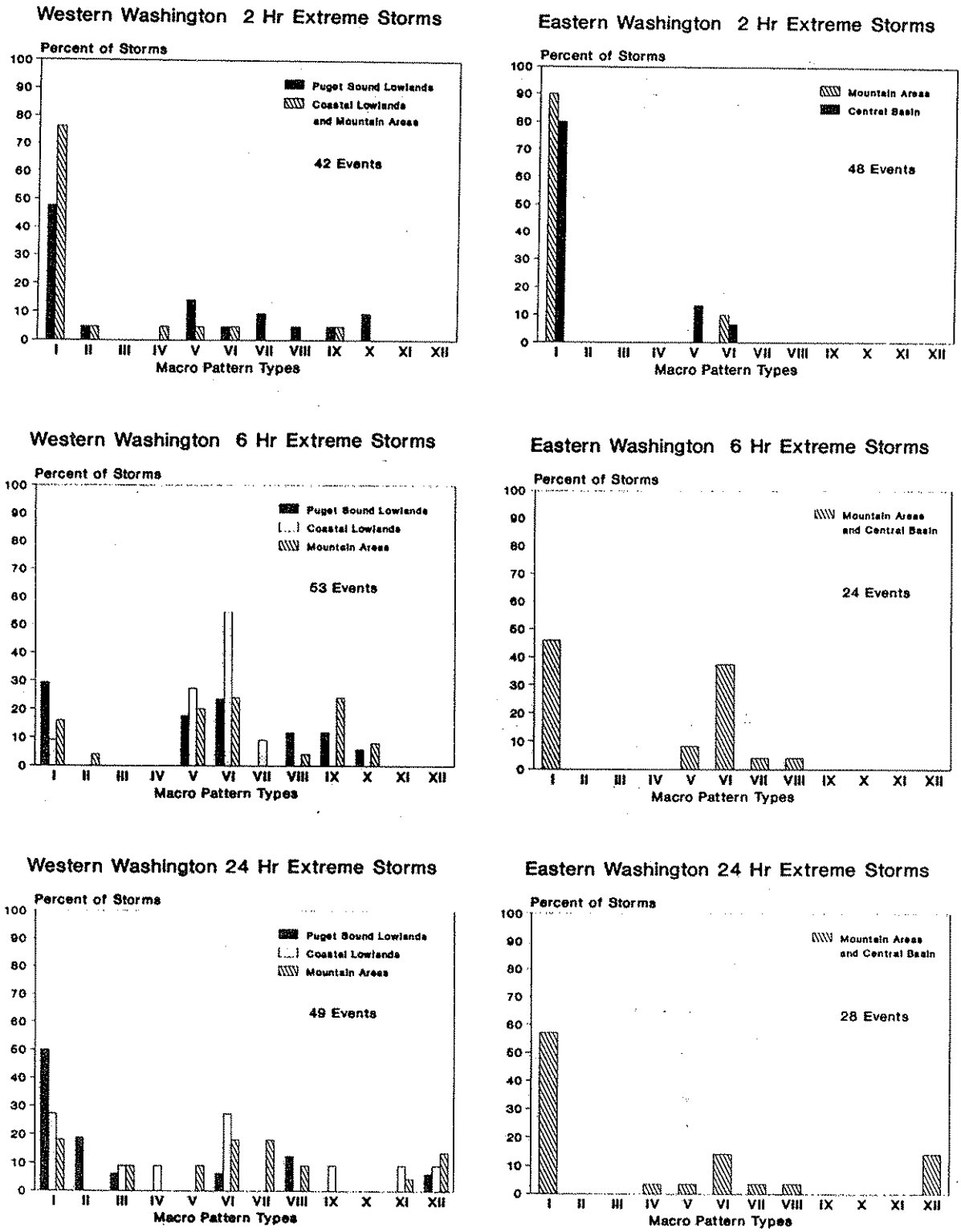



FIGURE 5. GENERALIZED MACRO STORM PATTERNS FOR CATEGORIZATION OF EXTREME STORMS.




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) | | EFFECTIVE DURATION (hours) | TYPICAL MACRO PATTERN |
| | | | MEAN | STND. DEVIATION | MEAN | |
| 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<br>TABULATION TIMES - - DEPENDENT DURATIONS<br>MINUTES | | | | | | HOURS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 | 75 | 90 | 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<br>TABULATION TIMES - - DEPENDENT DURATIONS<br>MINUTES | | | HOURS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 15 | 30 | 60 | 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).

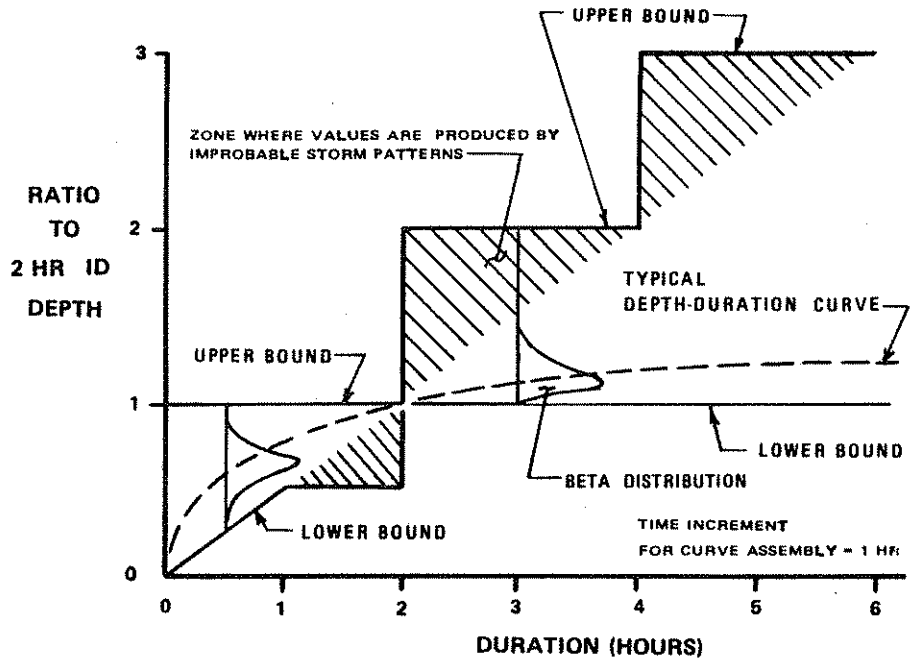



Figure 7. Depth-Duration Curve for 2 Hour ID Extreme Storm Depicting Typical Characteristics and Physical Boundaries

The probability density function for the Beta distribution is:

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

where:

$\delta_1$ and $\delta_2$ are the lower and upper bounds respectively
$\alpha$ and $\beta$ 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:

$\mu_x$, $\sigma_x^2$ and $\gamma_x$ 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.

This Page Intentionally Left Blank

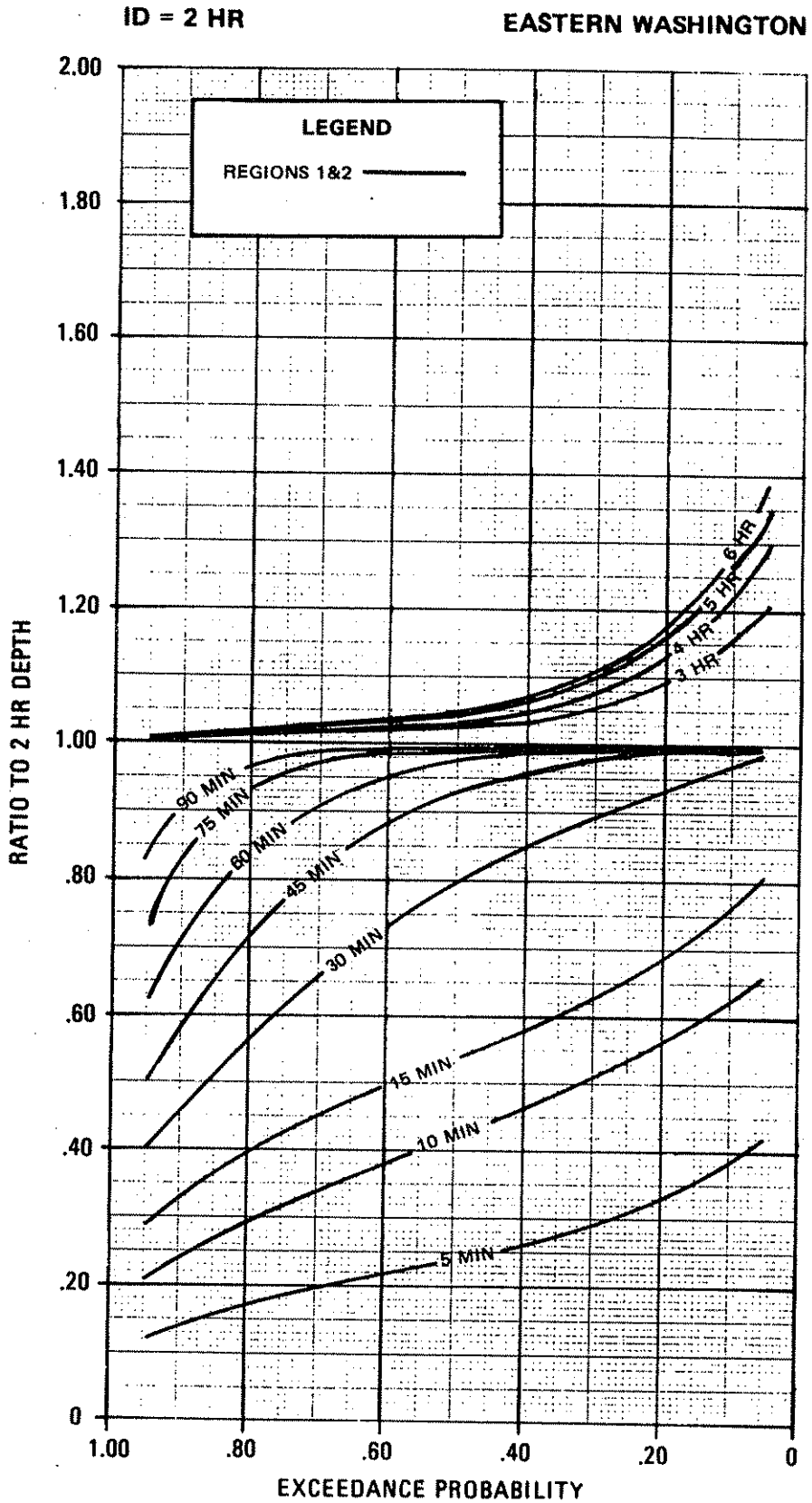



Figure 8a. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 2 Hour Extreme Storms in Eastern Washington

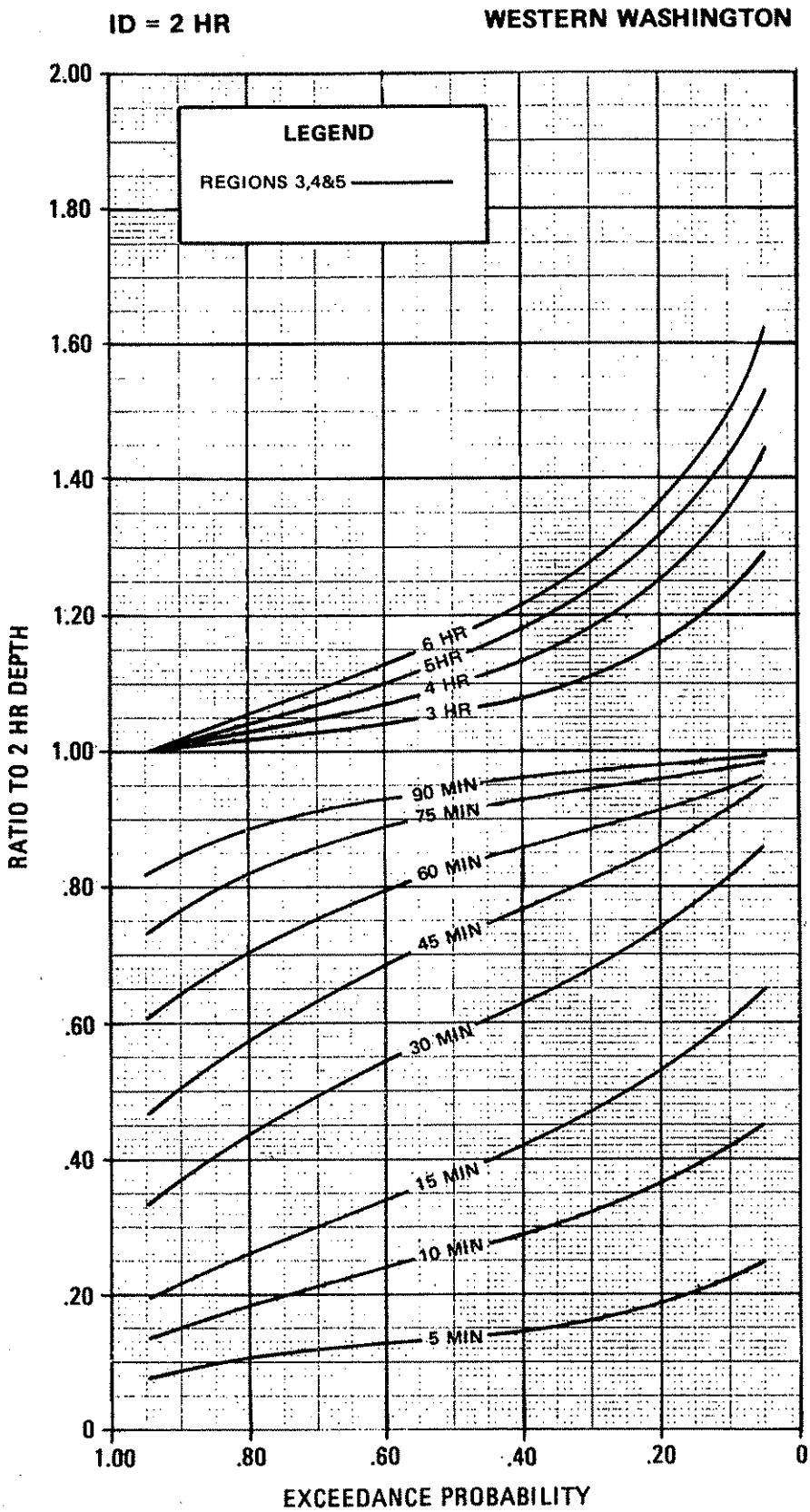



Figure 8b. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 2 Hour Extreme Storms in Western Washington

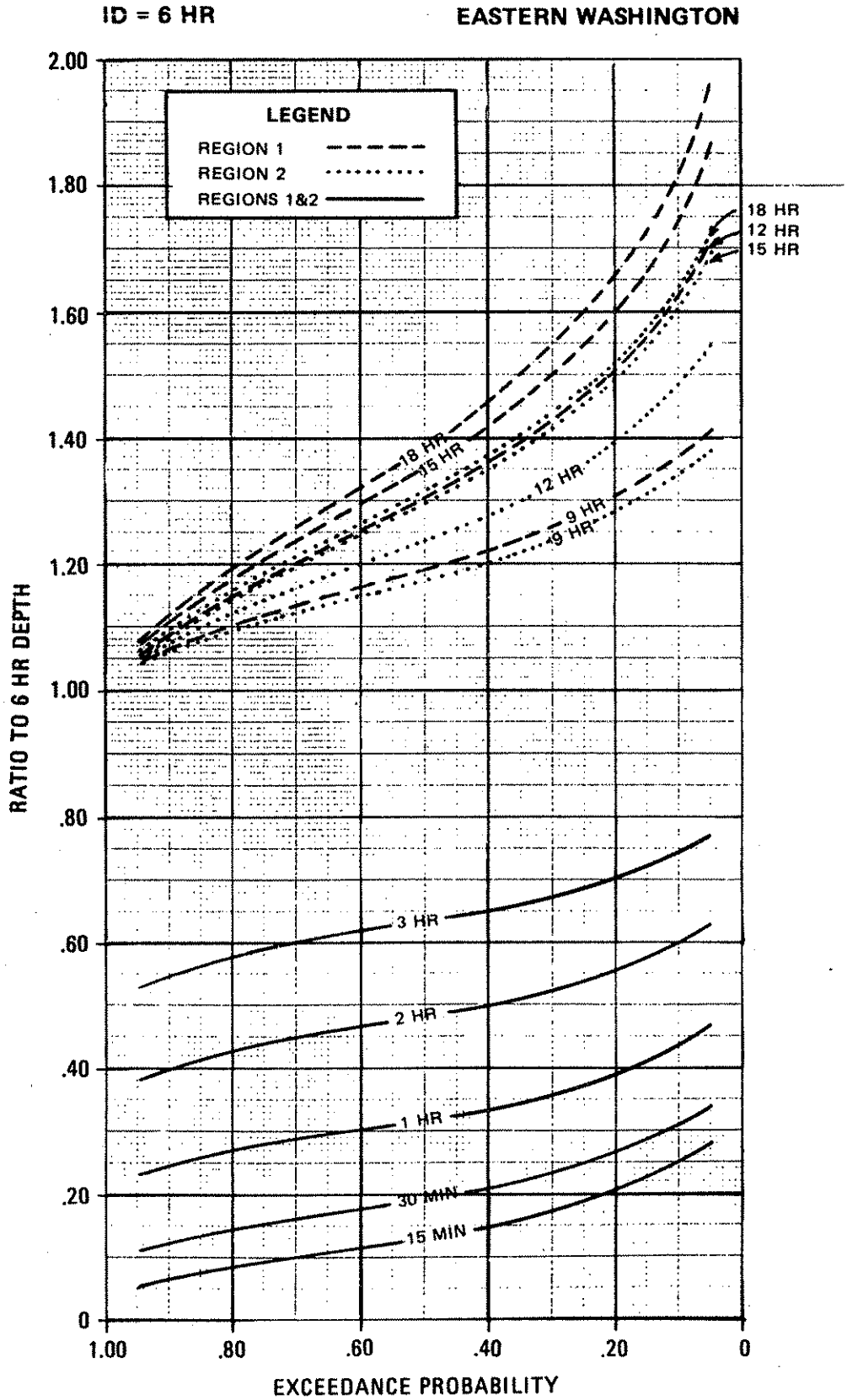



Figure 8c. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 6 Hour Extreme Storms in Eastern Washington

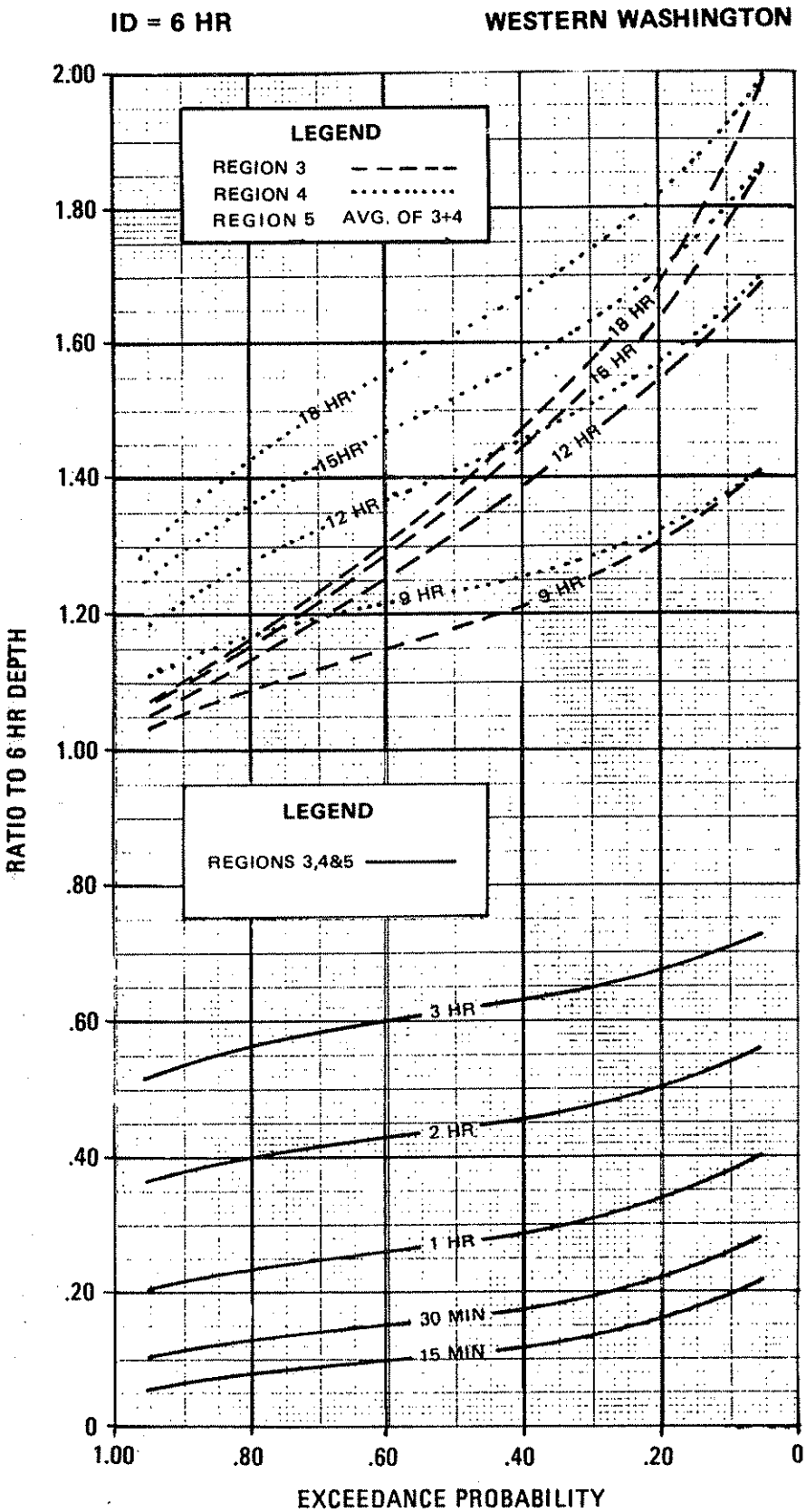



Figure 8d. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 6 Hour Extreme Storms in Western Washington

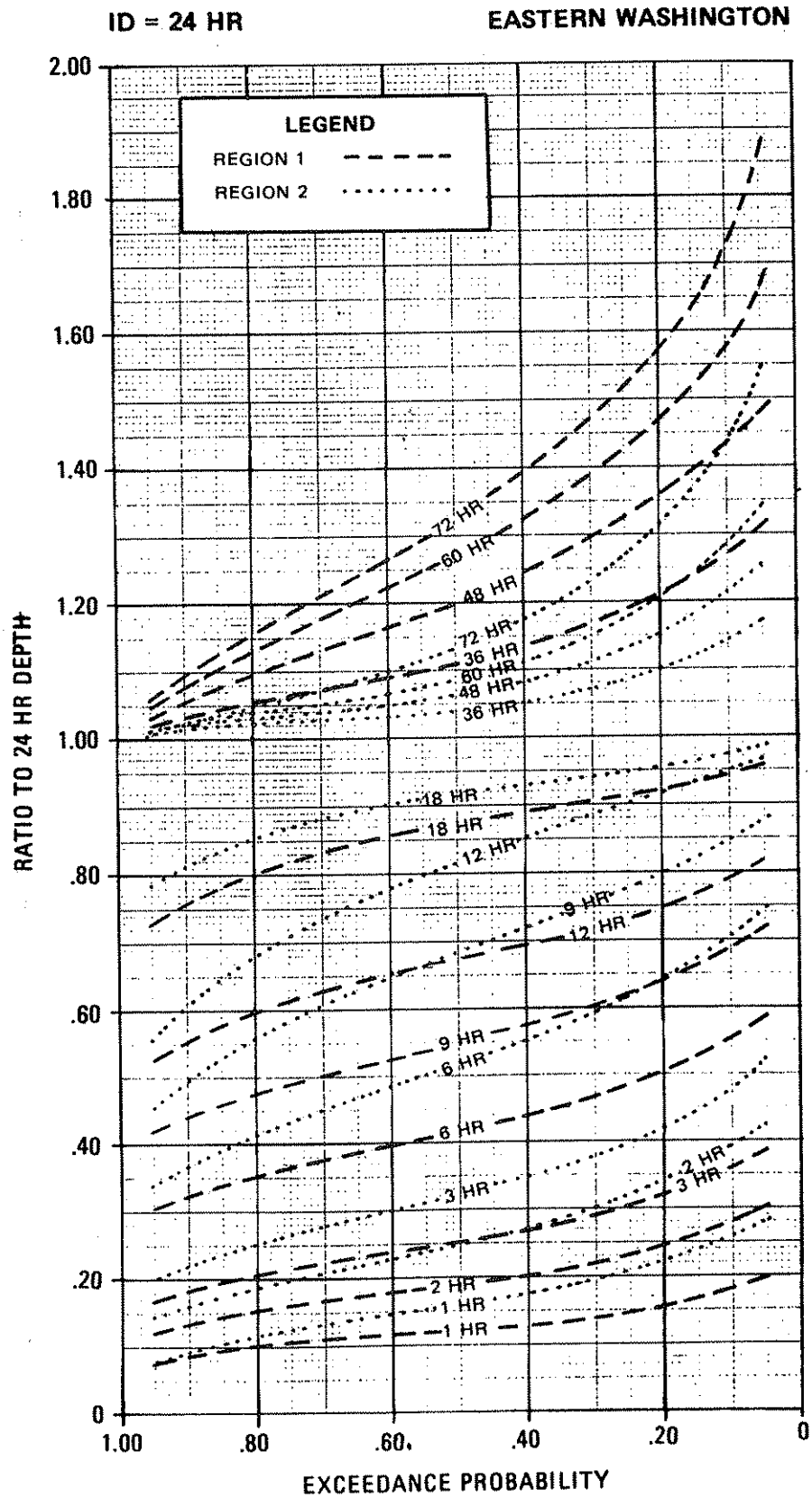



Figure 8e. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 24 Hour Extreme Storms in Eastern Washington

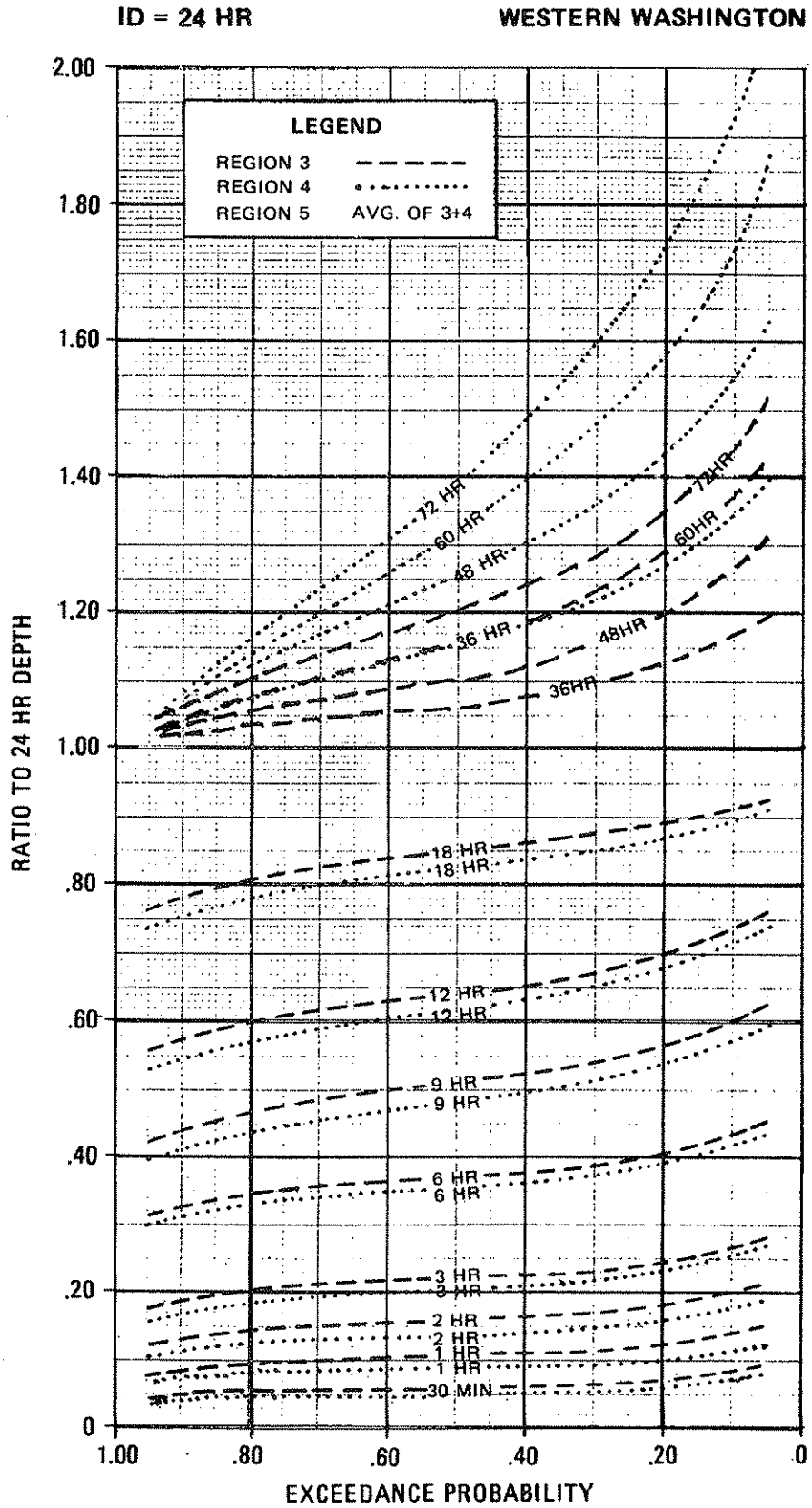



Figure 8f. Magnitude-Frequency Characteristics of Ordinate Values of Dimensionless Depth-Duration Curves for Dependent Durations of 24 Hour Extreme Storms in Western Washington

**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

| DEPENDENT DURATION (hours) | CROSS-CORRELATION MATRIX<br>2 HOUR EXTREME STORMS - - EASTERN WASHINGTON REGIONS 1 & 2<br>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

| DEPENDENT DURATION (hours) | CROSS - CORRELATION MATRIX<br>6 HOUR EXTREME STORMS - - WESTERN WASHINGTON REGION 4<br>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:

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

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).

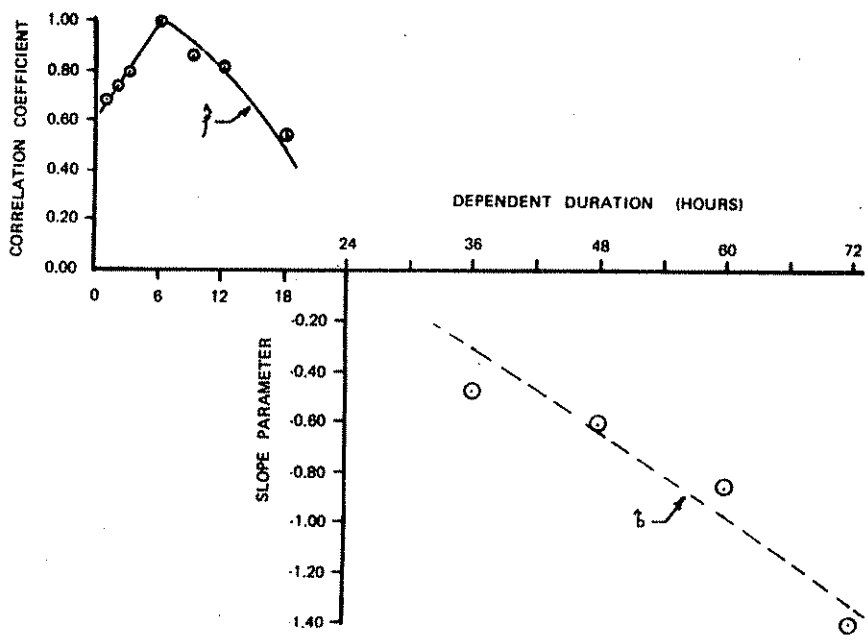



Figure 9. Smoothing Functions for Improving Regression Parameters
Example - 24 Hour ID Storms for Puget Sound Lowlands

## 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 and 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.

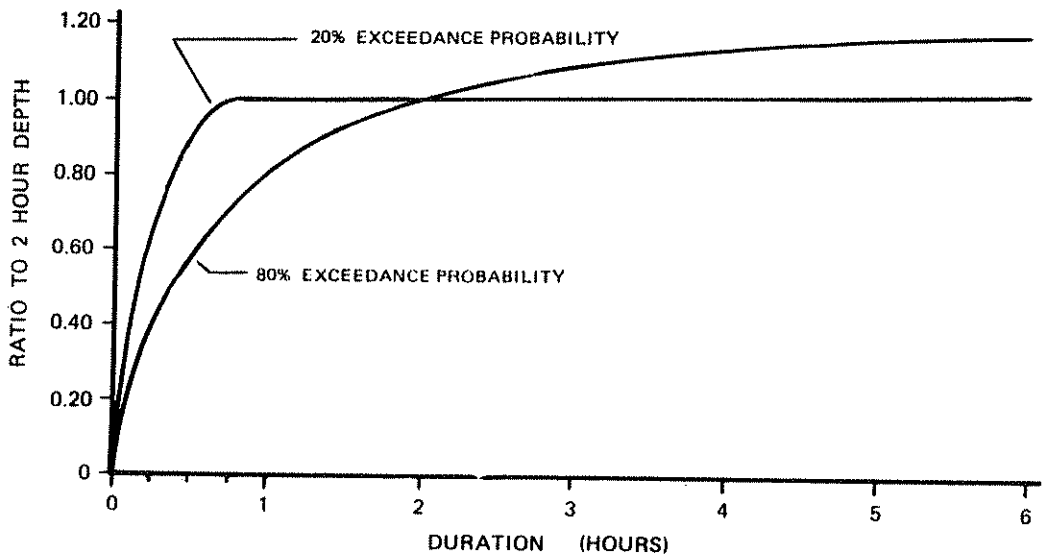



Figure 10. Typical Shape Characteristics of Depth-Duration Curves Example - 2 Hour ID Storms for Eastern Washington

## 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

| EXCEEDANCE PROBABILITY FOR KERNEL | ORDINATE VALUES DIMENSIONLESS DEPTH-DURATION CURVES 6 HOUR EXTREME STORMS - EASTERN WASHINGTON - MOUNTAINS - REGION 1 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 | .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 |

| EXCEEDANCE PROBABILITY FOR KERNEL | ORDINATE VALUES DIMENSIONLESS DEPTH-DURATION CURVES 6 HOUR EXTREME STORMS - EASTERN WASHINGTON - CENTRAL BASIN - REGION 2 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 | .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<br>DIMENSIONLESS DEPTH-DURATION CURVES<br>6 HOUR EXTREME STORMS - WESTERN WASHINGTON - COASTAL LOWLANDS - REGION 5<br>KERNEL VALUES AT 2.00 HOURS<br>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<br>DIMENSIONLESS DEPTH-DURATION CURVES<br>24 HOUR EXTREME STORMS - WESTERN WASHINGTON - COASTAL LOWLANDS - REGION 5<br>KERNEL VALUES AT 6.00 HOURS<br>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.

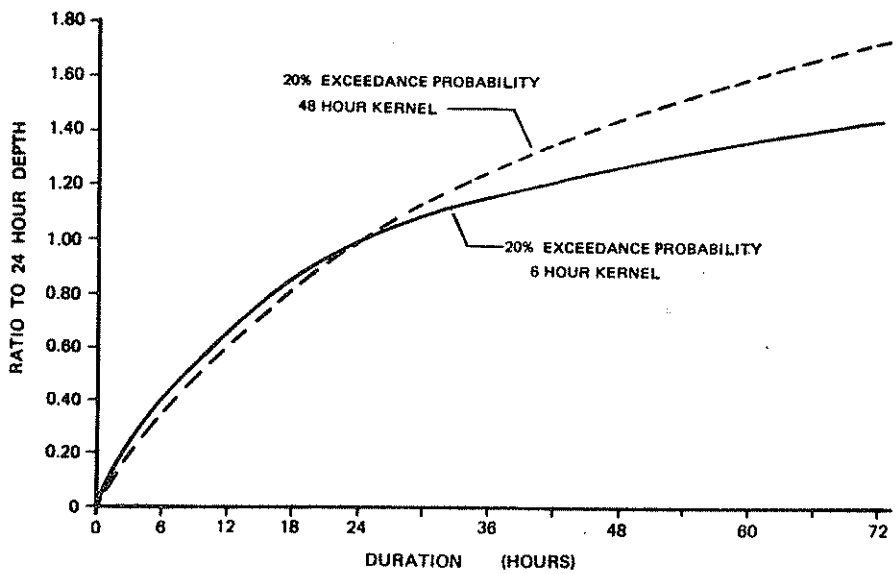



Figure 11. Comparison of Depth-Duration Curves for 24 Hour ID Storms Example - Western Washington Mountains

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 |

Table 9e 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 - COASTAL LOWLANDS - REGION 5

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 | .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.

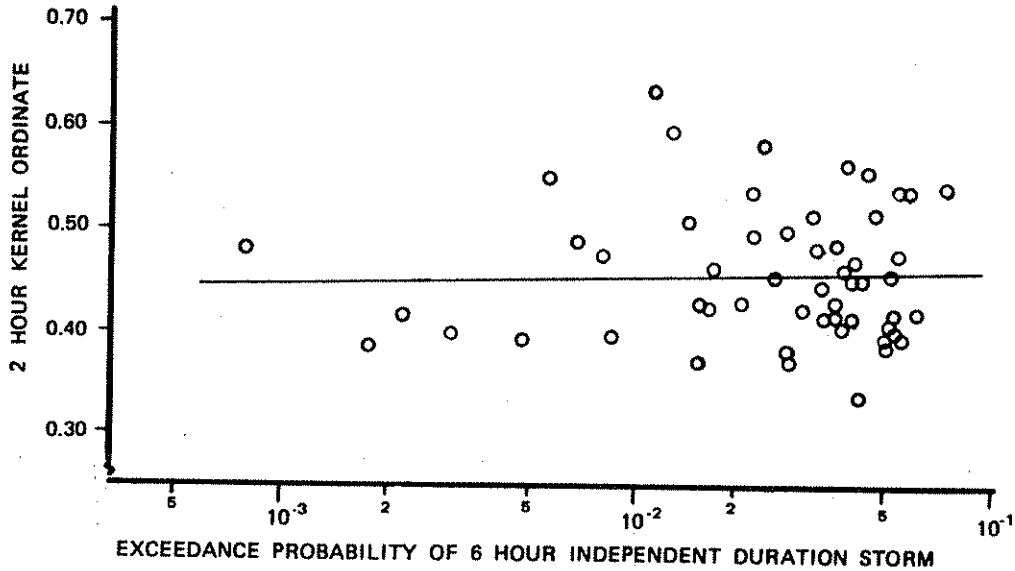



Figure 12a. Variation of Kernel Ordinates with Storm Annual Exceedance Probability
Example - 6 Hour ID Events Western Washington

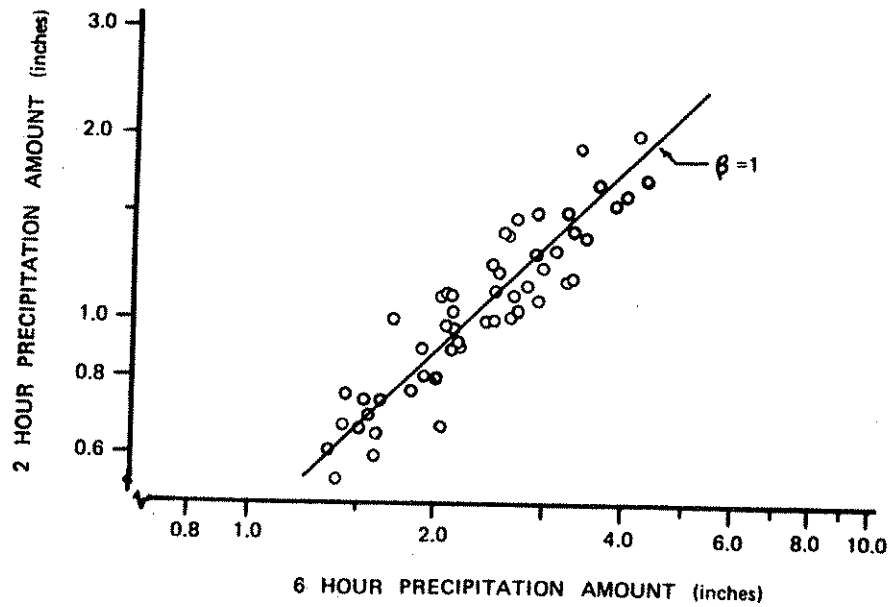



Figure 12b. Relationship of Kernel Duration Precipitation Amounts to Independent Duration Precipitation Amounts
Example - 6 Hour ID Events Western Washington

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:

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

where:

$P_{dd}$ is the precipitation amount for a specified DD
$P_{id}$ is the precipitation amount for the ID
$\alpha$ and $\beta$ 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 $\alpha$ 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:

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

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.

This Page Intentionally Left Blank

## 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 $\delta_2$ 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 not 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 |

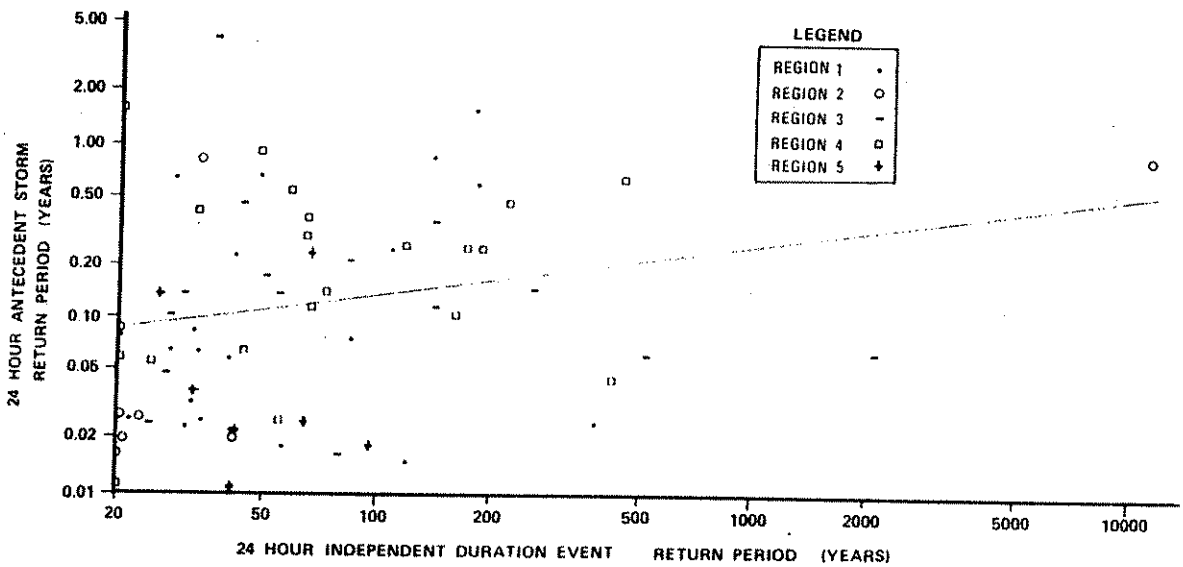



Figure 13. Relationship of Antecedent 24 Hour Duration Storms to 24 Hour ID Extreme Storms

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 extra-ordinarily 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.

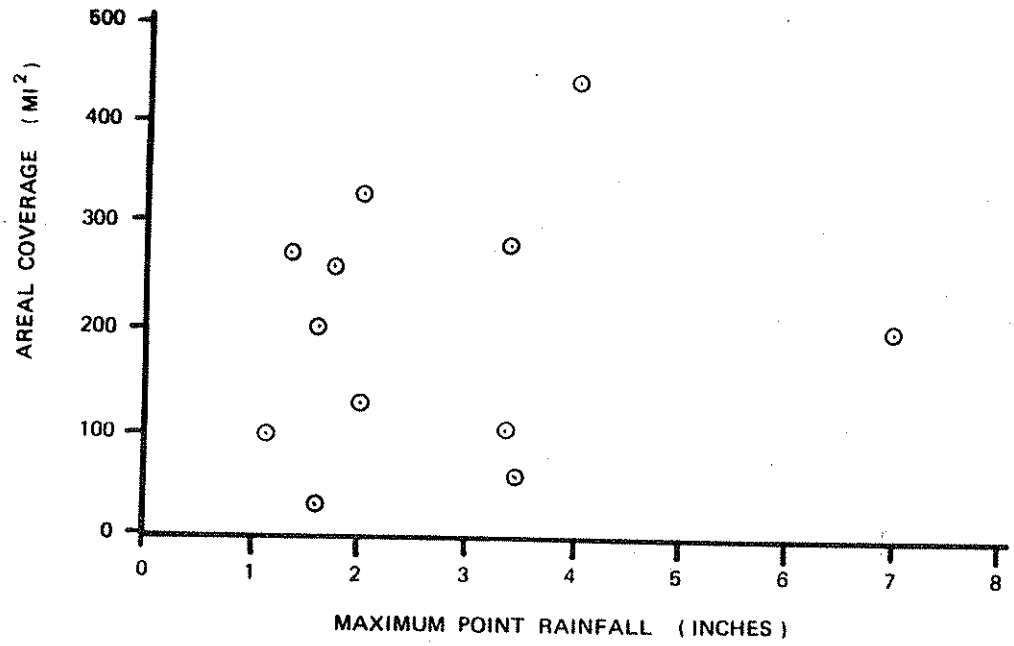



Figure 14. Variation of Areal Coverage with Maximum Point Rainfall for 2 Hour ID Pacific Northwest Thunderstorms

## 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.

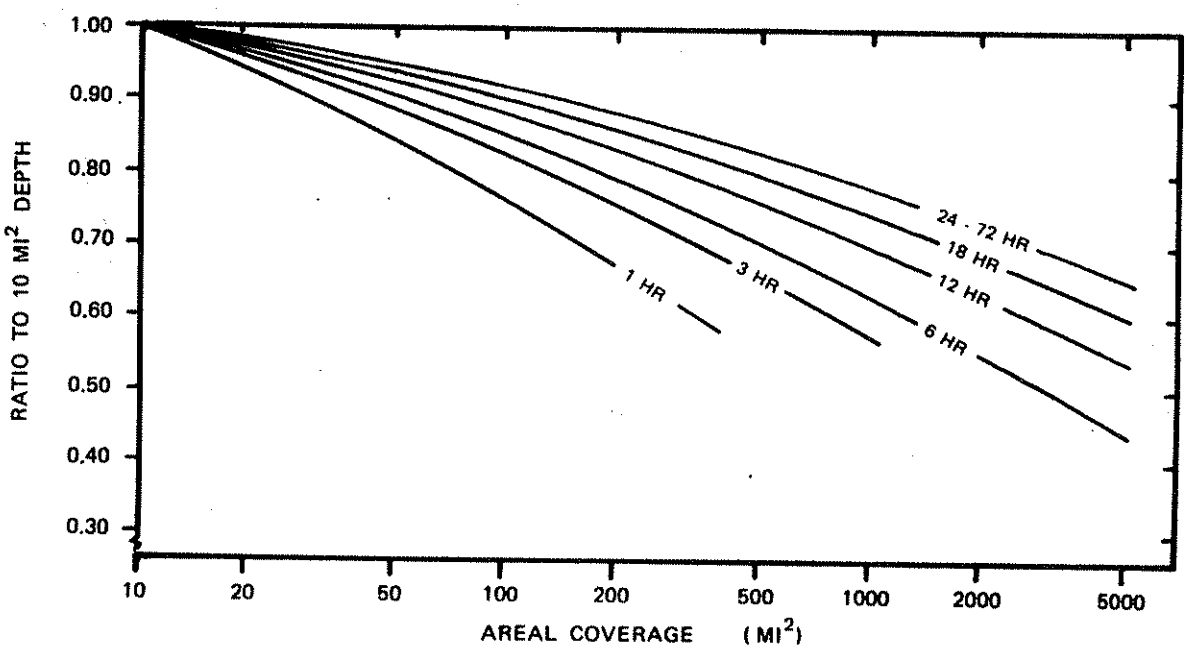



Figure 15. Depth-Area Curves for 6 Hour and 24 Hour ID Storms

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.

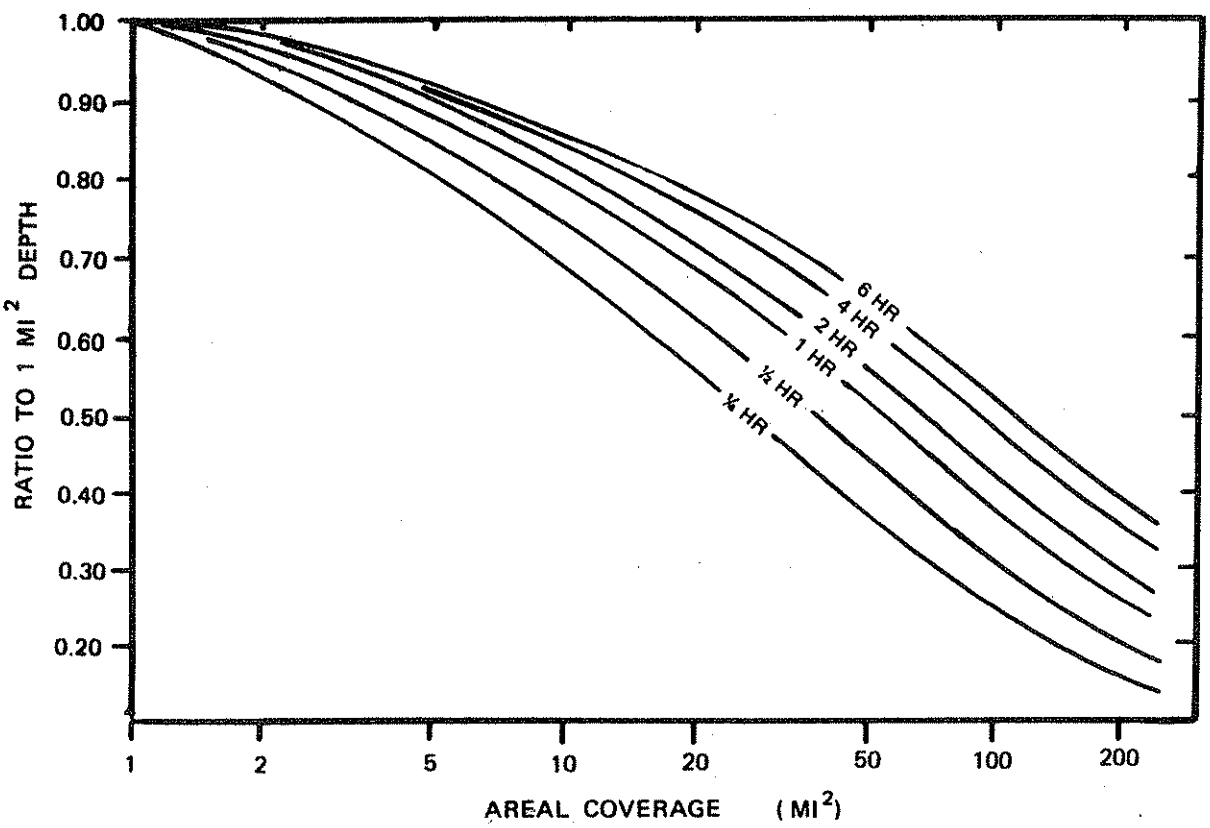



Figure 16. Depth-Area Curves for 2 Hour ID Storms

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

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

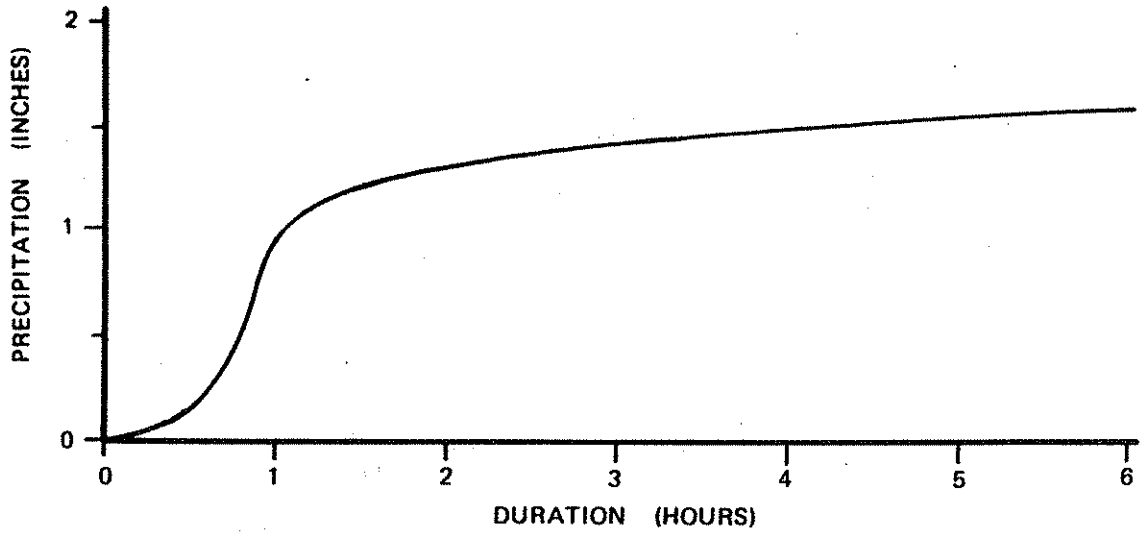



Figure 17. Synthetic Mass Hyetograph for 2 Hour ID Extreme Storm for a 1 Square Mile Watershed near Olympia, WA.

**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.

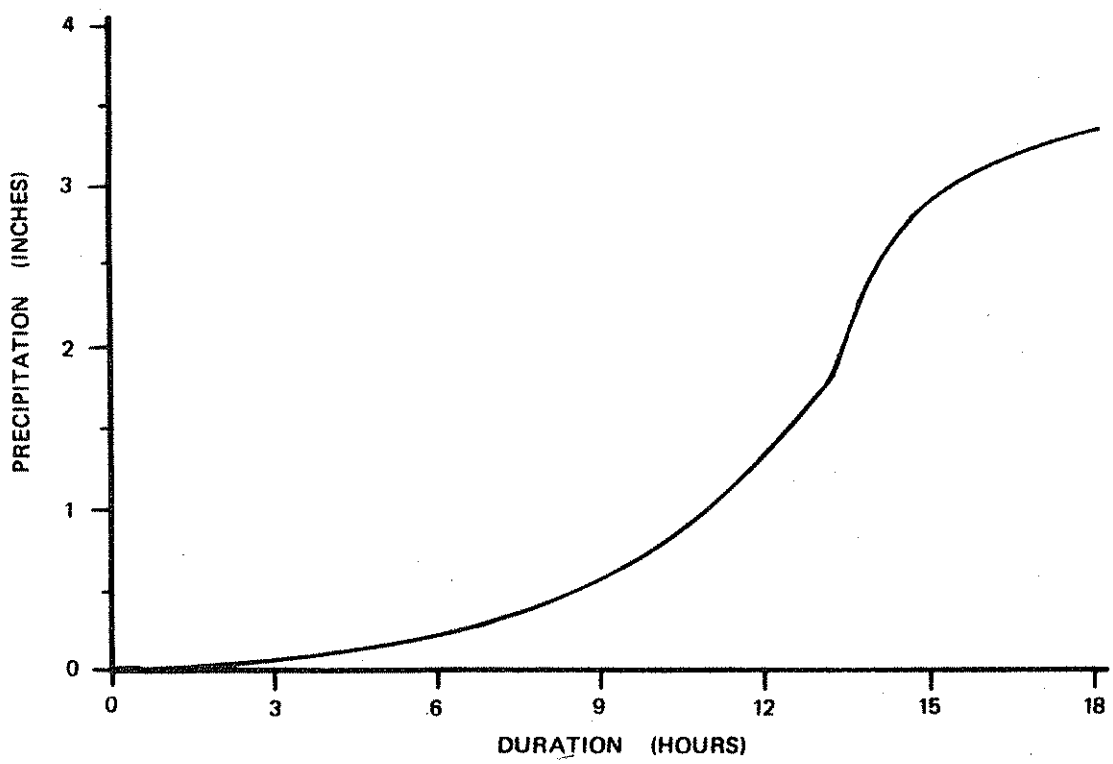



Figure 18. Synthetic Mass Hyetograph for 6 Hour ID Extreme Storm for 5 Square Mile Watershed near Olympia, WA.

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 | | | | TIME INCREMENT (hours) | INCREMENTAL PRECIPITATION AMOUNT (inches) | SEQUENCE NUMBER |
| | TABULAR | SCALED | AREAL REDUCTION | FINAL | | | |
| 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 |
| 3.00 | 0.664 | 1.59 | 1.00 | 1.59 | 1.00 | 0.35 | 1 macro 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 |
| 3.00 | 6 macro | 0.09 | 0.09 |
| 6.00 | 5 macro | 0.18 | 0.27 |
| 9.00 | 4 macro | 0.24 | 0.51 |
| 12.00 | 2 macro | 0.81 | 1.32 |
| 13.00 | 3 hi | 0.35 | 1.67 |
| 13.25 | within 1 hi | 0.15 | 1.82 |
| 13.50 | within 1 hi | 0.33 | 2.15 |
| 14.00 | within 1 hi | 0.27 | 2.42 |
| 15.00 | 2 hi | 0.49 | 2.91 |
| 18.00 | 3 macro | 0.41 | 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.

Step 1a:

The 24 hour average precipitation depth for the watershed was determined to be 5.40 inches.

Step 2:

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.

Step 3:

Select the 5% exceedance probability value (51.3 hours) from Table 10 for the time of occurrence for the high intensity segment.

Step 4:

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 | | | | TIME INCREMENT (hours) | INCREMENTAL PRECIPITATION AMOUNT (inches) | SEQUENCE NUMBER |
| | TABULAR | SCALED | AREAL REDUCTION | FINAL | | | |
| 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 | | | |
| | | | | | 3.00 | 0.94 | 1..6 hr |
| 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 | | | |
| | | | | | 6.00 | 0.75 | 3..6 hr |
| 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 |
| | | 0.74 | |
| 57.0 | 2....6 hr | | 4.93 |
| | | 0.64 | |
| 60.0 | | | 5.57 |
| | 3 macro | 0.27 | |
| 72.0 | | | 5.84 |

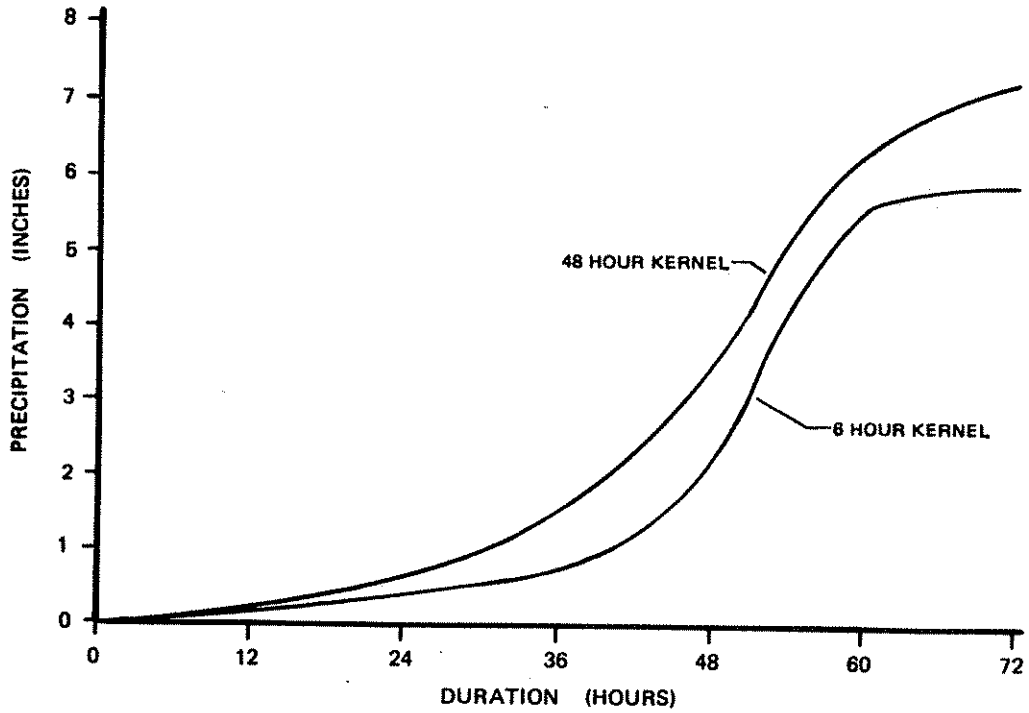



Figure 19. Synthetic Mass Hyetographs for 24 Hour ID Extreme Storms for 100 Square Mile Watershed near Olympia, WA.

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

The author is deeply appreciative of the support provided by the Department of Ecology and in particular by M. Edward Garling while this study was being conducted. Data collection and compilation by Mr. Joe Cason was instrumental to the completion of this study and his efforts are appreciated.

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

# R E F E R E N C E S


Benjamin,J.R. and Cornell,C.A., Probability, Statistics and Decision for Civil Engineers, pp287-292, McGraw-Hill, 1970

Box,G.E. and Jenkins,G.M., Time Series Analysis: Forecasting and Control, pp46-82, Holden-Day, 1976

Chow,V.T., Handbook of Applied Hydrology, pp9.1-9.68, McGraw-Hill, 1964

Istok,J.D. and Boersma,L., A Stochastic Cluster Model for Hourly Precipitation Data, pp257-285, Journal of Hydrology,106, 1989

Fisher,R.A. and Tippett,L.H.C., Limiting Forms of the Frequency Distribution of the Largest or Smallest Member of a Sample, Proceedings Cambridge Phil. Society, 24, 180-190, 1928.

Frederick,R.H., Miller,J.F., Richards,F.P. and Schwerdt, R.W., Interduration Precipitation Relations for Storms - Western United States, Technical Report NWS 27, NOAA, Washington,D.C., 1981

Melone,A.M., Regional Analysis of the Time Distribution of Rainfall, Canadian Society of Civil Engineering, Annual Conference, Saskatoon, SK., May 27-31, 1985.

Miller,J.F., Frederick,R.H. and Tracey,R.S., NOAA ATLAS 2, Precipitation - Frequency Atlas of the Western United States, Volume IX - Washington, U.S. Dept. of Commerce, NOAA, National Weather Service, Washington,D.C., 1973.

NCDC, National Climatic Data Center, Climatological Data-Washington, Monthly Periodical, 1900-present, NOAA, Asheville,NC.

NCDC, National Climatic Data Center, Hourly Precipitation Data Washington, Monthly Periodical, 1951-present, NOAA, Asheville, NC.

NWS, National Weather Service, Hydrometeorological Report 43, Probable Maximum Precipitation for the Pacific Northwest, U.S. Department of Commerce, NOAA, U.S. Weather Bureau, Washington,D.C., 1966

NWS, National Weather Service, Hydrometeorological Report 49, Probable Maximum Precipitation Estimates Colorado River and Great Basin Drainages, U.S. Department of Commerce, NOAA, U.S. Weather Bureau, Washington,D.C., 1966

NWS, National Weather Service, Hydrometeorological Report 55, Probable Maximum Precipitation Estimates-United States Between the Continental Divide and the 103rd Meridian, U.S. Department of Commerce, NOAA, U.S. Weather Bureau, Washington,D.C., 1984.

Phillips,E.J., Washington Climate, Multiple Volumes by County, Washington State University Extension Service, Pullman,WA.

Schaefer,M.G., Regional Analyses of Precipitation Annual Maxima in Washington State, Water Resources Research, Vol.26, No.1, pp119-132, January,1990.

USGS, United States Geological Survey, Water Resources Data-Washington, Annual Periodical, 1961-present, Pacific Northwest District, Tacoma,WA.

USGS, United States Geological Survey, Miscellaneous Streamflow Measurements - in the State of Washington 1890 - January 1961, Water Supply Bulletin No. 23, Pacific Northwest District, Tacoma,WA.

Valencia,D.R. and Schaake,J.C. Jr., Disaggregation Processes in Stochastic Hydrology, Water Resources Research, Vol.9, No.3, pp580-584, June,1973.

Weiss,L.L., Ratio of True to Fixed Interval Maximum Rainfall, Journal of the Hydraulics Division, Proceedings ASCE, Vol. 90, HY-1, pp77-82, January,1964.

Woolhiser,D.A., and Osborn,H.B., A Stochastic Model of Dimensionless Thunderstorm Rainfall, Water Resources Research, Vol. 21, No.4, pp511-522, April,1985.

WMO, World Meteorological Organization, Manual for Depth-Area-Duration Analysis of Storm Precipitation, WMO #237, Geneva,Switzerland, 1969.

# 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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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

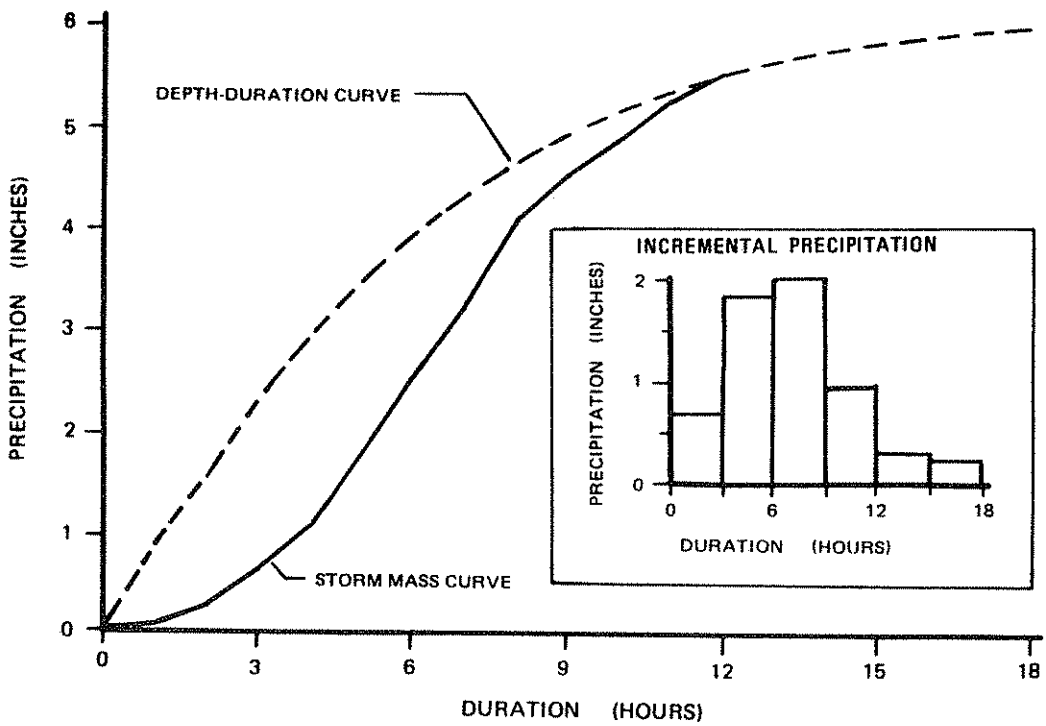



Figure 20. Comparison of Depth-Duration and Observed Mass Curves for Extreme Storm of October 14, 1945 at Snoqualmie Pass, WA.

# A P P E N D I X 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 | | |
| 0.17 | | | | | 0.08 | | within |
| 0.25 | | | | | 0.08 | | 1 hi |
| 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 | | | | TIME INCREMENT (hours) | INCREMENTAL PRECIPITATION AMOUNT (inches) | SEQUENCE NUMBER |
|---|---|---|---|---|---|---|---|
| | TABULAR | SCALED | AREAL REDUCTION | FINAL | | | |
| 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<br>1 macro |
| 3.00 | | | | | 1.00 | | 3 hi |
| 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<br>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.

# DETERMINING DESIGN/PERFORMANCE GOALS FOR SPILLWAY ADEQUACY: THE WASHINGTON STATE APPROACH

by Douglas L. Johnson, P.E.[a]

## A. Introduction

This paper summarizes the conclusions from many years of work by the Washington State Dam Safety Section towards developing a risk-based approach to spillway adequacy. Historically, spillway design for dams with population at risk has been based on deterministic methods (i.e. Probable Maximum Precipitation). This level of protection is widely recognized as appropriate for the design of large dams located above densely populated areas. However, the vast majority of dams regulated by state dam safety programs are small to intermediate in size, where the downstream hazard setting typically includes fewer than 10 homes. These types of projects and downstream hazard settings typically represent situations where the extreme storm used in flood analysis can often be justified as being something less than PMP. However, the key question arises - *What is an acceptable level of safety for these projects?* Our studies in extreme storms and risk-based methods attempt to answer this question.

The key elements to the Washington State approach to spillway design are contained in Technical Note 2: *Selection of Design/Performance Goals for Critical Project Elements*[1], along with its companion paper, Technical Note 3: *Design Storm Construction*[2]. Technical Note 2 is an application of the probability-based extreme storm studies developed by Dr. Mel Schaefer in *Regional Analysis of Precipitation Annual Maxima in Washington State*[3], and applied in Technical Note 3. Technical Note 2 takes a probabilistic approach to design levels for dams vs. a deterministic approach (i.e. PMP). However, the design levels discussed in Technical Note 2 were not intended to replace PMP, but to compliment it. PMP which is a "maximum" event, is still used as an upper limit for large dams with a large population at risk downstream. For smaller dams with less population at risk, however, a probabilistic or "risk-based" approach was developed.

## B. Balanced Protection Concept

Historically, the various engineering disciplines involved in dam design/safety evaluation used different methodologies that have resulted in various elements of the project being designed to different standards, resulting in widely dissimilar levels of protection from failure. For example, a spillway may be designed for PMP/PMF, while the outlet conduit is designed using methods common for roadway drainage structures. The *Balanced Protection Concept* sets a common design/performance goal for the design or evaluation of each critical project element to assist in providing reasonably consistent levels of protection. A design/performance goal is simply a goal for the performance of critical project elements (e.g. spillway, embankment stability), which may be used in design or evaluation. It is expressed as an Annual Exceedance Probability (AEP) and is a measure of the chance of adverse behavior, or failure of a critical project element. Technical Note 2 presents a methodology for determining a common design/performance goal for a given level of protection of any critical element of a project, including spillways.

## C. Consequence Dependent Design Levels

It is standard practice in civil engineering that the degree of conservativism in design should correspond with the consequences of failure of a given element. If failure of the element poses no public safety concern, the design level is usually based on economic considerations. However, if failure of a given element could pose threat to loss of life, design levels are typically much more conservative to protect from consequences of failure. Also, as the magnitude of loss of life and

---

[a] Dam Inspection Specialist, Dam Safety Section, Washington Department of Ecology

property damage resulting from a failure increases, design levels become more stringent. This concept is called *Consequence Dependent Design Levels*.

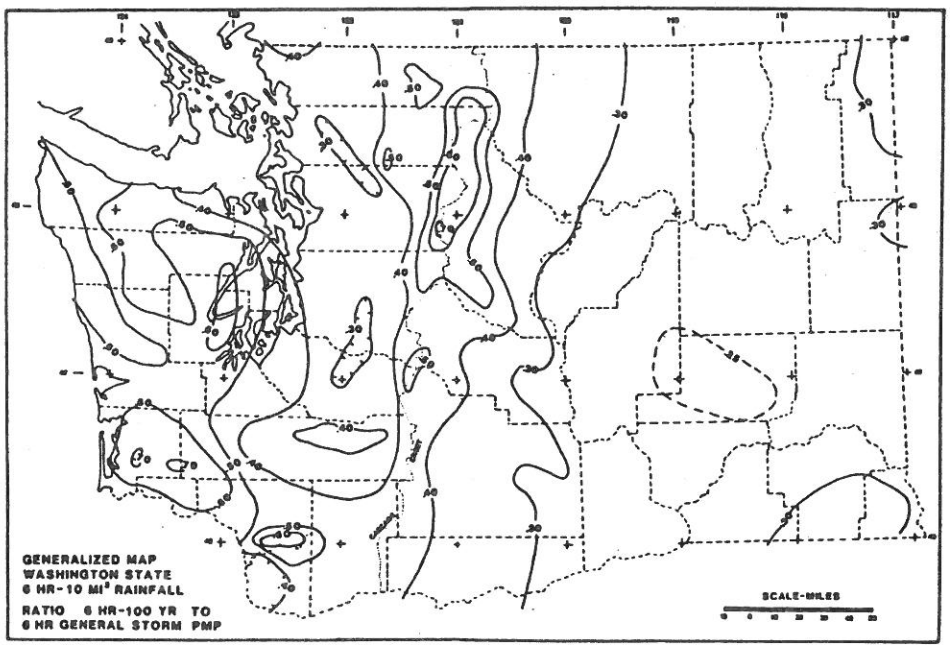
## D. Selection of Probabilistic Approach

In the past, the standard design storm in the dam safety community for the design of intermediate and large high hazard projects (3 or more homes) has been the Probable Maximum Precipitation (PMP). PMP is theoretically *the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of year*[4,5]. In the engineering community, it is commonly assumed that PMP provides a consistent level of protection and a "zero risk" design level. However, it is not possible to compute theoretical PMP directly, and numerous procedures and judgements must be used to estimate PMP. Thus, in reality, computed PMP approaches, rather than meets, the theoretical upper limit. This implies that real world precipitation can exceed computed PMP estimates, and use of these values does not carry zero risk.

Further studies by Dr. Schaefer showed that in Washington (as well as across the U.S.), the annual exceedance probability for PMP can vary widely across the state. On the Coast, where the moisture source is near at hand and the rainfall processes are very efficient, PMP (based on HMR-43) has an exceedance probability of about $10^{-5}$. In the Puget Sound Area, PMP has an exceedance probability of $10^{-6}$, while in Eastern Washington, where the sources of moisture are remote, PMP's exceedance probability approaches $10^{-9}$ for some locations. Thus using PMP as a design event can provide widely different levels of protection, depending on location within the State.

The situation is further complicated when we look at smaller dams where only a few lives may be at risk. The standards used by many regulatory organizations dictated that ratios of the PMP be used for the design of these facilities, with 50% PMP commonly used as the lower bound when any lives are at risk. However, when we use ratios of the PMP, we know nothing of the level of protection afforded. This is illustrated in Figure 1, which shows that a 100-year event is about 50% to 70% of the 6 hour PMP in coastal areas, while in Eastern Washington, the 100-year precip is only 15% to 20% of PMP.

**FIGURE 1 - RATIO OF 6 HR 10 MI² PRECIPITATION TO 6 HR 10 MI² GENERAL STORM PMP (HMR-43) IN WASHINGTON**



Recognizing that the PMP (and % PMP) approach is not zero risk, provides different levels of protection, and de facto has an associated exceedance probability and risk, the Dam Safety Section elected to pursue a probabilistic or risk-based approach to spillway design. The PMP was not, however, completely eliminated from consideration. Rather, it was selected as an upper bound for design events, to be used for large dams where the consequences of failure are great. The probabilistic approach was employed for the many small and intermediate sized dams with few to no homes at risk. This approach is termed the Design Step Format and is described in the following section.

## E. Design Step Format

The concepts of Balanced Protection and Consequence Dependent Design are implemented through a Design Step Format. The Design Step Format utilizes 8 steps, where the design events become increasingly more stringent as the consequences of a dam failure become more severe. Figure 1 shows the 8-step format employed by the Dam Safety Section.

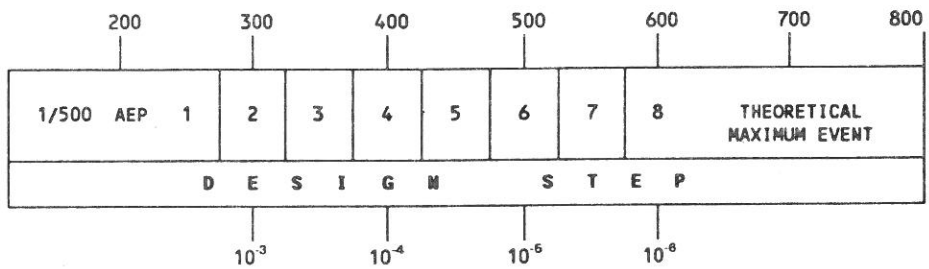



**FIGURE 2**

Design Step 1 would apply where consequences of a dam failure would be minimal and there would be no chance for loss of life. Step 1 has an annual exceedance probability (AEP) of 1 in 500, one chance in 500 of being exceeded in any given year. This design level is consistent with engineering design practice for dams in similar low hazard settings (National Research Council[6], ICE[7], ICOLD[8], BC Hydro[9]). Design Step 8 applies where a dam failure would be catastrophic with hundreds of lives at risk. In this situation, extreme design events and design loads are used to provide the extremely high levels of reliability needed to properly protect the public. For Design Step 8, the maximum design level is set at an AEP of $10^{-6}$ (1 chance in 1 million). Step 8 corresponds to theoretical maximum design events (PMP, MCE) and loading conditions. The use of a design/performance goal with an AEP of $10^{-6}$ is based on existing design standards (EPRI[10]) and review of recommendations for engineered structures with similar extremely serious consequences of failure (CSS[11], Kennedy[12], BC Hydro[9], Nuclear Regulatory Commission[13], Newton[14])

The design step format was completed by providing uniform performance increments between the design steps such that the AEP's for the design/performance goals decrease tenfold for every two design steps. Thus, this format strives to provide a reliability of design with a tenfold increase in protection for every 2 step increase.

## F. Benchmarks for Design Step Format

The next step in developing the design step format was the selection of benchmarks for setting design levels which would be consistent with levels of safety provided by other engineering disciplines and governmental regulation.

In many engineering applications, design levels are set by standards or codes which provide guidance or set design minimums. This obscures the actual levels of protection afforded by standards/codes. This result is not entirely unintentional, as governing bodies and standards boards are often hesitant to openly discuss acceptable levels of risk and probabilities of failure, where system failure could pose a threat to loss of life. This situation requires that design levels and probabilities of failure must be back-calculated for standards and codes. This back-calculation has been done for the establishment of design/performance goals in the design and evaluation of Department of Energy Facilities[12]. That information, as well as other sources provided background information for setting the benchmarks shown in Figure 3.

**FIGURE 3 - BENCHMARKS FOR CALIBRATING POINT RATING ALGORITHM FOR USE IN DECISION FRAMEWORK**

| BENCHMARK | CHARACTERISTICS OF IDEALIZED PROJECTS | MINIMUM DESIGN STEP | DESIGN/PERFORMANCE GOAL AEP |
|---|---|---|---|
| 1 | 1 or More Lives at Risk | 3 | $3 \times 10^{-4}$ |
| 2 | Large Dam, over 50 feet High<br>No Downstream Hazard | 3 | $3 \times 10^{-4}$ |
| 3 | Intermediate Dam<br>No Commercial Development<br>10 Residences at Risk | 4 | $10^{-4}$ |
| 4 | Large Dam<br>Limited Commercial Development<br>34 Residences at Risk | 6 | $10^{-5}$ |
| 5 | Large Dam<br>Significant Commercial Development<br>100 Residences at Risk | 8 | $10^{-6}$ |

Note: AEP - Annual Exceedance Probability

Additional guidance in setting design/performance goals was obtained by examining the levels of risk to which the public is exposed in ordinary life. Several of these risks are shown in Figure 4.

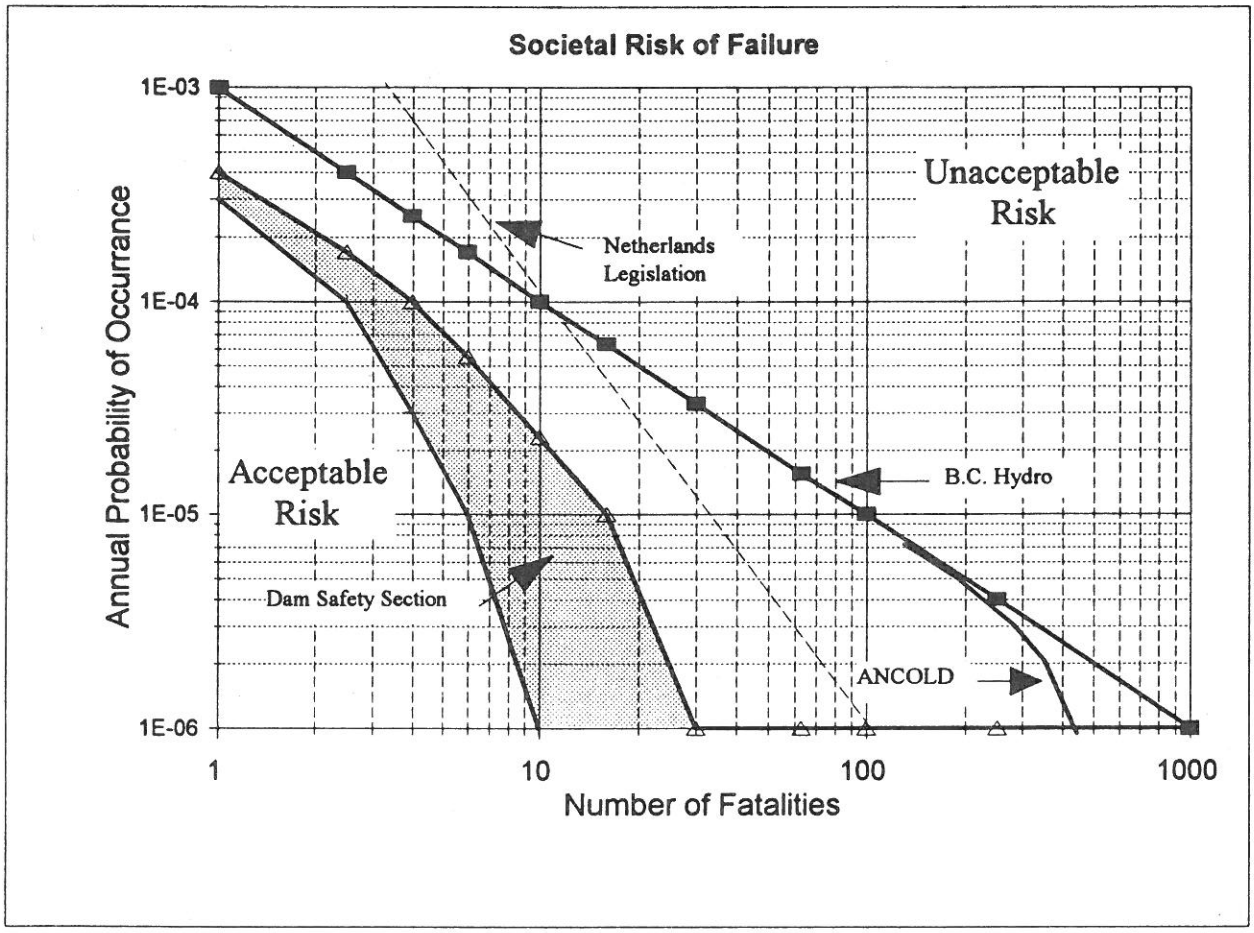
A review of the data in Figure 4 shows a basic trend. In those activities where few lives are at risk and the activity is voluntary in nature, nominal values of protection are accepted by the general public. Conversely, as the number of persons at risk and the level of hazard to the public from a certain activity increases, the level of protection expected by society and the engineering profession increases significantly. This viewpoint is called "risk averse" with regard to loss of life. This is illustrated in Figure 5, which shows the DSS criteria in comparison to other risk-based criteria, such as B.C. Hydro's, which is considered risk neutral.

## FIGURE 4 - LISTING OF RISKS FOR VARIOUS ACTIVITIES AND PERFORMANCE LEVELS FOR VARIOUS ENGINEERED SYSTEMS

| ACTIVITY/ITEM | TYPICAL NUMBER OF PERSONS AT RISK | RISK LEVEL | PERFORMANCE LEVEL |
|---|---|---|---|
| NATIONAL FLOOD INSURANCE PROGRAM<br>• Risk from Natural Flooding | Varies Widely | | 1/100 AEP<br>100 Year Flood |
| FATAL DISEASE[15]<br>• All Causes | 1 | 1/120 AC | |
| ASCE STRUCTURAL CODE[16]<br>• Performance of Individual Structural Members for Ordinary Buildings Subject to Natural Hazards due to Wind and Earthquake Loads | Typically 1-20 | | 1/1000 AEP |
| EXISTING OFFSHORE DRILLING PLATFORMS[17]<br>• Performance Subject to Wind, Wave and Earthquake Loads | Varies 0 - 25 | | 1/1000 AEP |
| ACCIDENTAL DEATH[18]<br>• All Causes | Few<br>1-3 | 1/2000 AC | |
| ACCIDENTAL DEATH[18]<br>• Motor Vehicles | 1-6 | 1/3000 AC | |
| ACCIDENTAL DEATH[18]<br>• Non-Motor Vehicles | Few<br>1-3 | 1/6000 AC | |
| UNIFORM BUILDING CODE[12,19]<br>• Performance of Essential Buildings such as Hospitals and Emergency Response Facilities to Maintain Building Functionality and Protect Occupants for Buildings Subjected to Wind and Earthquake Loads | Typically 50-200 | | 1/5,000 AEP |
| BRITISH SPILLWAY DESIGN[7] | Small Community<br>More than 30 | | 1/10,000 AEP<br>10,000 Year Flood |
| DEPT. OF ENERGY BUILDINGS[20,12]<br>• Performance of Building to Contain Radioactive or Toxic Materials and Protect Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads | Varies - Often Large Numbers of People at Risk | | 1/10,000 AEP |
| DEPT. OF ENERGY BUILDINGS[20,23]<br>• Very High Confidence of Containment of Radioactive and Toxic Materials and Protection to Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads | Varies - Often Large Numbers of People at Risk Both Onsite and Offsite | | 1/100,000 AEP |
| NUCLEAR POWERPLANTS[10]<br>• Damage to Core of Nuclear Powerplant from Earthquakes | Varies<br>Potentially Very Large Numbers of People | | 1/100,000 AEP |
| AIR TRANSPORTATION[15,18]<br>• Fatalities - All Aircraft | Varies<br>1-300 | 1/150,000 AC** | |
| AIR TRANSPORTATION[15,18]<br>• Fatalities - Commercial Airlines | Varies<br>50-350 | 1/700,000 AC** | |
| NUCLEAR POWERPLANTS[10]<br>• Performance Goal for Radioactive Releases Greater than 25 REM | Varies<br>Potentially Very Large Numbers of People at Risk | | 1/1,000,000 AEP |

Note: AC - Annual Chance of Occurrence AEP - Annual Exceedance Probability ** - Based on an "Average Traveller"

## FIGURE 5 - COMPARISON OF SOCIETAL RISK CRITERIA



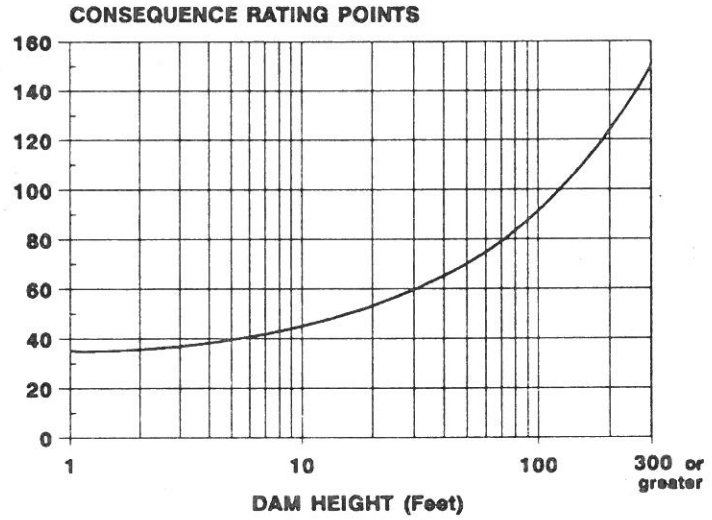

### G. Additive Point Rating Scheme for Determining Design/Performance Goals

An additive weighting scheme was developed to determine numerical ratings of the consequences of dam failure, which reflects the relative importance of each consequence, and the range of severity of the impacts posed by each consequence. Cumulative consequence rating points with values between 200 and 600 points were used to define the working range for the eight step format. Factors were selected within the 3 general categories shown in Figure 6, which described the nature of the consequences that could be quantified.

## FIGURE 6. NUMERICAL RATING FORMAT FOR ADDITIVE WEIGHTING SCHEME FOR ASSESSING CONSEQUENCES OF DAM FAILURE

| CONSEQUENCE CATEGORIES | CONSEQUENCE RATING POINTS | INDICATOR PARAMETER | CONSIDERATIONS |
|---|---|---|---|
| CAPITAL VALUE OF PROJECT | 0 - 150 | DAM HEIGHT | Capital Value of Dam |
| | 0 - 75 | PROJECT BENEFITS | Revenue Generation or Value of Reservoir Contents |
| POTENTIAL FOR LOSS OF LIFE | 0 - 75 | CATASTROPHIC INDEX | Ratio of Dam Breach Peak Discharge to 100 Year Flood |
| | 0 - 300 | POPULATION AT RISK | Population at Risk<br>Potential for Future Development |
| | 0 - 100 | ADEQUACY OF WARNING | Likely Adequacy of Warning in Event of Dam Failure |
| POTENTIAL FOR PROPERTY DAMAGE | 0 - 250 | ITEMS DAMAGED<br>OR<br>SERVICES DISRUPTED | Residential and Commercial Property<br>Roads, Bridges, Transportation Facilities<br>Lifeline Facilities Community Services<br>Environmental Degradation from Reservoir Contents (Tailings, Wastes, etc.) |

Utility Curves and consequence rating tables were developed for each of the indicator parameters in Figure 6 to implement the additive weighting scheme. A worksheet was then developed for compiling the rating points and selecting an appropriate design step. A typical utility curve is shown in Figure 7, and a rating table is shown in Figure 8.




## FIGURE 7. CONSEQUENCE RATING POINTS FOR DAM HEIGHT INDEX

## FIGURE 8. CONSEQUENCE RATING TABLE FOR LOSS OF PROJECT BENEFITS

| CONSEQUENCE SUB CATEGORY | CONSIDERATION | TYPICAL EXAMPLES | RATING POINTS |
|---|---|---|---|
| LIMITED RESOURCE LOSS WOULD AFFECT GENERAL PUBLIC | MANDATORY | PUBLIC WATER SUPPLY RESERVOIR | 25 - 75 |
| PRIVATE ENTERPRISE LOSS WOULD NOT AFFECT GENERAL PUBLIC | DISCRETIONARY | IRRIGATION OR INDUSTRIAL WATER SUPPLY | 10 - 75 |
| | | HYDROPOWER GENERATION | 10 - 75 |
| | | MINING OR MANUFACTURING | 10 - 75 |
| | | AESTHETICS, RECREATION OR WILDLIFE HABITAT | 10 - 25 |

## H. Selection of the Design Step

Cumulative rating points are used to select an appropriate design step using Figure 2. The design step and corresponding annual exceedance probability are then used to determine a design event/loading for a critical project element. Typical applications of the design step would include:

1. Computation of Inflow Design Floods
2. Assessing the Seismic Stability of Embankments
3. Design of Outlet Conduits
4. Reliability Levels for Critical Electrical and Mechanical Systems

There are several additional issues that need to be considered when applying decision framework to the selection of a design step.

1. **Modes of Failure for Various Critical Project Elements**
   Since procedures are applied for each critical element of project, it is possible to come up with different design steps for each element, due to different reservoir levels, dam break floods, etc. for different failure modes. However, a reasonable approach would be to use the design step for failure mode that would produce the worst consequences, and to use that step for the design of all critical project elements. This follows *the Balanced Protection* concept, and achieves reasonably similar design levels of conservatism and reliability. Under most circumstances, a dam failure by overtopping usually the worst case, and should be examined first in determining the design step.

2. **Projects with Multiple Dams**
   With multiple dam projects, dams are often of different size and have different consequences should they fail. It is reasonable and acceptable that design levels and loadings for each dam can be different. Thus the design loadings and protection afforded at the main dam could be greater than at a saddle dam.

3. **Dams in Series**
   When several dams are located in series on a stream, the failure of upper dam could cause failure of one or more lower dams. Consequently, the design step for any upstream dam which

can cause failure of downstream dam must be equal to or greater than the design step for the downstream dam.

4. **Engineering Judgement**
The Design Step Worksheet is an aid to decision making, and should not replace sound engineering judgement. Prudent reasoning may indicate that a higher or lower Design Step is appropriate.

5. **Design Step Minimum**
For small dams with only a few people at risk downstream, the numerical value of the rating points may not correspond to an adequate design step. Thus, **Design Step 3 is the minimum design step when <u>any</u> lives are at risk.**

## I. Relationship of Design Step to Downstream Hazard Classification

Oftentimes during the planning stage of a project there is a need to make a quick assessment of the value of the design step. This can be accomplished by utilizing the Downstream Hazard Classification for the project as a rough indicator for the design step. Experience has shown that the value of the design step typically falls within a small range for each of the Downstream Hazard Classes as shown in Figure 9.

**FIGURE 9. RELATIONSHIP OF DESIGN STEP TO DOWNSTREAM HAZARD CLASSIFICATION**

| DOWNSTREAM HAZARD POTENTIAL | DOWNSTREAM HAZARD CLASSIFICATION | POPULATION AT RISK | ECONOMIC LOSS GENERIC DESCRIPTIONS | ENVIRONMENTAL DAMAGES | TYPICAL DESIGN STEP |
|---|---|---|---|---|---|
| LOW | 3 | 0 | Minimal.<br>No inhabited structures.<br>Limited agriculture development. | No deleterious materials in reservoir | 1 - 2 |
| SIGNIFICANT | 2 | 1 to 6 | Appreciable.<br>1 or 2 inhabited structures.<br>Notable agriculture or work sites.<br>Secondary highway and/or rail lines. | Limited water quality degradation from reservoir contents and only short term consequences | 3 - 4 |
| HIGH | 1C | 7 to 30 | Major.<br>3 to 10 inhabited structures.<br>Low density suburban area with some industry and work sites.<br>Primary highways and rail lines. | Severe water quality degradation potential from reservoir contents and long term effects on aquatic and human life | 3 - 6 |
| HIGH | 1B | 31-300 | Extreme.<br>11 to 100 inhabited structures.<br>Medium density suburban or urban area with associated industry, property and transportation features. | | 4 - 8 |
| HIGH | 1A | More than 300 | Extreme.<br>More than 100 inhabited structures.<br>Highly developed, densely populated suburban or urban area with associated industry, property, transportation and community life line features. | | 8 |

## J. Summary

This paper summarized the approach used by the Washington State Dam Safety Section for the design/evaluation of spillways for dams. The concepts of *Consequence Dependent Design Levels* and *Balanced Protection* are the cornerstones of the decision framework discussed herein. The decision framework utilizes probabilistic methods rather than deterministic methods (such as PMP), for the selection of design/performance goals for spillways and other critical project elements. However, the design approach discussed is not intended to replace PMP but to augment it. PMP is still used as an upper limit for the design of large dams with large populations at risk. The probabilistic design step approach discussed herein attempts to provide a method for determining design/performance goals for smaller projects with less population at risk, where something less than PMP is justified. The design step approach represents an answer for the question - *What is an acceptable level of safety for these smaller projects?*

## REFERENCES


1. Schaefer, M.G., *Technical Note 2: Selection of Design/Performance Goals for Critical Project Elements*, Publication No. 92-55F, Water Resources Program, Department of Ecology, Olympia, WA, July 1992.

2. Schaefer, M.G., Dam Safety Guidelines, *Technical Note 3: Design Storm Construction*, Publication No. 92-55G, Water Resources Program, Department of Ecology, Olympia, WA, July 1992.

3. Schaefer, M.G., *Regional Analyses of Precipitation Annual Maxima in Washington State*, Water Resources Research, Vol.26, No.1, pp119-132, January, 1990.

4. Hansen, E.M., Schreiner, LC and Miller, JF, *Application of Probable Maximum Precipitation Estimates - United States East of 105th Meridian*, Hydrometeorological Report 52, US Dept. of Commerce, NOAA, US Weather Bureau, Washington DC, 1982.

5. World Meteorological Organization (WMO), *Manual for Estimation of Probable Maximum Precipitation*, Second Edition, Operational Hydrology Report No. 1, WMO 332, Geneva, Switzerland, 1986.

6. National Research Council, *Safety of Dams, Flood and Earthquake Criteria*, Committee on Safety Criteria for Dams, Water Science Technology Board, Commission on Engineering and Technical Systems, National Science Council, National Academy Press, Washington DC, 1985.

7. Institute of Civil Engineers (ICE), *Reservoir Flood Standards*, Institute of Hydrology, Wallingford, Great Britain, 1975.

8. Brouvard, M., Reporting for International Committee on Large Dams (ICOLD), *16th Congress of ICOLD - IV*, Water Power and Dam Construction, January, 1989.

9. BC Hydro, *Guidelines for Consequence Based Dam Safety Evaluations and Improvements*, BC Hydro, Vancouver, B.C., Draft February, 1993.

10. Electric Power Research Institute (EPRI), *Advanced Light Water Reactor Requirements Document, Appendix A, Probabilistic Risk Assessments Key Assumptions and Groundrules*, EPRI, June, 1989.

11. Council for Sciences and Society (CSS), *The acceptability of Risks*, Barry Rose Publishers Ltd, 1977, Great Britain, p 102.

12. Kennedy, et.al., *Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards*, United States Department of Energy, Office of the Assistant Secretary for Environment, Safety, and Health, Report UCRL-15910, June, 1990.

13. Nuclear Regulatory Commission (NRC), *Standard Review Plan, NUREG-0800*, Office of Nuclear Reactor Regulation, Section 2.2.3, Washington DC, 1975, 1981.

14. Newton, D.M., *Realistic Assessment of Maximum Flood Potentials*, ASCE Hydraulics Journal, Vol. 9, June 1983, pp 905-918.

15. Starr, C., *Social Benefit Versus Technological Risk, What is Our Society Willing to Pay for Safety*, Science, Vol 208, April 1980, pp 1232-1238.

16. ASCE, *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, ASCE 7-88, July, 1990.

17. Iwan, WD, et.al., *Seismic Safety Requalification of Offshore Platforms*, American Petroleum Institute, March 1992.

18. National Safety Council, *Accident Facts*, 1975, Chicago, Illinois.

19. International Conference of Building Officials, *Uniform Building Code, 1988 Edition*, Whittier, California, 1988.

20. Kennedy, R.P., et.al., *Progress Towards Developing Consistent Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Hazard Phenomena*, Proceedings DOE Natural Hazards Mitigation Conference, Las Vegas, Nevada, 1985.

# RISK IS NOT A FOUR LETTER WORD: TEN YEARS OF SUCCESS USING A RISK-BASED DAM SAFETY APPROACH IN WASHINGTON

*Doug Johnson*
*Washington State Dam Safety Supervisor*

## INTRODUCTION

This paper discusses the application of probability and risk concepts in the state of Washington's dam safety program. Our approach can be characterized as employing risk concepts in a standards-based framework, and using a risk-based prioritization scheme to correct dam safety deficiencies. Under this approach, probability methods, risk concepts, and elements of risk assessment are combined with decision making in setting performance standards that provide acceptable minimum levels of protection. This approach has been quite successful since its implementation in 1990. For similar downstream hazard settings, it has provided consistent levels of protection against flood induced overtopping failures across diverse climatic regions. It has been less successful in addressing the difficult, rapidly evolving seismic concerns confronting the Pacific Northwest. Furthermore, this approach has allowed us to make great progress in repairing the backlog of dams with identified safety deficiencies, as well as design new dams to more consistent standards across the State of Washington.

### Why Choose Probabilistic Over Deterministic Approach?

The use of risk-based approaches in the dam safety community is still highly controversial. There is much fear and trepidation among dam safety engineers when "risk" is mentioned in conjunction with dam safety. To many, the word risk implies that we would be designing to accept failure and loss of life, or more insidiously that risk assessment is a way of avoiding making expensive structural repairs to a dam. In addition, many think that using risk entails quantitative risk assessment, a highly complex and time-consuming analysis. Conversely, many dam safety professionals believe that using deterministic standards imply that a dam can pose zero risk to the public (as well as no liability risk to the engineer). Unfortunately, this viewpoint is based on misconceptions in the engineering community about the Probable Maximum Precipitation (PMP) and the Maximum Credible Earthquake (MCE). In reality, these values are estimates of the theoretical maxima that commonly approach, rather than meet, the theoretical upper limits. For example, studies have shown[1] that the annual exceedance probabilities (AEPs) of PMP events vary widely across the nation, from about $10^{-5}$ to perhaps $10^{-9}$. In the Pacific Northwest, PMP events have AEPs that vary from about $10^{-5}$ on the coast, to $10^{-6}$ in the Puget Sound region to $10^{-9}$ in some areas of Eastern Washington[1]. Thus, the use of these values may not only not provide zero risk, they likely do not provide consistent levels of protection across broad geographic areas.

The situation is further complicated when we look at smaller dams where only a few lives would be at risk. This situation represents the majority of dams regulated by Washington and, we believe, most other states (Figure 1). Regulatory organizations have long recognized that PMP and MCE loadings are too stringent for the design/analysis of these smaller projects. Consequently, some percentage of the theoretical maximum PMP is used for hydrologic assessment. An earthquake with a larger probability of exceedance is utilized in the seismic stability assessment. For example, 50% of the PMP is frequently used by many regulatory agencies as the lower bound for smaller dams

where only a few lives are at risk. However, when ratios of the PMP are taken, wildly differing levels of protection may result. For example, based on a regional analysis of some 10,000 station-years of precipitation data covering the Pacific Northwest, 50% of the PMP is only about a 100-year event in the marine climate on the Pacific Coast, while being closer to a 10,000-year event in parts of the arid eastern half of the state. Thus, by using ratios of PMP for design or repair of smaller, lower hazard dams, not only are we accepting that the dam is not zero risk, we often have no idea what the level of risk is!

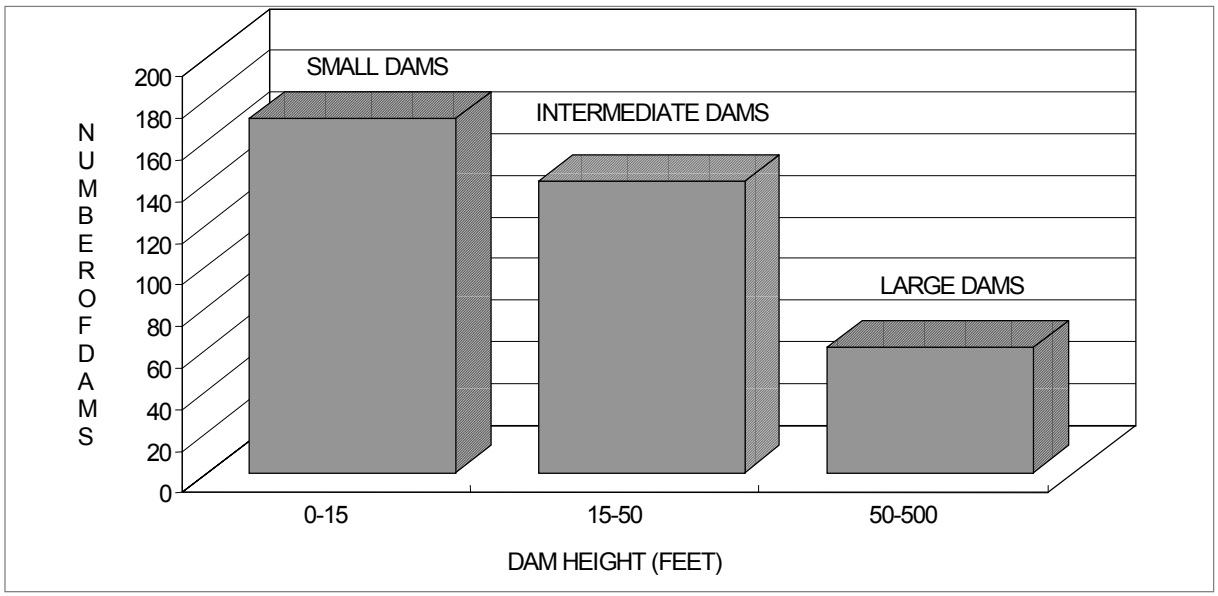



**Figure 1 – Dams Sited Above Populated Areas in Washington State**

## Selection of Risk Based Approach

Recognizing that the PMP/MCE (much less % PMP) approach is not zero risk and provides unbalanced protection across the state, the Dam Safety Office elected to employ a risk-based design approach. This approach was selected based on a number of considerations. The first consideration was the need to provide consistent minimum levels of protection across the state for similar downstream hazard settings. There was also a need to provide methods of analysis that were manageable with limited resources. The state is responsible for over 800 dams, and has limited staffing and resources to apply toward detailed risk assessment. Likewise, most of the regulated community has smaller dams with limited project budgets. Finally, we needed an approach that could be used for the design of new projects as well as for analysis of existing dams. Performing quantitative risk assessments for every project would not be feasible given these considerations. However, employing risk concepts and procedures in a standards-based framework allowed us to address these issues, while realizing the benefits of using a risk-based approach in a relatively simple and inexpensive manner.

We decided to utilize probability and risk concepts in two main areas. The first was to develop risk-based standards for dam design and evaluation of existing dams. These standards were applied through the design step format, which is detailed later in this paper. The second area where these concepts were applied was in the development of a risk-based ranking scheme to prioritize compliance and enforcement efforts on existing dams with identified safety deficiencies.

The combination of both areas was integral to the success of Washington's dam safety program and is detailed in the following sections.

## Design Philosophy

The philosophy of the Washington dam safety program utilizes several design principles that provide a framework for evaluating and establishing what design/performance levels are appropriate for the various elements of a dam project. The primary principles related to risk are *Balanced Protection* and *Consequence Dependent Design Levels.*

*Balanced Protection* - A dam is comprised of numerous critical elements, and like the old chain adage, "is only as strong as the weakest link". The goal of the *Balanced Protection* concept is to establish an appropriate common Annual Exceedance Probability (AEP) as the minimum design level for the evaluation of each critical project element. The term critical project element refers to an aspect of the structure, whose failure could precipitate an uncontrolled release of the reservoir. This office has only achieved partial success in this endeavor. As is noted below, the seismic design aspects lag behind the progress made in the hydrology arena.

*Consequence Dependent Design Levels* – Standard practice in the civil engineering community is that the degree of conservatism in design should correspond with the consequences of failure of a given element. If failure of a given element could pose a threat of loss of life, design levels are typically much more conservative. That conservatism increases with an increase in the potential magnitude of loss of life and property at risk. This concept is called *Consequence Dependent Design Levels*.

## Design Step Format

The philosophies of Balanced Protection and Consequence Dependent Design are implemented through the Design Step Format. This format utilizes eight steps, where the design events become increasingly more stringent as the consequences of failure become more severe. Design Step 1 has an annual exceedance probability of 1 in 500, and would apply where the consequences of dam failure are minimal and there would be no chance for loss of life. Design Step 8 applies to large dams where a dam failure would be catastrophic, with hundreds of lives at risk. In this situation, extreme design loads are used to provide the extremely high levels of reliability needed to properly protect the public. Thus, the AEP of Step 8 is set at 1 in 1,000,000, or the theoretical maximum events (PMP, MCE), whichever is smaller. The design Step 8 AEP of $10^{-6}$ is based on existing design standards (EPRI[2]) and a review of recommendations for engineered structures with extreme consequences of failure, such as nuclear power plants.

The design step format was completed by providing uniform performance increments between the design steps such that the AEP's decrease tenfold for every two design steps. Figure 2 shows the 8-step format employed by the Washington dam safety program.

**Figure 2. Design Step Format**

| Design Step | Exceedance Probability | Consequence Rating Points |
|---|---|---|
| 1 | 1 in 500 | < 275 |
| 2 | 1 in 1000 | 275 - 325 |
| 3 | 1 in 3000 (actually 3160) | 326 - 375 |
| 4 | 1 in 10,000 | 376 - 425 |
| 5 | 1 in 30,000 | 426 - 475 |
| 6 | 1 in 100,000 | 476 - 525 |
| 7 | 1 in 300,000 | 526 - 575 |
| 8 | 1 in 1,000,000 (or theoretical maximum) | > 575 |

## Benchmarks for Selecting Design Steps

A critical question when using risk-based design is "what is 'acceptable' (or tolerable) risk?" This is probably the most controversial aspect of using risk assessment in dam safety. This implies that above some threshold design event/performance level, loss of life would be tolerated. This is actually a common engineering precept used in bridge design, the UBC, and other engineering codes and standards. At the time we were developing our standards, there was very little guidance on tolerable risk criteria in the dam safety field. Thus, rather than try to come up with a definition of tolerable risk on our own, we decided to utilize design levels that would be consistent with the levels of safety provided by other engineering disciplines and governmental regulation. Because the actual levels of protection in many engineering applications are obscured by standards and codes (sometimes intentionally), the actual design levels and probabilities of failure had to be back calculated. This back calculation had been done for the establishment of performance goals in the design and evaluation of Department of Energy facilities[10]. That information, as well as other sources provided background information for setting the benchmarks shown in Figure 3.

**Figure 3 – Benchmarks for Calibrating Point rating Algorithm For Use in Decision Framework**

| BENCHMARK | CHARACTERISTICS OF IDEALIZED PROJECTS | MINIMUM DESIGN STEP | DESIGN/PERFORMANCE GOAL AEP |
|---|---|---|---|
| 1 | 1 or More Lives at Risk | 3 | $3 \times 10^{-4}$ |
| 2 | Large Dam, over 50 feet High<br>No Downstream Hazard | 3 | $3 \times 10^{-4}$ |
| 3 | Intermediate Dam<br>No Commercial Development<br>10 Residences at Risk | 4 | $10^{-4}$ |
| 4 | Large Dam<br>Limited Commercial Development<br>34 Residences at Risk | 6 | $10^{-5}$ |
| 5 | Large Dam<br>Significant Commercial Development<br>100 Residences at Risk | 8 | $10^{-6}$ |

Note: AEP - Annual Exceedance Probability

Additional guidance in setting design levels was obtained by examining the levels of risk to which the public is exposed to in ordinary life. Several of those risks are shown in Figure 4.

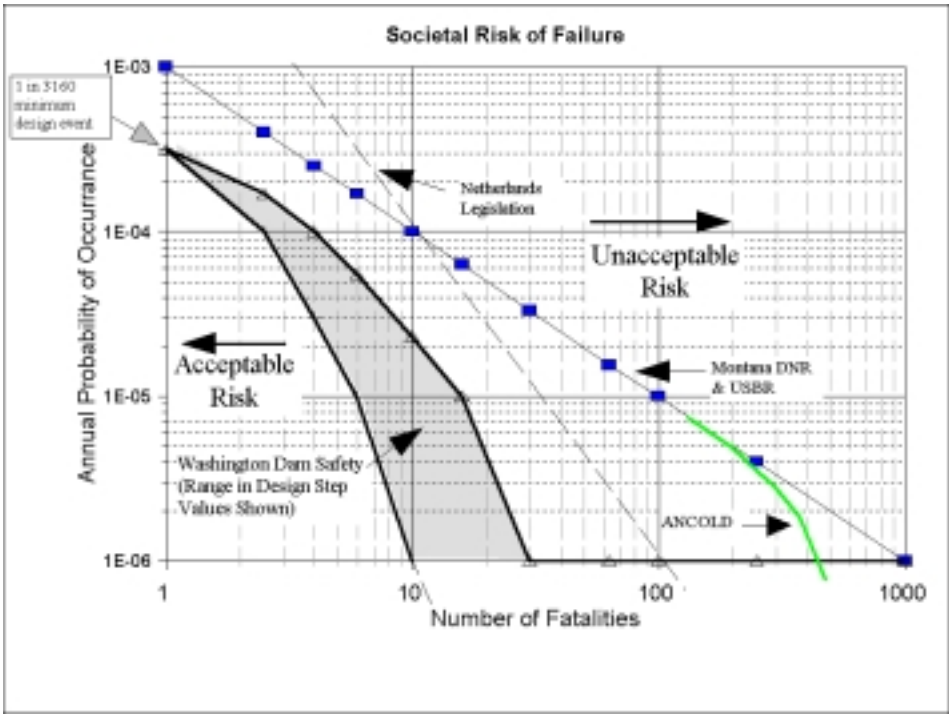
## Figure 4 – Listing of Risks and Performance Levels

| ACTIVITY/ITEM | TYPICAL NUMBER OF PERSONS AT RISK | RISK LEVEL | PERFORMANCE LEVEL |
|---|---|---|---|
| NATIONAL FLOOD INSURANCE PROGRAM<br>• Risk from Natural Flooding | Varies Widely | | 1/100 AEP<br>100 Year Flood |
| FATAL DISEASE[3]<br>• All Causes | 1 | 1/120 AC | |
| ASCE STRUCTURAL CODE[4]<br>• Performance of Individual Structural Members for Ordinary Buildings Subject to Natural Hazards due to Wind and Earthquake Loads | Typically 1-20 | | 1/1000 AEP |
| EXISTING OFFSHORE DRILLING PLATFORMS[5]<br>• Performance Subject to Wind, Wave and Earthquake Loads | Varies 0 – 25 | | 1/1000 AEP |
| ACCIDENTAL DEATH[6]<br>• All Causes | Few<br>1-3 | 1/2000 AC | |
| ACCIDENTAL DEATH[4]<br>• Motor Vehicles | 1-6 | 1/3000 AC | |
| ACCIDENTAL DEATH[4]<br>• Non-Motor Vehicles | Few<br>1-3 | 1/6000 AC | |
| UNIFORM BUILDING CODE[7]<br>• Performance of Essential Buildings such as Hospitals and Emergency Response Facilities to Maintain Building Functionality and Protect Occupants for Buildings Subjected to Wind and Earthquake Loads | Typically 50-200 | | 1/5,000 AEP |
| BRITISH SPILLWAY DESIGN[8] | Small Community<br>More than 30 | | 1/10,000 AEP<br>10,000 Year Flood |
| DEPT. OF ENERGY BUILDINGS[9]<br>• Performance of Building to Contain Radioactive or Toxic Materials and Protect Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads | Varies - Often Large Numbers of People at Risk | | 1/10,000 AEP |
| DEPT. OF ENERGY BUILDINGS[7]<br>• Very High Confidence of Containment of Radioactive and Toxic Materials and Protection to Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads | Varies - Often Large Numbers of People at Risk Both Onsite and Offsite | | 1/100,000 AEP |
| NUCLEAR POWERPLANTS[10]<br>• Damage to Core of Nuclear Powerplant from Earthquakes | Varies<br>Potentially Very Large Numbers of People | | 1/100,000 AEP |
| AIR TRANSPORTATION[4]<br>• Fatalities - All Aircraft | Varies<br>1-300 | 1/150,000<br>AC** | |
| AIR TRANSPORTATION[4]<br>• Fatalities - Commercial Airlines | Varies<br>50-350 | 1/700,000<br>AC** | |
| NUCLEAR POWERPLANTS[8]<br>• Performance Goal for Radioactive Releases Greater than 25 REM | Varies<br>Potentially Very Large Numbers of People at Risk | | 1/1,000,000 AEP |

Note: AC - Annual Chance of Occurrence AEP - Annual Exceedance Probability ** - Based on an "Average Traveler"

A review of both these tables shows a basic trend. In those activities where few lives are at risk, the public accepts nominal values of protection. Conversely, as the number of persons at risk and the consequences of a failure increase, the level of protection expected by society and the engineering profession increases significantly. This viewpoint is termed “risk-averse” with regard to loss of life. This is illustrated in Figure 6, which shows DSO criteria compared to other risk criteria such as Montana and the USBR[11], which are risk neutral (i.e., a constant value of risk of 1 in 1000 loss of life/year).

**Figure 5 – Comparison of Societal Risk Criteria**




## Additive Point Rating Scheme

The next step in developing the risk-based standards was the development of an additive weighting scheme to determine numerical ratings of the consequences of dam failure. This scheme reflects the relative importance and range of severity of the impacts posed by each consequence. Cumulative rating points with values between 200 and 800 points were used to define the working range for the eight-step format. Factors were selected within the 3 general categories shown in Figure 6, which described the nature of the consequences of dam failure.

Utility curves or consequence rating tables were developed for each of the indicator parameters in Figure 6 to implement the additive weighting scheme. A worksheet (Appendix B, Ref 14) was then developed for compiling the rating points and selecting an appropriate design step. The point rating scheme was calibrated using a wide cross-section of project types and downstream settings to yield results (design steps) consistent with the 5 benchmarks shown in Figure 3.

**Figure 6 – Numerical Rating Format for Assessing Consequences of Dam Failure**

| CONSEQUENCE CATEGORIES | CONSEQUENCE RATING POINTS | INDICATOR PARAMETER | CONSIDERATIONS |
|---|---|---|---|
| CAPITAL VALUE OF PROJECT | 0 - 150 | DAM HEIGHT | Capital Value of Dam |
| | 0 - 75 | PROJECT BENEFITS | Revenue Generation or Value of Reservoir Contents |
| POTENTIAL FOR LOSS OF LIFE | 0 - 75 | CATASTROPHIC INDEX | Ratio of Dam Breach Peak Discharge to 100 Year Flood |
| | 0 - 300 | POPULATION AT RISK | Population at Risk Potential for Future Development |
| | 0 - 100 | ADEQUACY OF WARNING | Likely Adequacy of Warning in Event of Dam Failure |
| POTENTIAL FOR PROPERTY DAMAGE | 0 - 250 | ITEMS DAMAGED OR SERVICES DISRUPTED | Residential and Commercial Property<br>Roads, Bridges, Transportation Facilities<br>Lifeline Facilities Community Services<br>Environmental Degradation from Reservoir Contents (Tailings, Wastes.) |

## Probabilistic Design Data

Before we could implement the risk-based standards described above, magnitude-frequency relationships were needed for extreme events such as floods and earthquakes. Unfortunately, this type of information is not readily available to most states, and much work is still needed around the United States to develop probabilistic precipitation and seismic data for extreme events. In Washington State, we benefited from Dr. Mel Schaefer's detailed studies of extreme storms in the Northwest[12,13], and his development of probabilistic based procedures[14] for generating precipitation magnitude-frequency relationships for any location in the state. Thus, Washington State has the necessary hydrologic data to employ them in a logical and consistent manner in our risk based design/performance practice. This data is used in determining a design storm event with an appropriate AEP to match the design/performance step for the dam in question. This storm is then used to compute the inflow design flood to size the spillway(s) for a new project, or to determine the adequacy of the spillway for an existing dam.

In the seismic arena, we are encountering difficulties on design Step 1 and above in Western Washington and Step 3 and above in Eastern Washington in dealing with the population of existing dams. Our difficulties stem from the severity of the earthquake loadings projected for the Pacific Northwest. Seven interface earthquakes of Moment Magnitude ($M_w$) 8 or larger are believed to have struck the coast in the last 3500 years[15]. The last event in 1700 was estimated from Japanese tidal records to have been a $M_w$ 9. Thus, all projects in the western half of the state must consider a seismogenic source capable of generating minutes of strong ground motion at a mean recurrence interval of 500 years. With the exception of California, Oregon and Alaska, few other states have to deal with such intense ground motion on so short a mean recurrence interval. In addition, the intensity and duration of shaking yields a high probability of liquefaction. Thus, a significant fraction of the analyses must predict the post-liquefied, deformation response of soils. This is an area of active research in the geotechnical profession. While data is being generated at considerable expense on high profile projects, little guidance is available for extrapolating to the small dams that comprise the majority of the projects under our purview.

Here, any rigorous assessment scheme would face the same difficulties confronting us. In much of the rest of the country the appreciably less intense seismic setting would minimize the difficulties of implementing our design step scheme.

## Design Standards for Other Critical Elements

For critical elements at new dam projects where a design loading is not readily applicable (e.g. conduits, seepage), a qualitative approach is used, where redundancy and survivability concepts are employed to achieve adequate reliability against failure. For these critical elements on existing dams, a qualitative approach is used, rather than a quantitative assessment. This is achieved through review of the design and identification of deficiencies for the critical element, coupled with a qualitative assessment of the likelihood of failure based on past experience and engineering judgement. However, we are considering the utilization of some of the more formal risk assessment procedures for these elements currently employed by the Bureau of Reclamation.

## Risk Prioritization Scheme

At the close of the 1980's, the Dam Safety Office had over 60 dams listed as having safety deficiencies. Many of these dams were projects inspected under the National Dam Safety Program from 1977-81, and had no action toward making repairs in 10 years. With such a large number of unsafe dams, and limited staffing, it became clear to the DSO that some way of prioritizing these projects was in order. Thus, in conjunction with the development of the risk-based standards described previously, in 1990 the DSO developed a prioritization ranking scheme for dams with safety deficiencies.

The scoring and ranking algorithm developed by the DSO is simple in concept and application, but was been found to be more than adequate for producing an initial ranking of projects. The algorithm is contained within our Microsoft Access database, and a report showing the ranking of projects can be generated by the touch of a key. This ranking is then used as a starting point where other project specific intangibles can be considered by management. The number of projects targeted for enforcement action at any time are chosen to maximize compliance, while not jeopardizing other critical functions of the dam safety program. Typically, this represents an active enforcement workload of about 10 projects.

The underlying logic in the development of this algorithm is fairly simple, and includes the following key ideas:

- For dams with similar deficiencies, those dams with the greatest consequences should be given higher priority.
- For dams with similar consequences, those dams with the more serious deficiencies should be given higher priority.
- For dams with similar deficiencies and similar consequences, those dams with a poorer chance for warning to the public should be given higher priority.
- Dams with only minor deficiencies should be ranked lower than dams with significant deficiencies, regardless of the consequences.
- The risk associated with three minor deficiencies is ranked just below that of one moderate deficiency.
- The risk associated with two moderate deficiencies is ranked just below that of one major deficiency.

- All things being equal, older dams should be given a higher priority.

These concepts were then incorporated into developing the equations for computing the number of priority points. Two different equations were developed for computing the priority points. The first equation is for dams where one or more of the safety deficiencies are rated moderate major or emergency. The second equation is for a project where all deficiencies are rated minor. These equations are shown in Figure 7. Rating points were then developed for the consequences, adequacy of warning, and seriousness of deficiencies, as shown if Figure 8. The points were selected and calibrated to meet the underlying logic goals discussed previously.

**Figure 7: Equations for Prioritization Ranking**

| | |
|---|---|
| One or More Safety Deficiencies Rated Moderate, Major or Emergency | **Priority = [*Hazard Class*] + [*Warning*] + [ ∑(*Seriousness of Deficiencies*)] + [*Age*/2]** |
| All Safety Deficiencies Rated Minor | **Priority = 0.5 ∗[ [*Hazard Class*] + [*Warning*] + [ ∑(*Seriousness of Deficiencies*)] + [*Age*/2] ]** |

**Figure 8: Rating Points for Prioritization**

| **RATING POINTS FOR CONSEQUENCES – BY HAZARD CLASS** | |
|---|---|
| *High Hazard* | |
| Hazard Classification 1A - (100+ homes at risk) | 500 points |
| Hazard Classification 1B – (11-99 homes at risk) | 400 points |
| Hazard Classification 1C – (3-10 homes at risk) | 300 points |
| *Significant Hazard* | |
| Hazard Classification 2 – (1 or 2 homes at risk) | 200 points |
| *Low Hazard* | |
| Hazard Classification 3 – (0 homes at risk) | 100 points |
| **RATING POINTS FOR ADEQUACY OF WARNING** | |
| Inadequate Warning – (< 10 minutes advanced warning) | 100 points |
| Marginal Warning – ( between 10 and 30 minutes) | 50 points |
| Adequate Warning – (greater than 30 minutes) | 0 points |
| **RATING POINTS FOR SERIOUSNESS OF EACH DEFICIENCY** (Primary focus on deficiencies that could lead to a dam failure or uncontrolled release of reservoir) | |
| Emergency Condition | 250 points |
| Major Deficiency | 145 points |
| Moderate Deficiency | 65 points |
| Uncertain Seriousness | 65 points |
| Minor Deficiency | 20 points |

The seriousness of safety deficiencies are evaluated based on the matrix in Figure 9. This matrix is intended for guidance only, and ultimately, the final rating of seriousness of deficiencies is based on knowledge of the project and on engineering judgement.

**Figure 9 – Matrix for Evaluating Seriousness of Deficiencies**

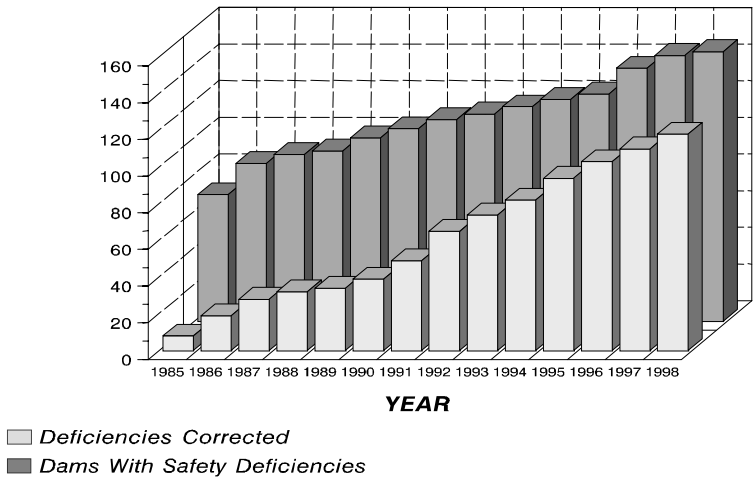
| CONDITION | HYDRAULIC ADEQUACY | EMBANKMENT STABILITY | SEEPAGE ON EMBANKMENTS, FOUNDATION, ABUTMENTS | OUTLET CONDUIT(S) |
|---|---|---|---|---|
| *SATISFACTORY* | Can accommodate IDF | Meets criteria for static & seismic stability | Minimal seepage consistent with past behavior | KSU Conduit Rating > 8 |
| *MINOR DEFICIENCIES* | Can only accommodate flood 1 step below Design Step | Meets criteria for static stability, marginal seismic stability under design earthquake | Minor seepage quantity, inconsistent with past behavior No evidence of internal erosion | KSU Conduit Rating 6-8 |
| *MODERATE DEFICIENCIES* | Can only accommodate flood 2 steps below Design Step | Marginal static stability 1.3 < FS < 1.5 inadequate seismic stability or liquefaction under design earthquake | Moderate seepage quantity Or Anomalous increase in quantity Minor concerns of piping | KSU Conduit Rating 4-6 |
| *MAJOR DEFICIENCIES* | Can only accommodate flood 3 steps below Design Step | Inadequate static stability 1.0 < FS < 1.3 inadequate seismic stability or liquefaction under design earthquake | Relative Large Seepage Quantity Multiple Points of Seepage And/or Significant concern of piping | KSU Conduit Rating 2-4 |
| *EMERGENCY* | Cannot Accommodate 25-year Flood | Significant slope failures that intercept dam crest or involve major portion of the embankment | Large or rapidly changing seepage quantity Multiple points of seepage and ongoing piping | KSU Conduit Rating 0-2 |

## CONCLUSIONS

Since its implementation in 1990, the use of the risk-based standards approach has been quite successful in Washington State. It has provided a consistent level of protection against failure between projects located across the state, despite significant differences in seismicity and rainfall. For new dams, we have been able to apply risk concepts in a standards-based approach that is fairly straightforward and easy to use.

For the evaluation of existing dams, we have been able to utilize a combination of probabilistic methods, risk concepts and risk-based standards to determine if the dam has an adequate level of protection against failure. If dams do not meet state standards, we are able to estimate the relative level of risk they currently pose, and prioritize our compliance efforts on those projects with the greatest risk. It has also allowed us to inform dam owners not only that their dams are “unsafe”, but also educate them as to what level of risk their unsafe project poses to the downstream public. In addition, we have utilized a prioritization scheme for compliance efforts on unsafe dams, based on the relative risk of each project. These combined approaches have resulted in great progress in repairing the backlog of dams with identified safety deficiencies in the State of Washington. For example, of the 46 dams inspected under the National Dam Inspection Program still listed as unsafe in 1990, 40 had been repaired by 1999. In addition, 78 of the 101 additional dams identified by the state dam safety program since 1985 have been repaired. Figure 10 shows the cumulative summary of corrective action since 1981.

**Figure 10 – Cumulative Number Of Dams Repaired in Washington Since 1981**




## ASPECTS OF RISK ASSESSMENT THAT MAY BE VALUABLE TO STATE PROGRAMS

Based on our experience, we feel that several aspects of risk assessment and risk management can be of benefit to other dam safety organizations. No matter what standards are used, all dam safety professionals are in the business of managing risk, and the more knowledgeable we are about risk, the better we can make decisions that protect public safety. Using probability and risk concepts allows a dam safety professional to understand the risks and manage them better.

At the 1999 ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams in Logan, Utah, several areas were identified as being potentially of use to state dam safety programs. The areas showing the most promise for the states included qualitative risk assessments such as Failure Mode Evaluation and Analysis (FMEA), prioritization and portfolio approaches, and developing risk-based standards for spillway and/or seismic design, as in Washington and Montana. These areas are highlighted as follows:

- FMEA can be a useful tool, even for those regulators that exclusively use deterministic standards. FMEA allows the regulator a better understanding of the potential site-specific failure modes, the possible failure scenarios and potential consequences, and effective risk reduction measures and dam safety related actions.
- Risk prioritization and portfolio approaches, such as Washington's, can be valuable tool for states to manage their limited resources toward fixing unsafe dams. Using a prioritization scheme, unsafe projects can be ranked for compliance and enforcement activity, based on the risk that they pose to downstream population. The most critical projects can then be targeted for enforcement action.
- Washington's risk-based standards approach may be of interest to some states, especially in spillway design. In fact, Montana's dam safety program has used our example to develop risk based spillway standards of their own. The drawback to implementing these standards on a broader scale is the current lack of probabilistic precipitation data in the U.S. beyond the 500-year event. It can be quite expensive for states to undertake this effort on their own. The Logan workshop identified the need for large-scale regional studies to be performed for probabilities of extreme rainfall events across the U.S. If these studies are completed, then it may be more attractive for some states to implement risk-based spillway standards.

- States using %PMP as a design level for analysis of spillways are already using a non-deterministic standard and by default are accepting risk, but the probability of the %PMP event, and corresponding risk to public safety is unknown. These states may benefit from the aforementioned regional precipitation studies, which would allow them to learn the probability of their %PMP standards. Depending on the results, the states may elect to go to risk-based standards, or may decide to adjust the percentage of PMP to increase or decrease the risk level.

- Quantitative risk assessment is not likely to be a useful tool for most state dam safety programs, due to the lack of probabilistic data, inadequate staffing levels, and amount of effort required to perform an assessment for each dam. Most states regulate a large number of small to medium sized dams, and would not have adequate staffing or resources to complete comprehensive studies on each dam.

## References


[1] Schaefer, M.G., *PMP and Other Extreme Storms: Concepts and Probabilities*, Presented at Symposium on Preliminary Assessment of Probabilities and Bounds on Extreme Precipitation Events, National Academy of Sciences, October 1993.

[2] Electric Power Research Institute, *Advanced Light Water Reactor Requirements Document, Appendix A, Probabilistic Risk Assessment Key Assumptions and Groundrules*, EPRI, June 1989.

[3] Starr, C., *Social Benefit Versus Technological Risk, What is Our Society Willing to Pay for Safety*, Science, Vol 208, April 1980, pp 1232-1238.

[4] ASCE, *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, ASCE 7-88, July, 1990.

[5] Iwan, WD, et.al., *Seismic Safety Requalification of Offshore Platforms*, American Petroleum Institute, March 1992.

[6] National Safety Council, *Accident Facts*, 1975, Chicago, Illinois.

[7] International Conference of Building Officials, *Uniform Building Code, 1988 Edition*, Whittier, California, 1988.

[8] Institute of Civil Engineers (ICE), *Reservoir Flood Standards*, Institute of Hydrology, Great Britain, 1975.

[9] Kennedy, R.P., et.al., *Progress Towards Developing Consistent Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Hazard Phenomena*, Proceedings DOE Natural Hazards Mitigation Conference, Las Vegas, Nevada, 1985.

[10] Kennedy, R.P., et. al., *Design and Evaluation Guidelines for Department of Energy facilities Subjected to Natural Phenomena Hazards*, US Department of Energy, Report UCRL-15910, June 1990.

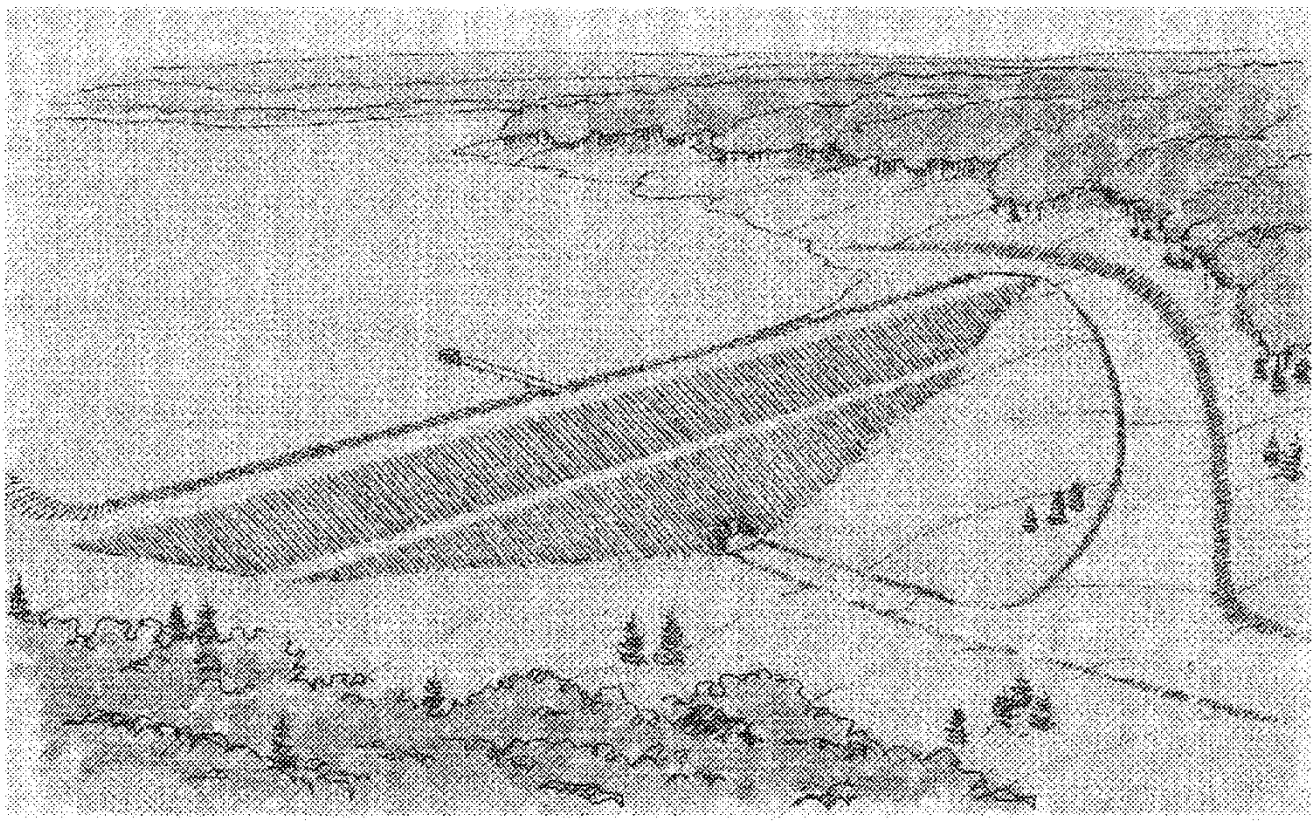
[11] US Bureau of Reclamation, *Guidelines for Achieving Public Protection in Dam Safety Decision Making*, Department of Interior, Denver, CO, Interim Guidelines, April 4, 1997.

[12] Schaefer, M.G., *Regional Analyses of Precipitation annual Maxima in Washington State*, Water resources Research, Vol. 26, No. 1, pp 119-132, January 1990.

[13] Schaefer, M.G., *Characteristics of Extreme Precipitation Events in Washington State*, Department of Ecology, Water Resources Program, Publication No. 89-51, Olympia, WA, October 1989.

[14] Schaefer, M.G., *Dam Safety Guidelines, Technical Note 3: Design Storm Construction*, Publication No. 92-55G, Water Resources Program, Department of Ecology, Olympia, WA, July 1992. Available on the web at http://www.wa.gov/ecology/wr/dams/technote_2.pdf

[15] Atwater, B.F., Hemphill-Haley, E. 1997, Recurrence Intervals for the Great Earthquakes of the Past 3,500 Years at Northeastern Willapa Bay, Washington, U.S. Geological Survey Professional Paper 1576, pg. 99.



# Dam Safety Guidelines

## Technical Note 3:

*Design Storm Construction*

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Revised October 2009
Publication #92-55G

Original printed on recycled paper

## Publication and Contact Information

This report is available on the Department of Ecology's website at
www.ecy.wa.gov/biblio/9255g.html

For more information contact:

Water Resources Program
P.O. Box 47600
Olympia, WA 98504-7600

Phone: 360-407-6872

Washington State Department of Ecology - www.ecy.wa.gov

| | |
|---|---|
| o Headquarters, Olympia | 360-407-6000 |
| o Northwest Regional Office, Bellevue | 425-649-7000 |
| o Southwest Regional Office, Olympia | 360-407-6300 |
| o Central Regional Office, Yakima | 509-575-2490 |
| o Eastern Regional Office, Spokane | 509-329-3400 |

*To ask about the availability of this document in a format for the visually impaired, call the Water Resources Program at 360-407-6872. Persons with hearing loss can call 711 for Washington Relay Service. Persons with a speech disability can call 877-833-6341.*

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

# DAM SAFETY GUIDELINES

## TECHNICAL NOTE 3

## *DESIGN STORM CONSTRUCTION*

MGS Engineering Consultants, Inc.

for

Water Resources Program
Dam Safety Office
P.O. Box 47600
Olympia, WA 98504-7600
(360) 407-6208

October 2009 (Revised)
92-55G

This page intentionally left blank.

# TABLE OF CONTENTS

Page

TABLE OF CONTENTS ..... i

LIST OF FIGURES AND TABLES ..... iii
Figures ..... iii
Tables ..... v

ACKNOWLEDGEMENTS ..... vi

OVERVIEW ..... 1

1. INTRODUCTION ..... 3
1.1 TERMINOLOGY ..... 3
1.2 GENERAL GUIDANCE IN APPLYING CANDIDATE DESIGN STORMS ..... 7
1.2.1 Western Washington ..... 8
1.2.2 Eastern Washington ..... 8
1.2.3 Design Storm Spatial Distribution ..... 8

2. SELECTING THE DESIGN STEP ..... 10
2.1 RELATION OF DESIGN STEP TO PROBABLE MAXIMUM PRECIPITATION ..... 11
2.1.1 Constraints on Applying PMP and Design Step ..... 11

3. COMPUTING PRECIPITATION FOR SCALING CANDIDATE DESIGN STORMS ..... 12
3.1 COMPUTING PRECIPITATION-FREQUENCY RELATIONSHIPS ..... 12
3.1.1 Large Watersheds ..... 14
3.1.2 Design Usage ..... 14

4. DEVELOPING CANDIDATE DESIGN STORMS ..... 15
4.1 DIMENSIONLESS DESIGN HYETOGRAPHS ..... 15
4.1.1 Dimensionless Design Hyetographs Organized by Climatic Region ..... 15
4.1.2 Changes Made in Updating Dimensionless Design Hyetographs ..... 19
4.1.3 Short-Duration Design Storms ..... 19
4.1.4 Intermediate-Duration Design Storms ..... 19
4.1.5 Long-Duration Design Storms ..... 20
4.1.6 Intensity Index Format for Dimensionless Design Hyetographs ..... 20
4.1.7 Dimensionless Depth-Duration Curves for Large Watersheds ..... 20
4.2 ASSEMBLING CANDIDATE DESIGN STORMS FOR SMALL WATERSHEDS ..... 26
4.2.1 Example Assembly of Short-Duration Candidate Design Storm ..... 26
4.2.1 Example Assembly of Long-Duration Candidate Design Storm ..... 28

4.3 ASSEMBLING CANDIDATE DESIGN STORMS FOR LARGE WATERSHEDS ....29
4.3.1 Example Assembly of Intermediate-Duration Candidate Design Storm.....30

5. REFERENCES .....33

APPENDIX A CATALOG OF HISTORICAL STORMS.....35
OVERVIEW .....37

APPENDIX B DIMENSIONLESS DEPTH-DURATION CURVES .....53
OVERVIEW .....55

# LIST OF FIGURES AND TABLES

Page

**Figures**

Figure 1 – Design Step Format as Applied to Design Storms ..... 10

Figure 2 – Color-Shaded Isopluvial Map of 24-Hour Precipitation Maxima for Washington State, 100-Year Recurrence Interval ..... 13

Figure 3 – Precipitation-Frequency Relationship for 24-hour Precipitation Maxima for a Site near Olympia, Washington ..... 13

Figure 4 – Delineation of Climatic Regions and Transition Zones for Washington State and Surrounding Areas ..... 17

Figure 5 – Short-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 5, 15, 31, 32, 142, 151, and Transition Zone 154 ..... 21

Figure 6 – Short-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 13, 14 and Transition Zone 147 ..... 21

Figure 7 – Short-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7 and 77 ..... 21

Figure 8 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Region 5 ..... 22

Figure 9 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 15, 151, 142 and Transition Zone 154 ..... 22

Figure 10 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 31, 32 ..... 22

Figure 11 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 14 ..... 23

Figure 12 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7 and 77 ..... 23

Figure 13 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 13 ..... 23

Figure 14 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Region 5 ..... 24

Figure 15 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 15, 142, 151 and Transition Zone 154 ..... 24

Figure 16 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 31, 32 ..... 24

Figure 17 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 14 ..... 25

Figure 18 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7, 77 ..... 25

Figure 19 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 13 ..... 25

Figure 20 – Flowchart for Construction of a Candidate Design Storm for Small Watersheds ..... 26

Figure 21 – Short-Duration Dimensionless Design Hyetograph for Transition Zone 147 ..... 27

Figure 22 – Scaled Short-Duration Candidate Design Storm for Site near Wenatchee, Washington ..... 27

Figure 23 – Long-Duration Dimensionless Design Hyetograph for Climatic Region 32 ..... 28

Figure 24 – Scaled Long-Duration Candidate Design Storm for Site near Olympia, Washington ..... 28

Figure 25 – Flowchart for Construction of a Candidate Design Storm for Large Watersheds ..... 29

Figure 26 – Intermediate-Duration Dimensionless Depth-Duration Curve for Climatic Region 31 ..... 31

Figure 27 – Scaled Intermediate-Duration Depth-Duration Curves for Climatic Region 31 for Site near Seattle ..... 31

Figure 28 - Intermediate-Duration Dimensionless Design Hyetograph for Climatic Region 31 ..... 31

Figure 29 – Intermediate-Duration Candidate Design Storm for a 50-$mi^2$ Watershed near Seattle, Washington, in Climatic Region 31 ..... 32

**Tables** Page

Table 1 – Areal Adjustment Factors to Account for Storm Spatial Distribution as a Percentage of At-Site Precipitation Amount ..... 10
Table 2 - Catalog of Short-Duration Extreme Storms for Region 5 - Coastal Lowlands ..... 39
Table 3 - Catalog of Short-Duration Extreme Storms for Regions 32 and 31 Interior Lowlands Western Washington ..... 39
Table 4 - Catalog of Short-Duration Extreme Storms for Regions 15, 151 and 142 Mountain Areas in Western Washington ..... 40
Table 5 - Catalog of Short-Duration Extreme Storms for Region 14 East Face of Cascade Mountains ..... 40
Table 6 - Catalog of Short-Duration Extreme Storms for Transition Zone 147 Cascade Foothills in Eastern Washington ..... 41
Table 7 - Catalog of Short-Duration Extreme Storms for Regions 77 and 7 Central Basin and Lowland Areas in Eastern Washington ..... 42
Table 8 - Catalog of Short-Duration Extreme Storms for Region 13 Mountain Areas in Eastern Washington Eastward of Cascade Mountains ..... 43
Table 9 - Catalog of Intermediate-Duration Extreme Storms for Region 5 Coastal Lowlands ..... 43
Table 10 - Catalog of Intermediate-Duration Extreme Storms for Regions 32 and 31 Interior Lowlands Western Washington ..... 44
Table 11 - Catalog of Intermediate-Duration Extreme Storms for Regions 15, 151 and 142 Mountain Areas in Western Washington ..... 45
Table 12 - Catalog of Intermediate-Duration Extreme Storms for Region 14 East Face of Cascade Mountains ..... 46
Table 13 - Catalog of Intermediate-Duration Extreme Storms for Transition Zone 147 Cascade Foothills in Eastern Washington ..... 46
Table 14 - Catalog of Intermediate-Duration Extreme Storms for Regions 77 and 7 Central Basin and Lowland Areas in Eastern Washington ..... 47
Table 15 - Catalog of Intermediate-Duration Extreme Storms for Region 13 Mountain Areas in Eastern Washington Eastward of Cascade Mountains ..... 47
Table 16 - Catalog of Long-Duration Extreme Storms for Region 5 - Coastal Lowlands ..... 48
Table 17 - Catalog of Long-Duration Extreme Storms for Regions 32 and 31 Interior Lowlands Western Washington ..... 49
Table 18 - Catalog of Long-Duration Extreme Storms for Regions 15, 151 and 142 Mountain Areas in Western Washington ..... 50
Table 19 - Catalog of Long-Duration Extreme Storms for Region 14 East Face of Cascade Mountains ..... 51
Table 20 - Catalog of Long-Duration Extreme Storms for Transition Zone 147 Cascade Foothills in Eastern Washington ..... 51
Table 21 - Catalog of Long-Duration Extreme Storms for Regions 77 and 7 Central Basin and Lowland Areas in Eastern Washington ..... 52
Table 22 - Catalog of Long -Duration Extreme Storms for Region 13 Mountain Areas in Eastern Washington Eastward of Cascade Mountains ..... 52
Table 23 – Listing of Ordinates of Dimensionless Depth-Duration Curves for Developing Short-Duration Candidate Design Storms for Large Watersheds ..... 55
Table 24 – Listing of Ordinates of Dimensionless Depth-Duration Curves for Developing Intermediate-Duration Candidate Design Storms for Large Watersheds ..... 56
Table 25 – Listing of Ordinates of Dimensionless Depth-Duration Curves for Developing Long-Duration Candidate Design Storms for Large Watersheds ..... 57

# ACKNOWLEDGEMENTS

The revisions and updates to Technical Note 3 were accomplished under the authorship of Melvin Schaefer, Ph.D., P.E., and Bruce Barker, P.E., of MGS Engineering Consultants, Olympia, Washington.

The original Technical Note 3 was compiled in 1993 under the leadership and principal authorship of Dr. Schaefer, supervisor of the Department of Ecology's Dam Safety Section at that time.

# OVERVIEW

This Technical Note provides engineering guidance for developing design storms for use in computing Inflow Design Floods (IDFs) using rainfall-runoff computer models. It is a companion document to Technical Note 2, *Selection of Design/Performance Goals for Critical Project Elements*[24], and to Chapter 2.4 of *Part IV* of the *Dam Safety Guidelines* on the computation of Inflow Design Floods.

Originally published in April 1993, the procedures in the original Technical Note 3 were based on the findings of two studies that had been completed in the early 1990s. Site-specific precipitation-frequency estimates were based on the findings of a regional precipitation-frequency analysis that was published in *Regional Analyses of Precipitation Annual Maxima in Washington State*[18]. The temporal patterns of design storms were based on the findings of an analysis of 252 storms, which were published in Ecology Report 89-51, *Characteristics of Extreme Precipitation Events in Washington State*[19].

The original Technical Note 3 was based on storm data collected from 1940-1986. Nearly 20-years have now passed, and in that time, many noteworthy storms have occurred and new technologies have become available. These changes warranted an update of Technical Note 3 to incorporate the additional information and improved techniques.

Of particular note, regional precipitation-frequency analyses were completed in 2006 for Washington State (Schaefer[20, 21]) using more than 700 precipitation gages and high-resolution spatial mapping techniques within a GIS framework. This has resulted in increased reliability for developing site-specific precipitation-frequency estimates.

A study of short-duration precipitation in the Seattle area was completed in 2003 (Schaefer[22]) that provided the first comprehensive examination of the magnitude of 5-minute, 10-minute, and 15-minute precipitation maxima within short, intermediate, and long-duration storms in Western Washington. This has increased the reliability of specifying the high-intensity portions of design storms for Western Washington.

Lastly, analyses have been conducted for the temporal characteristics of 142 noteworthy storms that occurred in the period from 1986 to 2007. Thus, this update of Technical Note 3 is now based on a database of 394 storms for the short, intermediate, and long-duration storms for the various climatic regions across Washington State.

# 1. INTRODUCTION

Developing candidate design storms is a key step in creating a rainfall-runoff model for computing an Inflow Design Flood (IDF). In particular, the amount and timing of precipitation of a storm are usually dominant factors in determining the size of the resultant flood.

If a project under design/evaluation has a small reservoir relative to the potential runoff of the contributing watershed, then flood peak discharge is normally the controlling consideration. Precipitation intensity is usually the primary consideration in developing the design storm for this case.

In contrast, if the reservoir is very large relative to the potential runoff of the contributing watershed, then runoff volume will be the controlling factor. The total volume of precipitation is then the primary consideration.

For most real world situations, projects are sensitive to various combinations of flood peak discharge and runoff volume. Therefore, both precipitation intensity and volume must be considered in developing design storms.

In the Northwest, considerations of precipitation volume and intensity are further complicated by seasonal effects, which must be accounted for in rainfall-runoff modeling. Short duration thunderstorms, which can contain very high precipitation intensities, typically occur in the warm season. Conversely, the long duration general storm events occur primarily in the winter months. These are characterized by large precipitation volumes but relatively moderate and uniform intensities. To accommodate these meteorological characteristics, it is normally necessary to develop several candidate design storms, representing various storm durations, intensities, and volumes. This allows a determination of the controlling event for design/evaluation of spillway size and hydraulic adequacy.

This technical note is intended to provide engineering guidance in developing candidate design storms that reflect the diversity of storm duration, intensity and volume found in the Northwest.

## 1.1 TERMINOLOGY

A variety of terms are needed to describe the characteristics of design storms. The following selected terms are defined to clarify their meaning in this technical note and *Part IV of the Dam Safety Guidelines* regarding *Dam Design and Construction.*

At-Site - Refers to site-specific characteristics as distinguished from regional characteristics. When used in the context of regional analyses, it refers to precipitation characteristics at a specific measurement recording station or geographic location of interest.

Annual Exceedance Probability (AEP) - The chance that a specified magnitude of some phenomenon of interest is equaled or exceeded during a given year. Herein, AEP refers to the chance that a specified magnitude of precipitation will be equaled or exceeded during a given year. For example, in Olympia, Washington, a 24-hour precipitation depth of 5.3 inches has an AEP of 0.01. Stated another way, there is one chance in one-hundred that 5.3 inches of precipitation or more will fall in Olympia in some 24-hour period in any given year.

Candidate Design Storm - A hyetograph that is used in rainfall-runoff modeling to examine the flood response of a watershed and the response of a project's reservoir and spillways. The candidate design storm that produces the most stringent loading condition for a project's reservoir and spillway(s) is deemed the Design Storm.

Depth-Duration Curve - A precipitation mass curve constructed in a manner whereby the largest incremental precipitation amounts are located at the start of the mass curve and progressively smaller amounts are accumulated to produce the remainder of the curve (see also reference 24).

Design Step - An integer value from one through eight that is used as an index for increasingly stringent design/performance goals. The design step is used to set design events and loading conditions for critical project elements such as spillways.

Design Storm - The hyetograph, depicting the precipitation volume, intensities, and duration, used in rainfall-runoff modeling to generate the Inflow Design Flood for determining the hydraulic adequacy of a project.

General Storm - A generic term for precipitation produced over large areas by synoptic scale weather features such as cyclones and associated fronts.

Hyetograph - A graphical representation of precipitation as it occurs with time. It may be for a specific location or represent an average over a specified area. It may be

discretized or continuous over time, displaying either precipitation intensities, incremental precipitation or accumulated precipitation.

Interduration - A generic term used for specifying some period of time within a storm. For example, there may be interest in the greatest precipitation amount (precipitation maxima) within any given 1-hour period (the 1-hour interduration) within a long-duration storm.

Intensity Index - A dimensionless measure of the precipitation intensity used in dimensionless design hyetographs to graphically characterize the precipitation intensity. Actual intensities are obtained by multiplying the intensity index values by the applicable value of the 2-hour, 6-hour, or 24-hour *Precipitation Scaling Depth* for the short, intermediate, and long-duration design storms respectively.

Intermediate-Duration Precipitation Event - A precipitation event where the duration of precipitation typically persists from 6 to 18 hours. When used in the context of a design storm, this term refers to 18-hour events which are characterized by moderate to high rainfall intensities, contain a large total precipitation volume.

Large Watershed - For purposes of this technical note, a large watershed is large enough that a storm's spatial distribution may vary significantly over the watershed and must be accounted for explicitly. Generally, these watersheds exceed 10 $mi^2$ for a long-duration or intermediate-duration storm design event, and larger than 1 $mi^2$ for a short-duration thunderstorm design event.

Local Storm - A storm comprised of an isolated convective cell or group of cells, commonly referred to as a *Thunderstorm*. These storms can produce very high precipitation intensities over localized areas. Its occurrence is unrelated to any synoptic weather feature such as a cyclone or associated front.

Long-Duration Precipitation Event - A precipitation event that typically persists from 24 to 72 hours. When used in the context of a design storm, this term refers to 72-hour events characterized by relatively moderate and uniform intensities, containing a very large total volume.

Orographic Precipitation - Precipitation that occurs from lifting of atmospheric moisture over mountain barriers.

Precipitation Magnitude-Frequency Curve - A graphical description of the relationship between precipitation magnitude (depth or volume) and annual exceedance probability. Also called a precipitation-frequency curve.

Precipitation Depth - The amount of precipitation, expressed in inches or millimeters, that would collect in a standard measuring device. It is synonymous with point rainfall. When used in connection with a geographic area, such as a watershed, it represents the average precipitation depth over the entire area.

Precipitation Intensity - The rate of precipitation expressed in inches/hour or millimeters/hour.

Precipitation Scaling Depth - The watershed-specific precipitation depth used to scale a dimensionless design hyetograph to the magnitude of interest for the specified Design Step. Precipitation scaling depths for the 2-hour, 6-hour, and 24-hour duration are used for scaling the short-duration, intermediate-duration and long-duration dimensionless design hyetographs, respectively.

Probable Maximum Precipitation (PMP) - Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year (National Weather Service[14] definition).

Short-Duration Precipitation Event - A precipitation event lasting from 30 minutes to 6 hours. When used in the context of a design storm, this term commonly refers to thunderstorm events characterized by short bursts of very high rainfall intensities, often with limited total volume occurring over isolated areas.

Small Watershed - For purposes of this technical note, a small watershed is small enough that the spatial variability of precipitation over the watershed is not significant. This corresponds to watersheds smaller than 10 $mi^2$ when a long-duration or intermediate-duration storm is the design event, and watersheds smaller than 1 $mi^2$ when a short-duration thunderstorm is the design event.

Storm Characteristics – A generic term that encompasses a variety of statistical measures of features of interest about a storm. This would include such measures as: the elapsed time from onset of precipitation to the occurrence of the maximum intensity; the sequencing of precipitation amounts for 5-minute increments during the 15-minute period of maximum precipitation in the storm; the greatest 1-hour precipitation amount as a proportion of the maximum 24-hour amount; and for

long-duration intermittent storms, the length of the dry period between successive major blocks of precipitation.[1]

Thunderstorm - A generic term for precipitation produced by a convective storm event where thunder is heard. Thunderstorms in the Pacific Northwest are characterized by high precipitation intensities occurring over relatively small areas for short periods of time. They may be accompanied by hail and lightning. (Also see local storm.)

Total Precipitation Depth - The total precipitation amount within a design storm. The total precipitation depth is larger than the precipitation scaling depth for a design storm.

## 1.2 GENERAL GUIDANCE IN APPLYING CANDIDATE DESIGN STORMS

For most investigations, it is necessary to develop several candidate design storms to analyze the response of the reservoir and spillway(s) to various flood characteristics. The principal storm characteristics that affect the flood peak discharge, runoff volume, and flood hydrograph shape are the intensity, volume, and duration of precipitation. The diversity of these characteristics for storms in Washington can be suitably described using three candidate storms, one for each of three durations. The terms Short-Duration, Intermediate-Duration, and Long-Duration are used to differentiate between the durations of the candidate design storms.

It will be seen later that the precipitation amounts for the 2-hour, 6-hour, and 24-hour durations are used to scale the dimensionless hyetographs for the short, intermediate and long-duration candidate design storms, respectively.

The following general guidance is provided for applying candidate design storms to the design/evaluation of spillway size, hydraulic adequacy, and/or reservoir floodwater storage capacity. This guidance is based on past experience in rainfall-runoff modeling using the design storm procedures described here. However, this does not preclude the user from investigating the flood response from other candidate design storms or historical storms as deemed necessary to determine the controlling event.

[1] See *Characteristics of Extreme Precipitation Events in Washington State*[19] for a detailed discussion of storm characteristics.

### 1.2.1 Western Washington

Long-duration storms are commonly the controlling design events in Western Washington. This is particularly the case when the reservoir has a relatively large storage volume relative to the runoff potential of the tributary watershed. It is always the design event for off-channel storage reservoirs with minimal tributary watershed area.

Projects with small storage capacity relative to the runoff potential of the tributary watershed are sensitive to flood peak discharge. In these situations, the higher intensities in intermediate-duration storms may become the controlling consideration.

Short-duration thunderstorm events usually do not produce sufficient runoff volume to be the controlling event for project spillways. Stormwater detention facilities in urban areas are the possible exception. In this situation, there may be a high percentage of impervious area, which could make the peak discharge from a short-duration event the controlling consideration.

### 1.2.2 Eastern Washington

The short duration thunderstorm is commonly the controlling design event in Eastern Washington when the tributary watershed is less than about 20 $mi^2$. The very high intensities in these storms can produce very large flood peak discharges, which often becomes the dominant consideration in sizing the spillway(s).

The long-duration storm is usually the controlling design event when the tributary watershed is very large or when the reservoir storage capacity is large relative to the runoff potential of the tributary watershed. The long-duration storm is always the design event for off-channel storage reservoirs where there is minimal area tributary to the reservoir. Intermediate-duration storms in Eastern Washington are occasionally found to be the controlling event for design of project hydraulic works.

### 1.2.3 Design Storm Spatial Distribution

There are two basic approaches used in rainfall-runoff modeling to describe the spatial (areal) distribution of precipitation over the watershed. The most commonly used approach is a “lumped” method where a single temporal distribution of precipitation is used and is expressed in terms of basin-average values. This approach is well-suited to situations where the variability of precipitation depth and temporal distribution does not vary greatly over the watershed. The second approach is a “distributed” method where precipitation depth and the temporal distribution of precipitation vary over the watershed. The variation in precipitation depth and temporal distribution may be allocated on a grid-

cell or polygon basis or may vary by sub-basin depending on the computational structure of the watershed model.

The vast majority of impoundments in Washington reside in small watersheds. As used here, the term *small watershed* refers to the size of the watershed relative to the areal coverage of the storm. In these cases, it is often reasonable to use a lumped method where a single hyetograph describes the temporal distribution of precipitation over the watershed. Since most state regulated dams are on small watersheds, the procedures described here are intended for application of a lumped approach.

The areal reduction factors listed in Table 1[13, 19] may be used for computing basin-average values from point precipitation values. The range of watershed sizes shown in Table 1 may be used as general guidance for the limit of using a lumped method. Specifically, areal adjustments are needed when the watershed under investigation exceeds 10 $mi^2$ and a long-duration or intermediate-duration storm is the design event. Areal adjustments are also needed when the watershed under investigation is larger than 1 $mi^2$ and a short-duration thunderstorm is the design event. Additional information on storm attenuation and areal adjustments can be found in *Characteristics of Extreme Precipitation Events in Washington State*[19], HMR-57[14], and NOAA Atlas 2[13].

For large watersheds, there will be cases where it is reasonable to explicitly depict the spatial distribution of precipitation over the watershed. For those cases, GIS-based isopluvial maps have been provided as part of this Technical Note, which are available from Ecology's Dam Safety Office.

Table 1 – Areal Adjustment Factors to Account for Storm Spatial Distribution as a Percentage of At-Site Precipitation Amount

| WATERSHED SIZE | STORM INTERDURATION | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ¼-HR | 1-HR | 2-HR | 3-HR | 6-HR | 12-HR | 18-HR | 24-HR | 48-HR | 72-HR |
| **Short-Duration Storm** | | | | | | | | | | |
| **1-mi$^2$** | 100% | 100% | 100% | 100% | 100% | - | - | - | - | - |
| **2-mi$^2$** | 93% | 97% | 98% | 98% | 99% | - | - | - | - | - |
| **5-mi$^2$** | 80% | 88% | 90% | 91% | 92% | - | - | - | - | - |
| **10-mi$^2$** | 69% | 79% | 82% | 83% | 85% | - | - | - | - | - |
| **Intermediate-Duration Storm** | | | | | | | | | | |
| **10-mi$^2$** | 100% | 100% | 100% | 100% | 100% | 100% | 100% | - | - | - |
| **20-mi$^2$** | 85% | 94% | 95% | 95% | 96% | 97% | 97% | - | - | - |
| **50-mi$^2$** | 76% | 84% | 86% | 88% | 91% | 93% | 93% | - | - | - |
| **100-mi$^2$** | 67% | 75% | 79% | 83% | 85% | 88% | 88% | - | - | - |
| **Long-Duration Storm** | | | | | | | | | | |
| **10-mi$^2$** | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| **20-mi$^2$** | 85% | 94% | 95% | 95% | 96% | 97% | 97% | 98% | 98% | 98% |
| **50-mi$^2$** | 76% | 84% | 86% | 88% | 91% | 93% | 93% | 95% | 95% | 95% |
| **100-mi$^2$** | 67% | 75% | 79% | 83% | 85% | 88% | 88% | 92% | 92% | 92% |

# 2. SELECTING THE DESIGN STEP

Technical Note 2, *Selection of Design/Performance Goals for Critical Project Elements*[24] discusses the procedures for selecting the Design Step. Technical Note 2 also explains the relationship between the design steps and the design/performance goals. The Design Step format as applied to design storms is reproduced here for convenience (Figure 1).

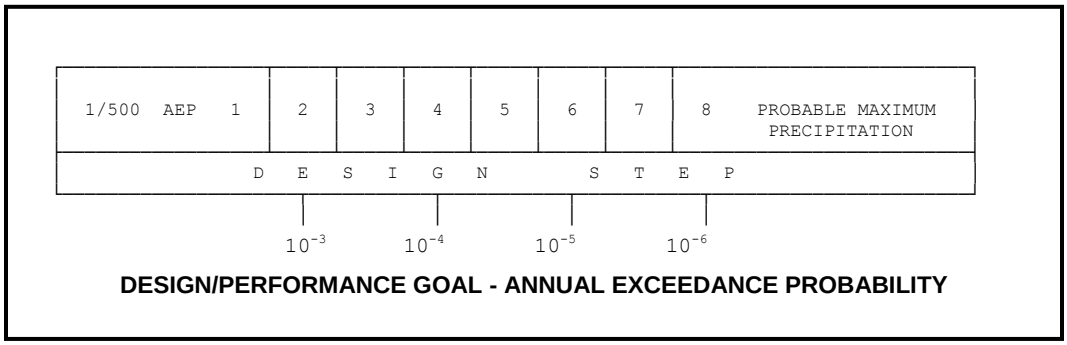



Figure 1 – Design Step Format as Applied to Design Storms

## 2.1 RELATION OF DESIGN STEP TO PROBABLE MAXIMUM PRECIPITATION

When Design Step 8 is indicated as the appropriate design level, Probable Maximum Precipitation (PMP) is used as the precipitation scaling depth. PMP values are obtained from HMR-57[14] and the design storm may be assembled using HMR-57 procedures or dimensionless design storms may be used from this Technical Note. However, use of PMP values from HMR-57 does not necessarily provide a level of protection equal to a design/performance goal of $10^{-6}$ AEP.

Since PMP is a deterministic procedure that does not employ probabilistic methods, there is not a fixed relationship between PMP and annual exceedance probability. A comparison of the findings of the recent regional precipitation analysis for Washington (Schaefer et al[20, 21]) with PMP estimates (HMR-57[14]) indicates that the AEP of PMP varies widely across Washington. The AEP of PMP varies with both geographic location and duration, from a minimum of about $10^{-5}$ AEP to perhaps $10^{-8}$ AEP.

### 2.1.1 Constraints on Applying PMP and Design Step

PMP values are estimates. Those estimates, like probabilistic estimates, are subject to uncertainties. Recognizing these uncertainties and the very large variability across Washington in the level of protection afforded by PMP, it was determined that PMP applications must also meet a minimum design/performance goal. This requirement improves consistency of application and avoids the potential for under-design. Therefore, when Design Step 8 is indicated and PMP is selected, the actual precipitation value used in design must be at least as large as that associated with an event with a computed AEP of $10^{-5}$ (Design Step 6).

Situations may also arise when the precipitation magnitude for the chosen Design Step exceeds the PMP estimate. In these cases, the PMP value is used as the precipitation scaling depth for developing the design storm.

# 3. COMPUTING PRECIPITATION FOR SCALING CANDIDATE DESIGN STORMS

Studies over past decades have shown that regionalization techniques (Hosking and Wallis[10], National Research Council[25], Potter[16], and Stedinger et al[23]) are vastly superior for estimating magnitude-frequency characteristics than past practices of single station analyses. The procedures used here to provide site-specific precipitation magnitude-frequency estimates are based on regional analysis procedures contained in *Regional Precipitation-Frequency Analysis and Spatial Mapping of Precipitation for 24-Hour and 2-Hour Durations in Western and Eastern Washington* (Schaefer et al[20, 21]). This was a statewide study completed in 2006 for the Washington State Department of Transportation.

## 3.1 COMPUTING PRECIPITATION-FREQUENCY RELATIONSHIPS

The first step in developing a candidate storm is to determine the precipitation depth, for the selected location and storm duration, to use for scaling the candidate design storm. Gridded GIS datasets for a grid-cell resolution of approximately 0.23 $mi^2$ were developed as part of the statewide regional precipitation-frequency analysis. A separate gridded dataset was developed for 2-hour, 6-hour, and 24-hour precipitation maxima for the 10-yr, 25-yr, 100-yr, and all 8 Design Steps. These gridded datasets are available as part of this Technical Note. Figure 2 depicts a color-shaded isopluvial[2] map for 24-hour precipitation maxima for the 100-year recurrence interval, created from a gridded dataset.

These datasets can be queried to produce a precipitation-frequency relationship for the site of interest and obtain the precipitation scaling depths for construction of candidate storms. Queries of the gridded datasets can be made using standard GIS software or software that is available through the Dam Safety Office. Figure 3 depicts a precipitation-frequency relationship for 24-hour precipitation maxima for a site near Olympia, Washington. Precipitation-frequency relationships can be developed for 2-hour and 6-hour precipitation maxima in a similar manner for scaling short-duration and intermediate-duration candidate storms, respectively.

[2] A line on a map drawn through geographical points having the same rainfall or precipitation index.

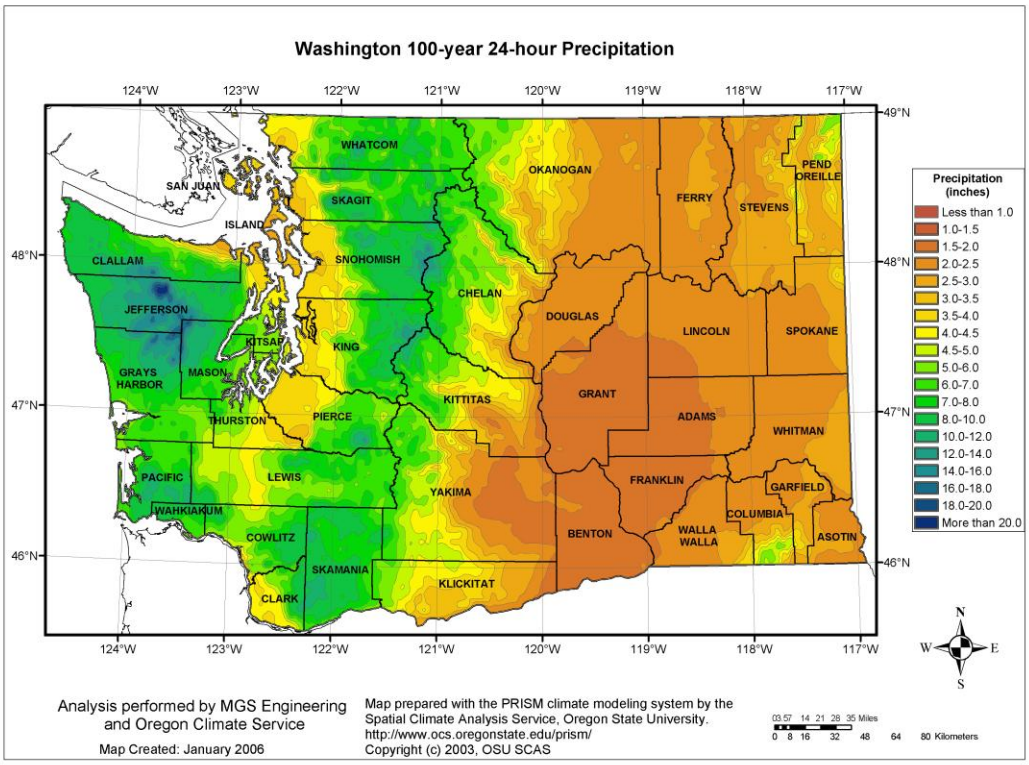



Figure 2 – Color-Shaded Isopluvial Map of 24-Hour Precipitation Maxima for Washington State, 100-Year Recurrence Interval

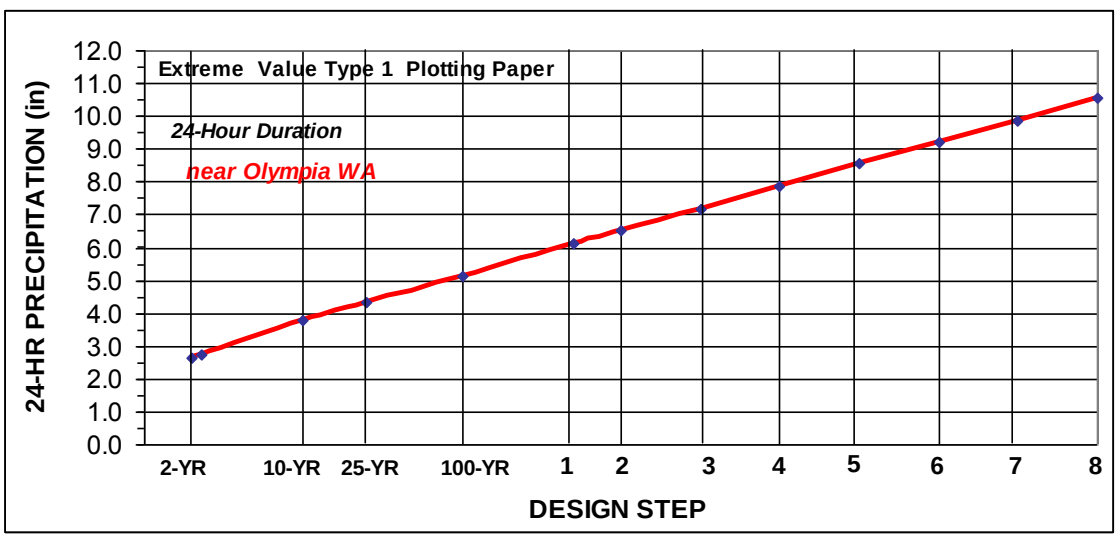



Figure 3 – Precipitation-Frequency Relationship for 24-hour Precipitation Maxima for a Site near Olympia, Washington

### 3.1.1 Large Watersheds

For large watersheds, a basin-average precipitation value is used for scaling in developing a candidate design storm. A basin-average precipitation value is obtained using GIS software and intersecting the polygon for the watershed boundary with the appropriate gridded precipitation dataset for the selected Design Step. A basin-average value is computed from an areal weighting of the precipitation values for the grid-cells within the watershed. To develop a spatial distribution of precipitation for use with a distributed watershed model, the spatial distribution from the gridded dataset provides a logical starting point.

### 3.1.2 Design Usage

The gridded precipitation datasets provide expected values (best-estimates) based on the regional solutions for each grid-cell location. In engineering design applications, it is common practice to incorporate some design conservatisms to account for uncertainties and to provide protection from under-design. For probabilistic methods, accounting for uncertainties usually employs some type of confidence interval. Monte Carlo analyses have been conducted to investigate the uncertainties associated with precipitation estimates based on the at-site and regional statistics used to make quantile estimates.

Based on these findings, it was determined that an overage of 15 percent would provide about an 80 percent level of protection from under-design. Thus, all precipitation values obtained from the gridded precipitation datasets which are to be used in a design application are to be increased by 15 percent as shown in Equation (1).

$$P_{sd} = 1.15\ P_{gds} \qquad \text{Equation (1)}$$

where: $P_{sd}$ = Precipitation amount to be used for scaling in developing a candidate storm for design application (*precipitation scaling depth*)

$P_{gds}$ = Precipitation value obtained from gridded dataset for the chosen Design Step

# 4. DEVELOPING CANDIDATE DESIGN STORMS

A hyetograph describes the time history of precipitation depth or intensity at a given location or over a specific area. The hyetograph is the standard form to input precipitation into rainfall-runoff computer models. The temporal and spatial distribution of precipitation, as described by a hyetograph, are inherently stochastic (random) and vary widely from storm to storm. Therefore, it is important that hyetographs used in design or evaluation of a project be developed using probabilistic procedures. This allows incorporation of storm characteristics that reflect the manner in which extreme storms have historically occurred (Schaefer[19]).

The procedures used here for constructing hyetographs are based on probabilistic analyses of 394 extreme storms in Washington from the period 1940-2006. A thorough discussion of those procedures is contained in *Characteristics of Extreme Precipitation Events in Washington State*[19]. Information and procedures from that document have been used to develop dimensionless hyetographs for small watersheds.

The simplified methods presented in Section 4.2.2 will allow the user to easily assemble candidate design storms using the library of dimensionless design hyetographs available through Ecology's Dam Safety Office.

## 4.1 DIMENSIONLESS DESIGN HYETOGRAPHS

As discussed previously, it is usually necessary to develop several candidate design storms to analyze the response of the reservoir and spillway(s) to various flood characteristics. The principal storm characteristics which affect the flood peak discharge, runoff volume, and hydrograph shape are the precipitation intensity, volume and duration. The diversity of these storm characteristics can be suitably described using several candidate storms, reflecting a range of storm durations. The following sections present information and procedures for scaling dimensionless design hyetographs to create short, intermediate, and long-duration candidate design storms. Applying the design storms in rainfall-runoff models is discussed in Chapter 2.4 of *Part IV* of the *Dam Safety Guidelines*, titled *Inflow Design Flood*.

### 4.1.1 Dimensionless Design Hyetographs Organized by Climatic Region

Climatic regions are geographic areas with similar climatic and topographic characteristics that result in storms having similar storm characteristics. One of the major changes that affected this Technical Note was a refinement of the climatic region delineation contained in the 2006 regional precipitation-frequency analysis (Schaefer

et al[20, 21]). This required regrouping of the 252 historical storms that were analyzed in Ecology Report 89-51 (Schaefer[19]). Similarly, the 142 historical storms observed in the period from 1986-2006 were grouped according to the new climatic regions, and analyzed according to procedures described in the report 89-51. Separate analyses were then conducted for each climatic region for each of the three storm durations.

The dimensionless design hyetographs used to develop candidate design storms are organized according to climatic region and duration (short, intermediate, and long). Thus, the user must first identify the climatic region where the project watershed is located in order to select the appropriate dimensionless design hyetograph. Climatic regions (shown in Figure 4) and boundaries are described below.

**Climatic Regions for Western Washington**

***Region 5* - Coastal Lowlands** – The lowlands along the west coast of Washington, Oregon, and Vancouver Island open to the Pacific Ocean. The eastern boundary is either a generalized contour line of 1,000 feet elevation, or the ridgeline of mean annual precipitation that separates the coastal lowlands from the interior lowlands, such as within the Aberdeen-Montesano gap.

***Region 151* - Coastal Mountains West** – The windward faces of the Olympic Mountains, Willapa Hills, Black Hills, Coastal Mountains in Oregon, and Vancouver Island Mountains in British Columbia above a generalized contour line of 1,000 feet elevation. These areas are bounded to the west by the 1,000 feet contour line, and bounded to the east by the ridgeline of mean annual precipitation near the crestline of the mountain barrier.

***Region 142* - Coastal Mountains East** – The leeward faces of the Olympic Mountains, Willapa Hills, Coastal Mountains in Oregon, and Vancouver Island Mountains in British Columbia above a generalized contour line of 1,000 feet elevation. These areas are bounded to the west by the ridgeline of mean annual precipitation near the crestline of the mountain barrier, and bounded to the east by the 1,000 feet contour line. This also includes isolated mountain features such as the Black Hills.

***Region 32* - Interior Lowlands West** – The interior lowlands below a generalized contour line of 1,000 feet elevation bounded to the east by the trough-line of mean annual precipitation through the Strait of Juan De Fuca, Puget Sound Lowlands and Willamette Valley. This is a zone of low orography where mean annual precipitation generally decreases from west to east.

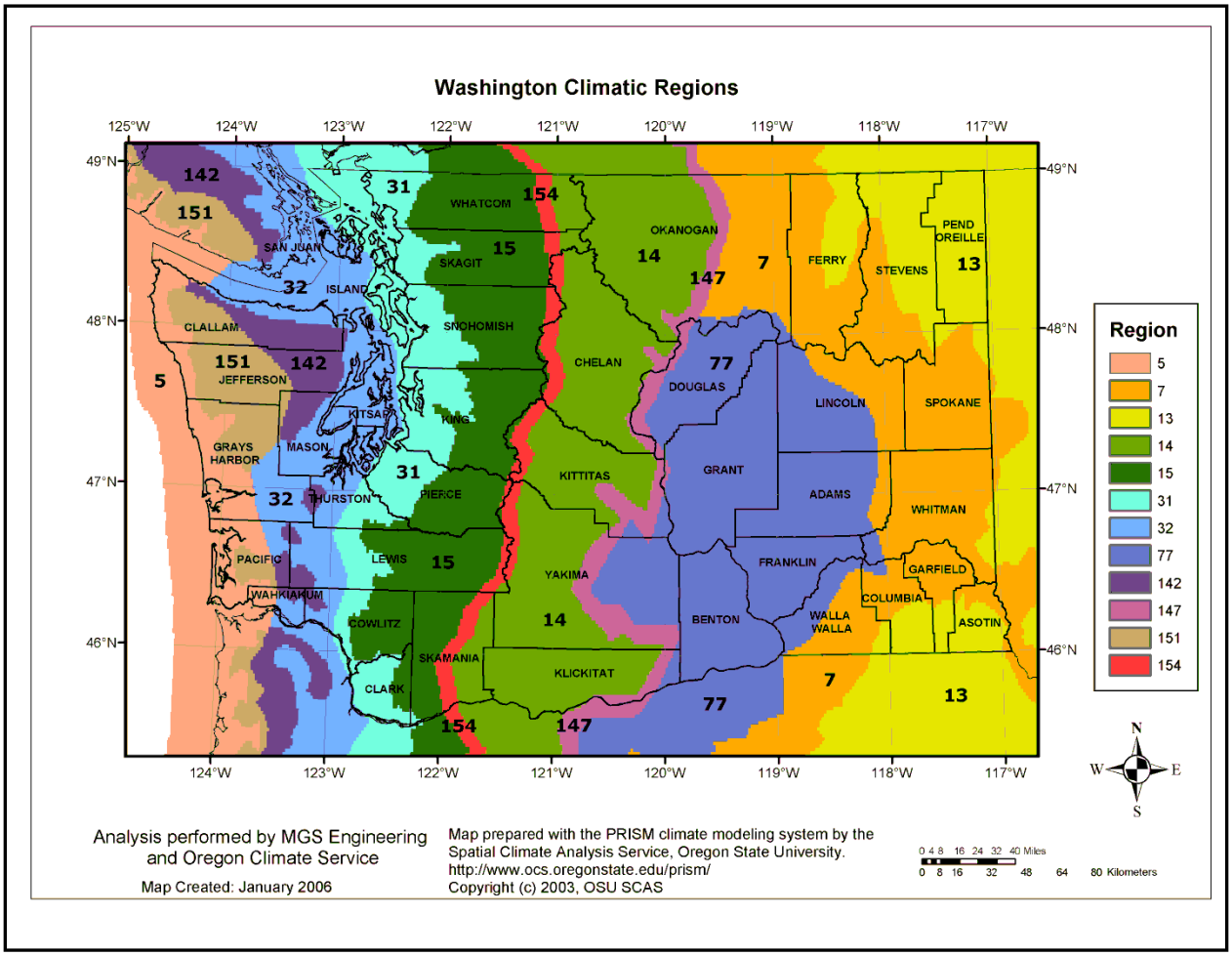



Figure 4 – Delineation of Climatic Regions and Transition Zones for Washington State and Surrounding Areas

***Region 31*** **- Interior Lowlands East** – The interior lowlands below a generalized contour line of 1,000 feet elevation bounded to the west by the trough-line of mean annual precipitation through the Strait of Juan De Fuca, Puget Sound Lowlands, and Willamette Valley. This is a zone of low orography where mean annual precipitation generally increases from west to east.

***Region 15*** **- West Slopes of Cascade Mountains** – This region is comprised of the windward face of the Cascade Mountains in Washington, Oregon, and British Columbia above a generalized contour line of 1,000 feet elevation. This region is bounded to the east by the ridgeline of mean annual precipitation near the Cascade crest that forms the boundary with Region 14 located on the east slopes of the Cascade Mountains.

**Climatic Regions[3] for Eastern Washington**

***Zone 154* - Cascade Crest Transition Zone –** This is a transition zone near the crest of the Cascade Mountains between the west and east slopes of the Cascade Mountains (Regions 15 and 14). The transition zone has a nominal width of about 6 miles.

***Region 14* - East Slopes of Cascade Mountains** – This region is comprised of mountain areas on the east slopes of the Cascade Mountains where precipitation annual maxima are produced predominately by winter storm events. This region is bounded to the west by the ridgeline of mean annual precipitation that generally parallels the crest line of the Cascade Mountains. Region 14 is bounded to the east by the contour of 14 inches mean annual precipitation for locations north of the Methow River Valley and by the contour line of 12 inches mean annual precipitation for areas to the south of the Methow River Valley.

***Zone 147* - Cascade Foothills Transition Zone** – This is a transition zone between the east slopes of the Cascade Mountains (Region 14) and arid and semi-arid areas to the east. The transition zone has a nominal width of about 6 miles.

***Region 77* - Central Basin –** The Central Basin region is comprised of the Columbia Basin and adjacent low elevation (non-orographic) areas in central eastern Washington. It is bounded to the west by Region 14. The region is bounded to the north and east by the generalized (smoothed) contour line of 12 inches mean annual precipitation.

***Region 7* - Okanogan , Spokane, Palouse –** This region is comprised of a mixture of lowland areas of low to moderate relief and extensive valley areas between mountain barriers. This includes areas near Spokane, the Palouse, and areas along the Okanogan River. The region is bounded to the northwest by Region 14. It is bounded to the south and west by Region 77, which generally conforms to the contour line of 12 inches mean annual precipitation at the eastern edge of the Central Basin. It is bounded to the northeast by the Kettle River Range and Selkirk Mountains at approximately the contour line of 22 inches mean annual precipitation. It is bounded to the southeast by the Blue Mountains also at the contour line of 22 inches mean annual precipitation.

***Region 13* - Northeastern Mountains and Blue Mountains –** This region is comprised of mountain areas in the easternmost part of Washington State where there is a significant orographic effect on precipitation depths. It includes portions of the Kettle River Range, Selkirk Mountains, and Cabinet Mountains in the northeast, the Bitterroot Range to the East, and the Blue Mountains in the southeast corner of Eastern Washington. Mean annual precipitation ranges from a minimum of 22 inches

[3] The list of regions in Eastern Washington includes two transition zones.

to over 70 inches in the mountain areas. The western boundary of this region generally conforms to the contour line of 22 inches mean annual precipitation.

### 4.1.2 Changes Made in Updating Dimensionless Design Hyetographs

As compared to the original release of Technical Note 3, changes to the dimensionless design hyetographs were made in response to four separate sources of new information. First, the new climatic region delineation (Figure 4) resulted in new groupings of historical storms and greater homogeneity of storm characteristics within the new regions. Second, 142 additional storms were analyzed for the short, intermediate and long-durations for the period from 1986-2006. This large number of storm events added greatly to the total database of storms and altered the sample statistics slightly. Third, analyses of short 5-minute, 10-minute and 15-minute precipitation maxima in the Seattle area improved resolution of high-intensity portions of storms for western Washington. Fourth, experience gained since 1990 about the temporal behavior of extreme storms allowed improvements and simplification in the approach to assembly of the dimensionless hyetographs.

The following sections provide brief summaries of the differences in the updated dimensionless design hyetographs relative to those contained in the original Technical Note 3.

### 4.1.3 Short-Duration Design Storms

Figures 5, 6, and 7 depict short-duration dimensionless design hyetographs for the selected climatic regions. Significant increases were made to the high-intensity portion of the short-duration storm for Western Washington based on data from the Seattle precipitation gaging network and NOAA automated gages (Schaefer[22]). The storm characteristics for Eastern Washington are very similar to those in the original Technical Note 3.

### 4.1.4 Intermediate-Duration Design Storms

Figures 8 through 13 depict intermediate-duration dimensionless design hyetographs for selected groupings of climatic regions. In general, the high-intensity portions of the new design storms nearly match those for design storms in the original Technical Note 3. Minor changes were made to precipitation maxima for the 15-minute and 30-minute durations for Climatic Regions 14 and 13 for Eastern Washington. Minor increases were also made to the total precipitation for all design hyetographs. The greatest increases in the total precipitation occurred for Climatic Regions 15 and 14 in the Cascade Mountains.

### 4.1.5 Long-Duration Design Storms

Figures 14 through 19 depict long-duration synthetic design hyetographs for selected climatic regions. In general, the high-intensity portions of the new design hyetographs are similar to the high-intensity sections for design storms in the original Technical Note 3. The largest changes came from regrouping the storms according to the new climatic regions in Eastern Washington. In addition, the time resolution was improved by using a 15-minute time-step to replace the 30-minute time-step used in the original design hyetographs. Lastly, additional data and experience allowed use of one long-duration design storm per climatic region instead of two design storms per region as done in the original Technical Note 3.

### 4.1.6 Intensity Index Format for Dimensionless Design Hyetographs

The dimensionless design hyetographs displayed in Figures 5 through 20 are constructed using an Intensity Index. This format allows direct conversion to a precipitation intensity hyetograph with units of inches/hour by scaling (multiplying) by the chosen *Precipitation Scaling Depth* for the selected Design Step (2-hour, 6-hour, or 24-hour precipitation for the short, intermediate or long-duration dimensionless design hyetograph, respectively). For example, a precipitation scaling depth of 2.0 inches for the 2-hour duration would yield a maximum intensity of 5.2 inches/hour if applied to Figure 5. Multiply all ordinate values in Figure 5 by 2.0 to yield a precipitation intensity hyetograph.

### 4.1.7 Dimensionless Depth-Duration Curves for Large Watersheds

Assembly of a candidate design storm for a large watershed represents a watershed-specific application. Generic dimensionless design hyetographs cannot be developed in advance because the scaling of the storm is dependent on areal adjustments for watershed size as well as scaling by precipitation depth. Appendix B contains dimensionless depth-duration curves for all of the dimensionless design hyetographs for use on large watersheds.

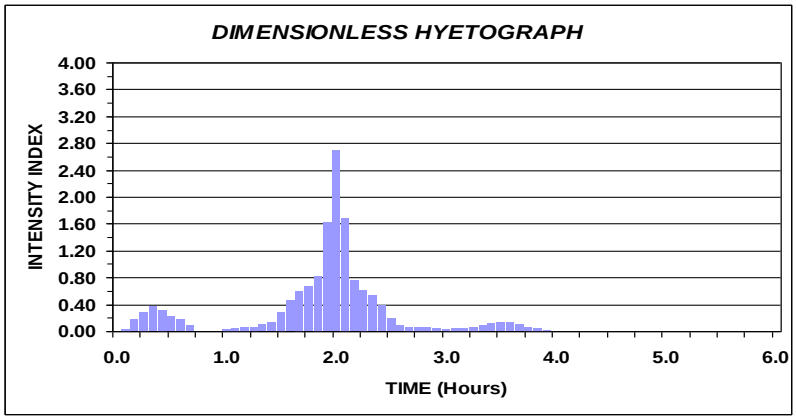



Figure 5 – Short-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 5, 15, 31, 32, 142, 151, and Transition Zone 154

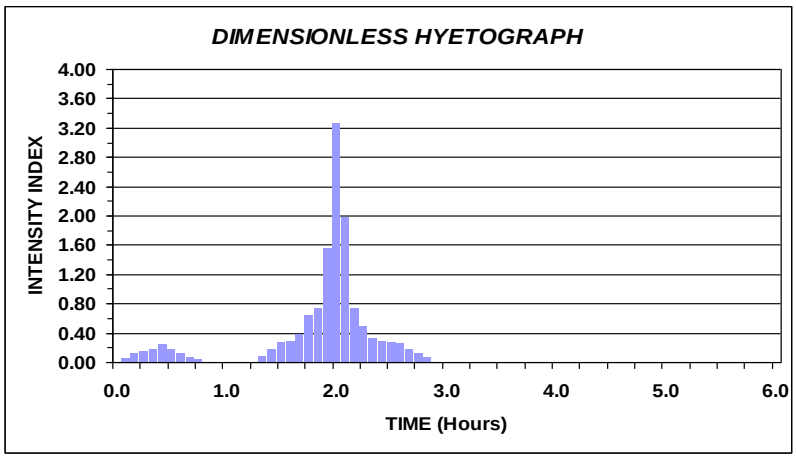



Figure 6 – Short-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 13, 14 and Transition Zone 147

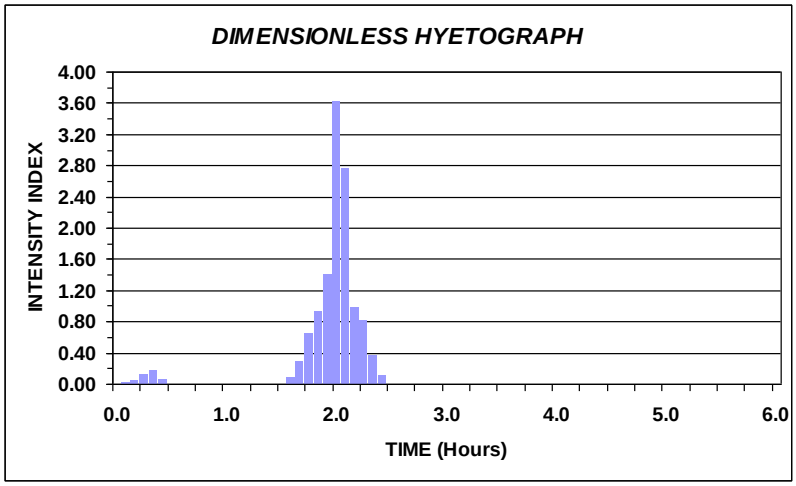



Figure 7 – Short-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7 and 77

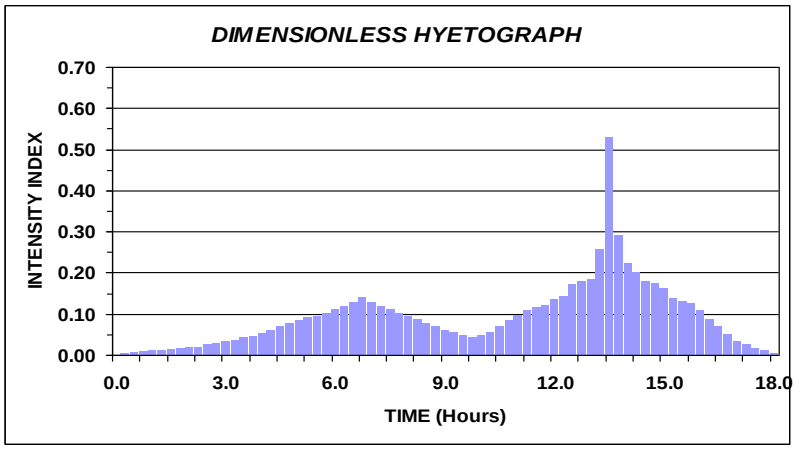



Figure 8 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Region 5

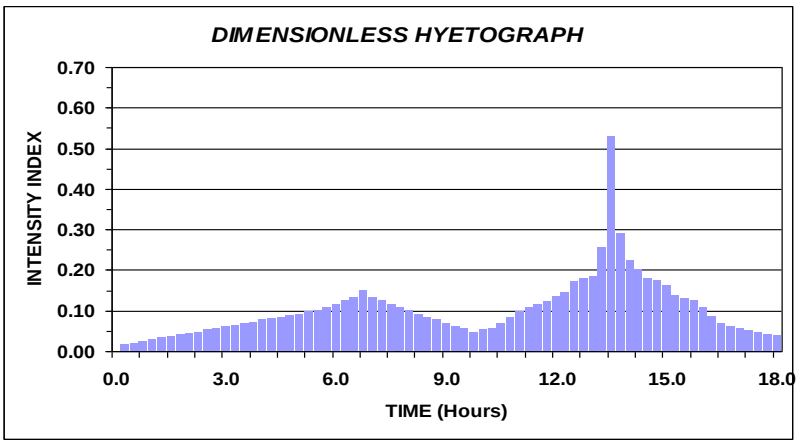



Figure 9 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 15, 151, 142 and Transition Zone 154

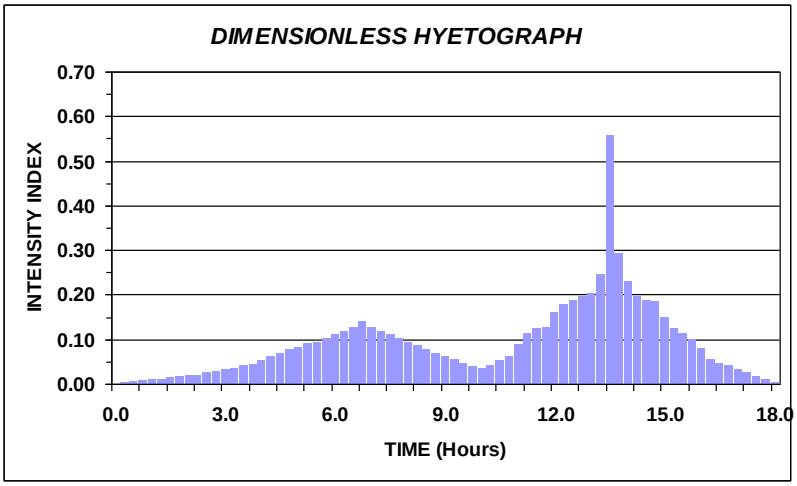



Figure 10 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 31, 32

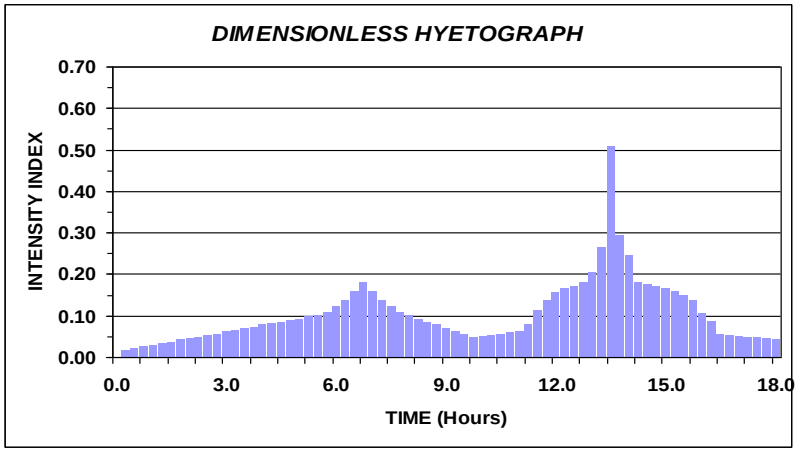



Figure 11 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 14

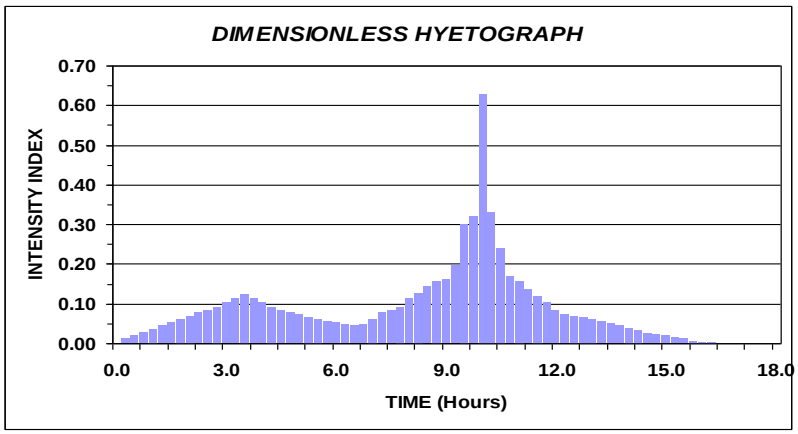



Figure 12 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7 and 77

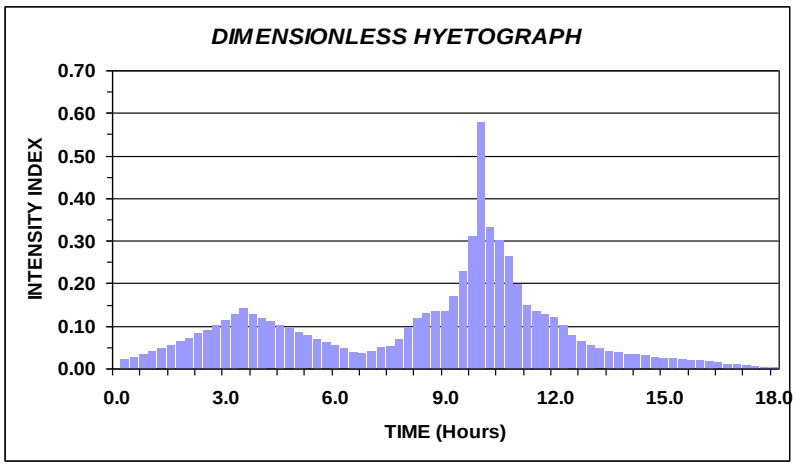



Figure 13 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 13

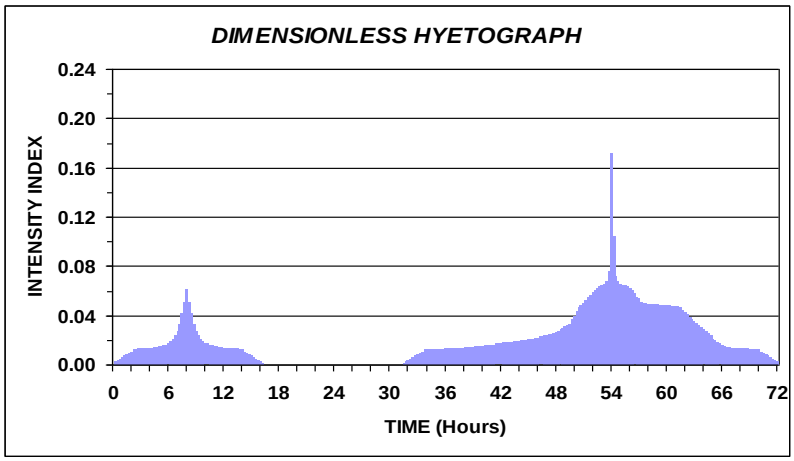



Figure 14 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Region 5

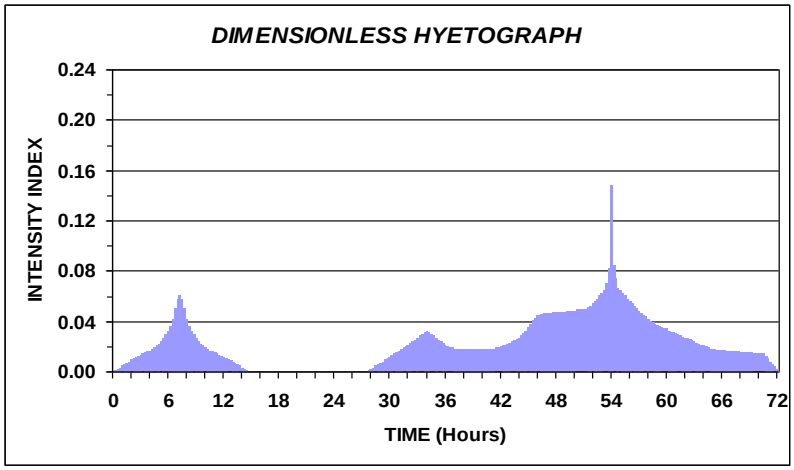



Figure 15 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 15, 142, 151 and Transition Zone 154

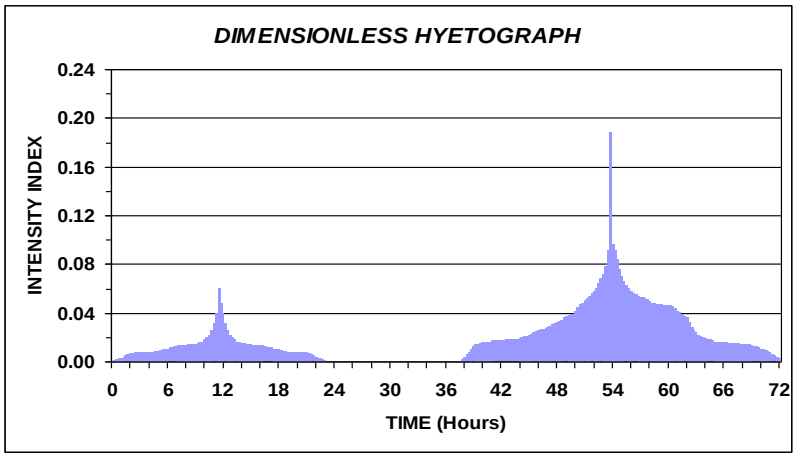



Figure 16 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 31, 32

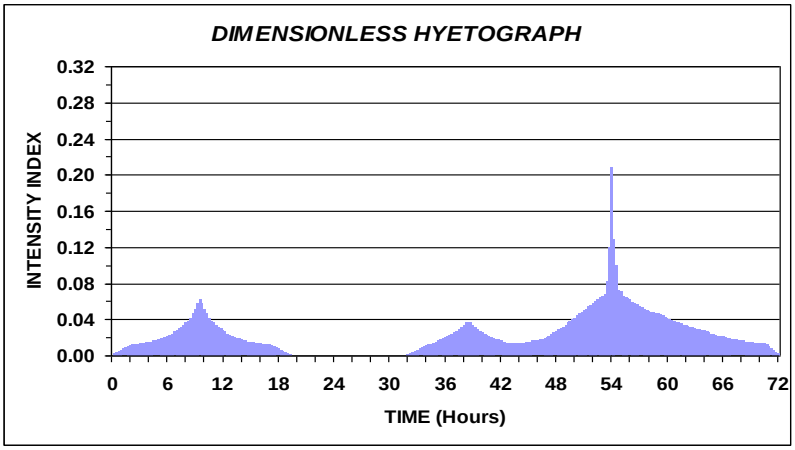



Figure 17 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 14

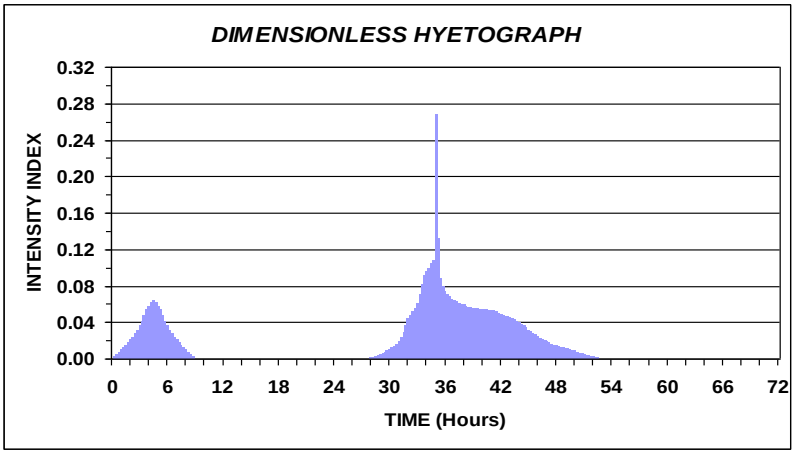



Figure 18 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7, 77

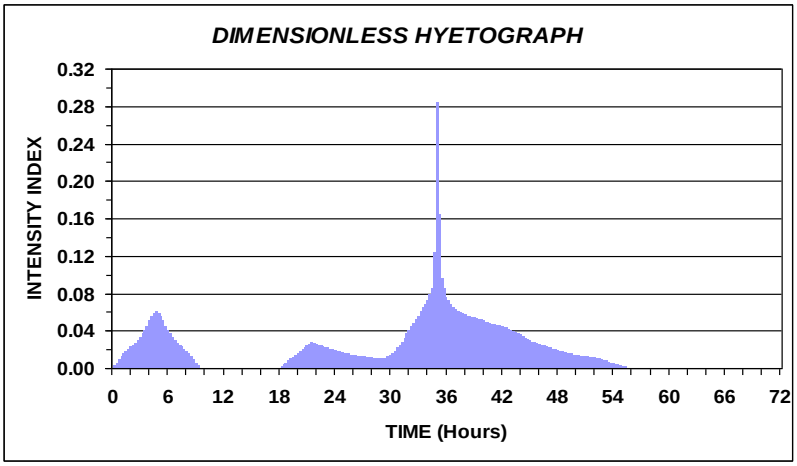



Figure 19 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 13

## 4.2 ASSEMBLING CANDIDATE DESIGN STORMS FOR SMALL WATERSHEDS

In the majority of impoundment projects constructed in Washington, the size of the tributary watershed is very small relative to the areal coverage of the design storm. For these situations, no adjustments to the at-site precipitation estimates are needed to account for the storm's areal distribution over the watershed. For small watersheds, where no adjustments are required to account for the spatial distribution of the storm, dimensionless design hyetographs are available in electronic format on Compact Disc (CD) or on the Department of Ecology website.

The standard steps to construct candidate design storms, when no areal adjustments are required, are shown in the flow chart in Figure 20. The same procedure is used for short, intermediate, and long-duration candidate design storms that are scaled by separate precipitation scaling depths for the 2-hour, 6-hour and 24-hour durations, respectively.

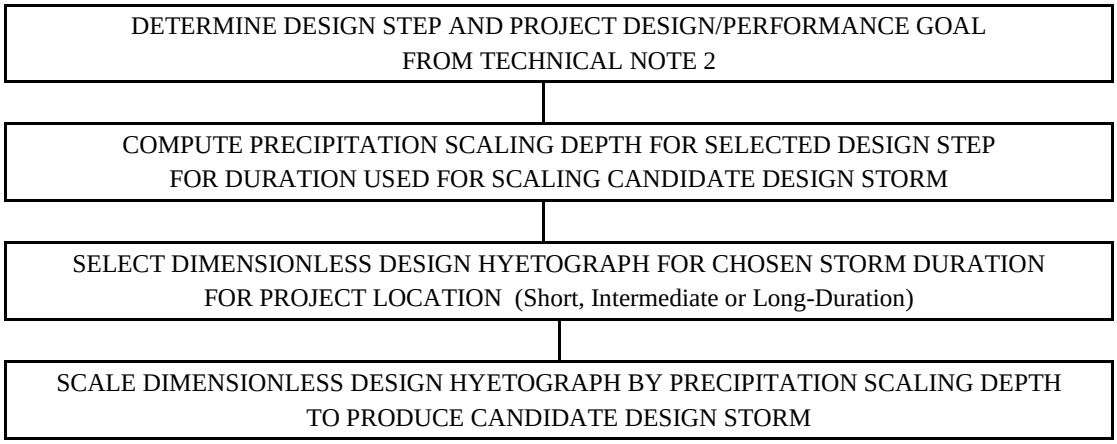



Figure 20 – Flowchart for Construction of a Candidate Design Storm for Small Watersheds

### 4.2.1 Example Assembly of Short-Duration Candidate Design Storm

Construct a short-duration candidate design storm for a site near Wenatchee, WA.

Given: Climatic Region – Transition Zone 147; 2-hour precipitation scaling depth for Design Step 3 is 3.14-inches, obtained from querying the gridded precipitation dataset for 2-hour precipitation maxima for Design Step 3, and applying the 15 percent design factor per Equation 1 as appropriate.

1. Multiply the ordinates of the short-duration dimensionless design hyetograph for Transition Zone 147 (Figures 6 and 21) by the precipitation scaling depth of

3.14-inches. (The dimensionless design hyetographs are available in electronic format through Ecology's Dam Safety Office.) The resultant candidate design storm is shown in Figure 22.

2. Many watershed models use precipitation depth as input. For these applications, convert precipitation intensities to precipitation depths by multiplying the intensities from Step 1 by 12 for a 5-minute time-step.

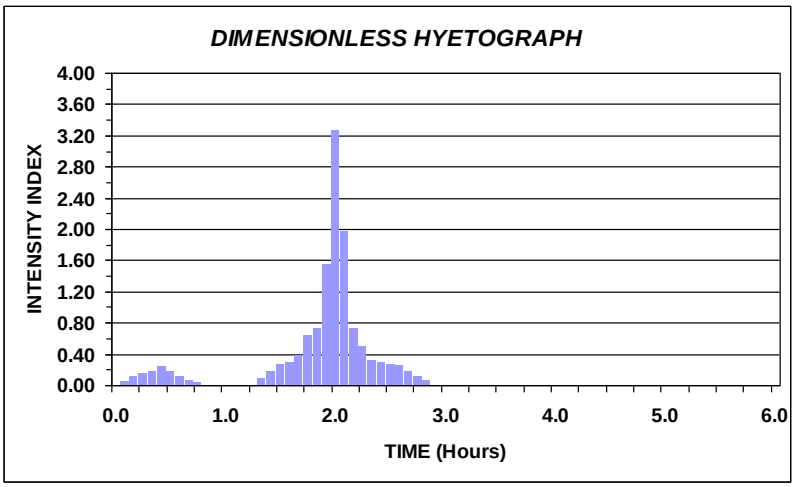



Figure 21 – Short-Duration Dimensionless Design Hyetograph for Transition Zone 147

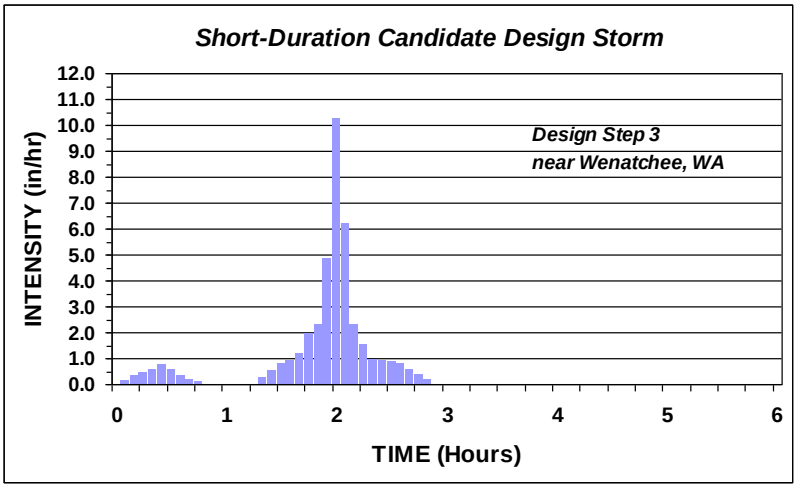



Figure 22 – Scaled Short-Duration Candidate Design Storm for Site near Wenatchee, Washington

### 4.2.1 Example Assembly of Long-Duration Candidate Design Storm

Construct a long-duration candidate design storm for a site near Olympia, Washington. Given: Climatic Region 32; 24-hr precipitation scaling depth for Design Step 5 is 8.54 inches, obtained from querying gridded precipitation dataset for 24-hour precipitation maxima for Design Step 5, and applying the 15 percent design factor as appropriate.

1. Multiply the ordinates of the long-duration dimensionless design hyetograph for Climatic Region 32 (Figures 16 and 23) by the precipitation scaling depth of 8.54 inches. The resultant candidate design storm is shown in Figure 24.
2. For those watershed models that use precipitation depth as input, convert precipitation intensities to precipitation depths by multiplying the intensities from Step 1 by 4 for a 15-minute time-step.

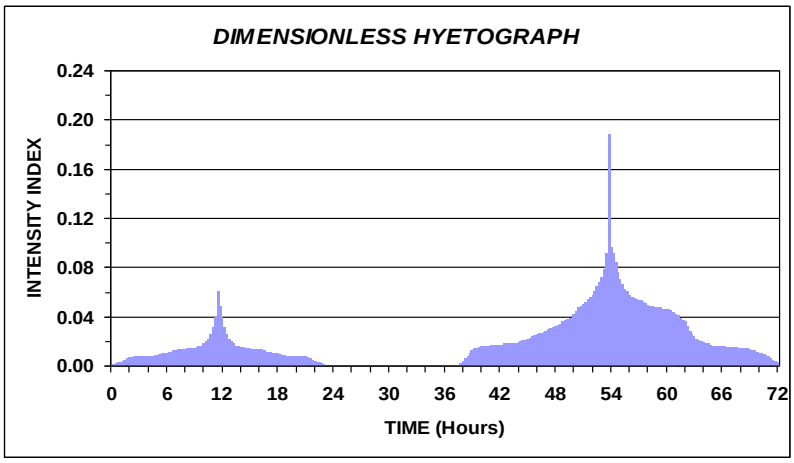



Figure 23 – Long-Duration Dimensionless Design Hyetograph for Climatic Region 32

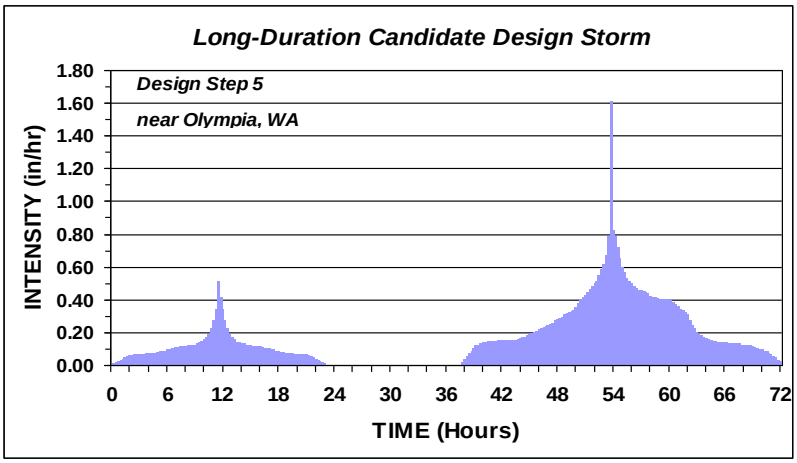



Figure 24 – Scaled Long-Duration Candidate Design Storm for Site near Olympia, Washington

## 4.3 ASSEMBLING CANDIDATE DESIGN STORMS FOR LARGE WATERSHEDS

As discussed previously, a large watershed is one where the basin-average precipitation varies sufficiently from the maximum point precipitation depth that the spatial distribution of the storm is an important consideration. This corresponds to watersheds that exceed 10 $mi^2$ for long or intermediate-duration storms as the design event, and watersheds larger than 1 $mi^2$ for a short-duration thunderstorm as the design event.

Constructing a design storm hyetograph for a large watershed is a watershed-specific application. Thus, generic hyetographs for large watersheds cannot be developed in advance. The areal adjustment values in Table 1 may be used in determining if the dimensionless design hyetographs for small watersheds may be acceptable. Alternatively, if areal adjustments will be important in assembling the candidate design storms for the large watershed, then watershed-specific hyetographs must be developed.

The flow chart in Figure 25 illustrates the standard steps for constructing candidate design storms when areal adjustments are required. Appendix B contains dimensionless depth-duration curves used for assembling the candidate design storms.

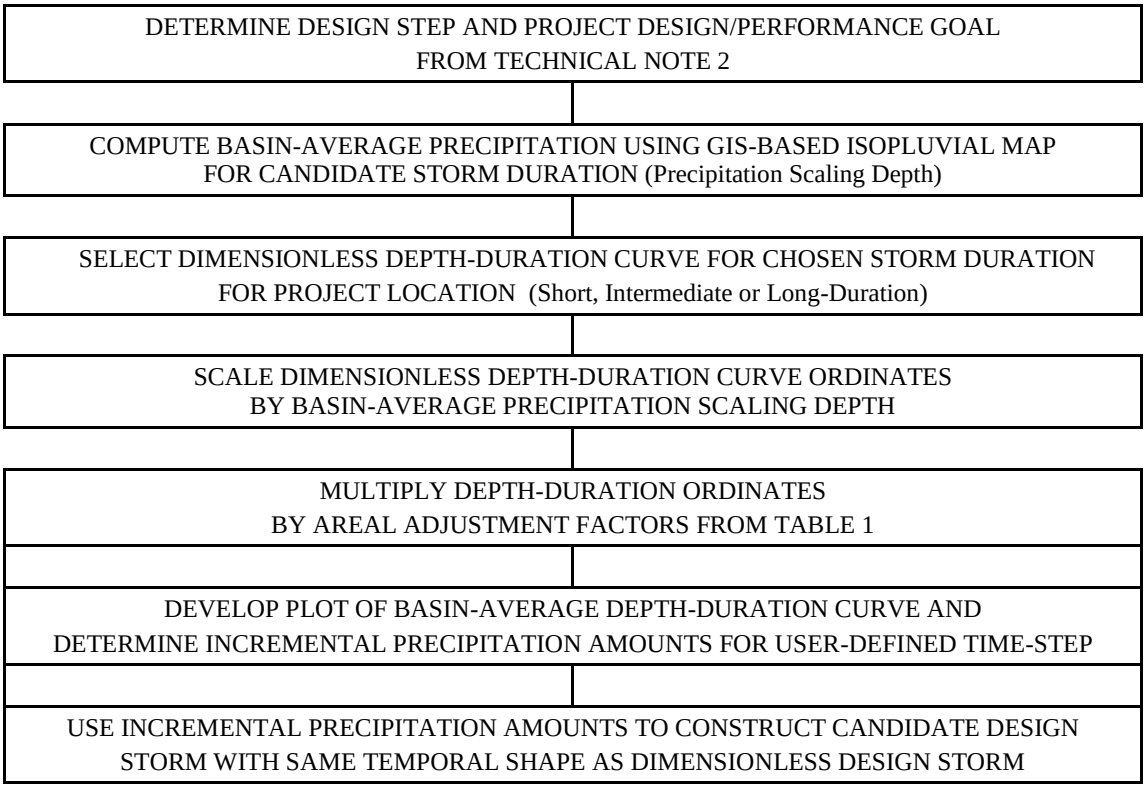



Figure 25 – Flowchart for Construction of a Candidate Design Storm for Large Watersheds

### 4.3.1 Example Assembly of Intermediate-Duration Candidate Design Storm

Construct an intermediate-duration candidate design storm for a site near Seattle, WA.

Given: Watershed area is 50-mi$^2$; Climatic Region 31; 6-hour precipitation scaling depth for Design Step 4 is 3.02-inches, obtained from querying the gridded precipitation dataset for 6-hour precipitation maxima for Design Step 4 and computing basin-average precipitation for the watershed, and applying the 15 percent design factor per Equation 1 as appropriate.

1. Multiply the ordinates of the intermediate-duration dimensionless depth-duration curve Figure 26) for Climatic Region 31 (Appendix B) by the precipitation scaling depth of 3.02-inches. This produces a depth-duration curve for watersheds up to 10 mi$^2$ (Figure 27).
2. Multiply the scaled depth-duration curve ordinate values by the areal reduction factors for the intermediate-duration listed in Table 1 for a 50-mi$^2$ watershed. Use linear interpolation to obtain areal reduction factors for interdurations residing between listed values. This produces the scaled depth-duration curve for a 50-mi$^2$ watershed (Figure 27).
3. Obtain incremental precipitation amounts by successively subtracting values from the scaled depth-duration curve (Step 2) on a 15-minute time-step.
4. Multiply the incremental precipitation amounts from Step 3 by a factor of 4 to convert to precipitation intensities (in/hr).
5. Rearrange the incremental intensities in the same pattern as shown for the dimensionless design hyetograph (Figures 10 and 28). This produces the intermediate-duration candidate design storm for the 50-mi$^2$ watershed (Figure 29).
6. For those watershed models that use precipitation depth as input, convert precipitation intensities to precipitation depths by multiplying the intensities from Step 5 by 4 for a 15-minute time-step.

Note the higher intensity portion of the candidate design storm (Figure 29) is muted relative to the shape of the dimensionless design hyetograph (Figure 28). This is a result of applying the areal reduction factors.

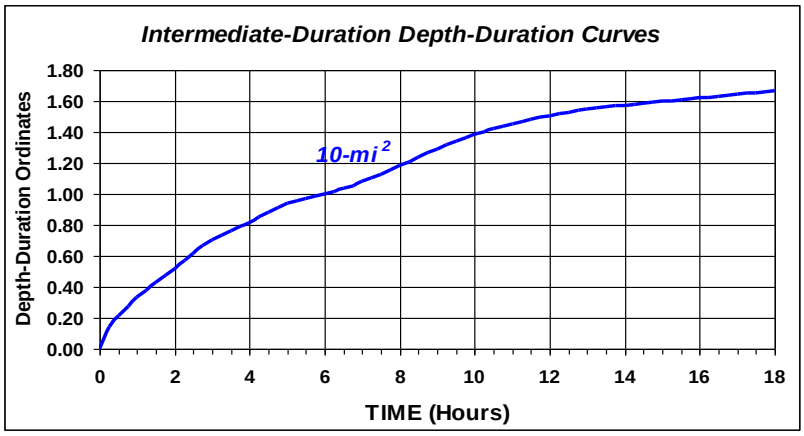



Figure 26 – Intermediate-Duration Dimensionless Depth-Duration Curve for Climatic Region 31

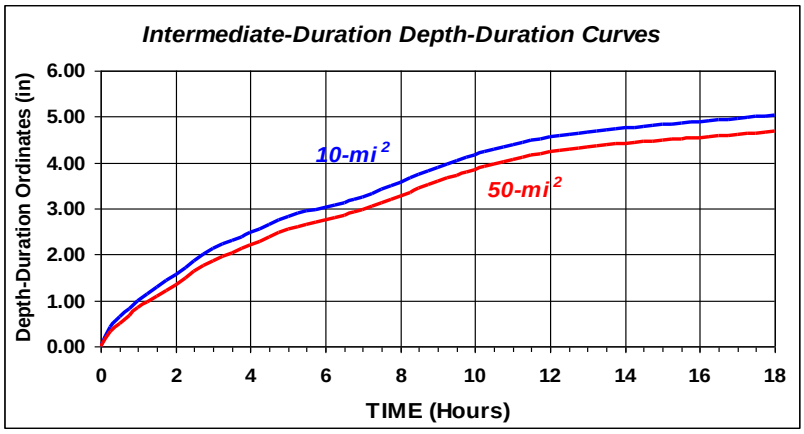



Figure 27 – Scaled Intermediate-Duration Depth-Duration Curves for Climatic Region 31 for Site near Seattle

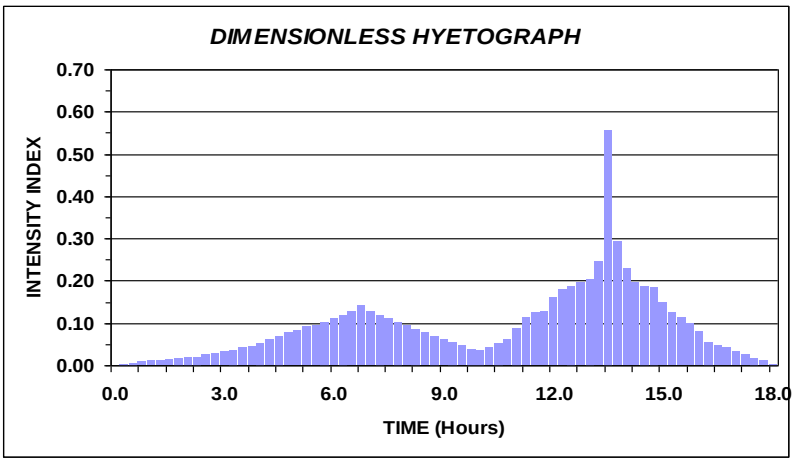



Figure 28 - Intermediate-Duration Dimensionless Design Hyetograph for Climatic Region 31

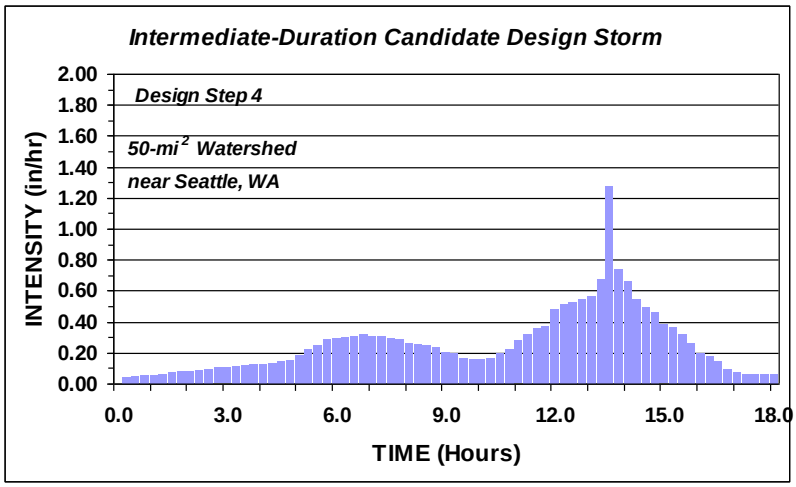



Figure 29 – Intermediate-Duration Candidate Design Storm for a 50-mi$^2$ Watershed near Seattle, Washington, in Climatic Region 31

# 5. REFERENCES


1. Bell FC, The Areal Reduction Factors in Rainfall-Frequency Estimation, Natural Environmental Research Council, (NERC), Report 35, Institute of Hydrology, Wallingford UK, 1976.
2. Chow VT, Handbook of Applied Hydrology, pp9.1-9.68, McGraw-Hill, 1964.
3. Cunnane C, Unbiased Plotting Positions - A Review, Journal of Hydrology, 37, 205-222, 1978.
4. Frederick RH, Miller JF, Richards FP and Schwerdt RW, Interduration Precipitation Relations for Storms - Western United States, Technical Report NWS 27, NOAA, Washington, DC, 1981.
5. Helsel DR and Hirsch RM, Statistical Methods in Water Resources, Elsevier Studies in Environmental Science 49, NY, 1992.
6. Hosking JRM, The Theory of Probability Weighted Moments, IBM Research Report RC12210, October 1986.
7. Hosking JRM, L-Moments: Analysis and Estimation of Distributions using Linear Combinations of Order Statistics, Journal Royal Statistical Society, Ser B, 52, pp105-124, 1990.
8. Hosking JRM, The Four Parameter KAPPA Distribution, IBM Research Report RC13412, IBM Research Yorktown Heights NY, 1988.
9. Hosking JRM, and Wallis JR, Some Statistics Useful in Regional Frequency Analysis, Water Resources Research, Vol 29, No. 2, pp271-281, Feb 1993.
10. Hosking JRM, and Wallis JR, Regional Frequency Analysis - An Approach Based on L-Moments, Cambridge Press, 1997.
11. Kuczera G, Combining Site Specific and Regional Information: An Empirical Bayes Approach, Water Resources Research, Vol 18, No. 2, pp306-314, April 1982.
12. Meyers VA, and Zehr RM, A Methodology for Point-to-Area Rainfall Frequency Ratios, NOAA Technical Report NWS 24, NOAA, US Department of Commerce, National Weather Service, Washington DC, 1980.
13. Miller JF, Frederick RH and Tracey RS, NOAA ATLAS 2, Precipitation - Frequency Atlas of the Western United States, Volume IX - Washington, US Dept. of Commerce, NOAA, National Weather Service, Washington, DC, 1973.
14. NWS, National Weather Service, Hydrometeorological Report 57, Probable Maximum Precipitation for the Pacific Northwest, US Department of Commerce, NOAA, National Weather Service, Washington, DC, 1994.

15. NWS, National Weather Service, Hydrometeorological Report 43, Probable Maximum Precipitation for the Pacific Northwest, US Department of Commerce, NOAA, US Weather Bureau, Washington, DC, 1966.

16. Potter KW, Research on Flood Frequency Analysis, 1983-1986, US National Report, International Union of Geodesy and Geophysics, 25(2), pp113-118, 1987.

17. Siriwardena L and Weinmann PE, Derivation of Areal Reduction Factors for Design Rainfalls in Victoria for Rainfall Durations 18-120 Hours, Cooperative Research Centre for Catchment Hydrology, Department of Civil Engineering Monash University, Victoria Australia, Report 96/4, October 1996.

18. Schaefer MG, Regional Analyses of Precipitation Annual Maxima in Washington State, Water Resources Research, Vol 26, No. 1, pp119-132, January 1990.

19. Schaefer MG, Characteristics of Extreme Precipitation Events in Washington State, Washington State Dept. of Ecology, Report 89-51, October 1989.

20. Schaefer MG, Barker BL, Taylor GH and Wallis JR, Regional Precipitation-Frequency Analysis and Spatial Mapping of Precipitation for 24-Hour and 2-Hour Durations in Western Washington, prepared for Washington State Department of Transportation, Report WA-RD 544.1, MGS Engineering Consultants, March 2002.

21. Schaefer MG, Barker BL, Taylor GH and Wallis JR, Regional Precipitation-Frequency Analysis and Spatial Mapping of Precipitation for 24-Hour and 2-Hour Durations in Eastern Washington, prepared for Washington State Department of Transportation, MGS Engineering Consultants, January 2006.

22. Schaefer MG, Analyses of Precipitation-Frequency and Storm Characteristics for the City of Seattle, prepared for Seattle Public Utilities, MGS Engineering Consultants, December 2003.

23. Stedinger JR, Vogel RM, and Foufoula-Georgiou E, Frequency Analysis of Extreme Events, Chapter 18, *Handbook of Hydrology*, McGraw Hill, 1992.

24. Technical Note 2, Selection of Design/Performance Goals for Critical Project Elements, Dam Safety Guidelines, Washington State Dept. of Ecology, Report 92-55F, July 1992.

25. U.S. National Research Council, Estimating Probabilities of Extreme Floods, Methods and Recommended Research, National Academy Press, Washington DC, 1988.

26. Wallis JR, Risk and Uncertainties in the Evaluation of Flood Events for the Design of Hydraulic Structures, in *Pienne e Siccita*, editted by E. Guggino, G. Rossi, and E. Todini, pp3-36, Fondazione Politecnica del Mediterranes, Catania, Italy, 1980.

# APPENDIX A
# CATALOG OF HISTORICAL STORMS

## OVERVIEW

Storm dates and locations listed in this catalog are associated with precipitation amounts that have exceeded a 20-year recurrence interval at a given location at one or more durations. Categorization of a storm as being a short-duration, intermediate duration or long-duration extreme storm is based on comparison of the precipitation maxima for the storm being most rare at the 2-hour, 6-hour or 24-hour duration, respectively. This is the same approach that was used in the original study of extreme storms entitled *Characteristics of Extreme Precipitation Events in Washington State* and completed in October 1989 (Ecology Publication 89-51). Data collection for that study ended in early 1986 and included storms recorded at automated precipitation gages that operated in the period from 1940-1986. Storms identified in the earlier study are listed in black in this catalog.

Records from precipitation gages in Washington State and border areas have been scanned to identify storms that have occurred since 1986 that have exceeded the 20-year recurrence interval criterion as discussed above. As in the original study, storms have been categorized as either short, intermediate or long-duration based on the precipitation maxima at the 2-hour, 6-hour and 24-hour durations respectively. These recent storms are listed in blue in this catalog.

Storms in the original study were grouped into orographic and non-orographic regions in both western and eastern Washington. These regions were defined based on NWS climatic zones in use at that time. Since the original study, regional precipitation-frequency analyses have been conducted for Washington State which included delineation of climatic regions. The complete collection of noteworthy storms from 1940-2007 have been regrouped in this catalog using the new climatic region delineations for Washington State (Figure 4).

Many of the most extreme storms listed in the catalog have been placed in Excel spreadsheets and configured to allow scaling of the storms into larger or smaller storm events. These storms are termed *scalable historical storms* and are particularly useful for examining the flood response of a reservoir and spillway system to the type of storm event that has occurred in the climatic region where a given project is located. Scaling of these storms is done in a manner similar to that for the dimensionless design hyetographs. Use of scalable historical storms provides another avenue to confirm the hydrologic adequacy of a spillway system using a suite of diverse storm characteristics.

Scalable historical storms are available through the Dam Safety Office.

Table 2 - Catalog of Short-Duration Extreme Storms for Region 5 - Coastal Lowlands

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2-HR | 6-HR |
| 45-8332 | Tatoosh Island WB | WA | 5 | 48.38 | -124.73 | 100 | 11/3/1941 | 1.41 | 1.89 |
| 45-8332 | Tatoosh Island WB | WA | 5 | 48.38 | -124.73 | 100 | 10/10/1942 | 1.53 | 2.32 |
| 45-9112 | Westport 2 S | WA | 5 | 46.87 | -124.10 | 20 | 10/30/1950 | 1.47 | 2.24 |
| 45-5488 | Moclips | WA | 5 | 47.22 | -124.20 | 120 | 1/2/1951 | 1.30 | 1.97 |
| 45-9112 | Westport 2 S | WA | 5 | 46.87 | -124.10 | 20 | 10/18/1979 | 1.20 | 1.65 |
| 35-0328 | Astoria AP Port | OR | 5 | 46.15 | -123.87 | 9 | 11/25/1998 | 1.84 | 2.49 |

Table 3 - Catalog of Short-Duration Extreme Storms for Regions 32 and 31
Interior Lowlands Western Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2-HR | 6-HR |
| 45-2675 | Everett | WA | 31 | 47.98 | -122.18 | 60 | 9/28/1944 | 1.01 | 1.52 |
| 45-5224 | Mc Millin Reservoir | WA | 31 | 47.13 | -122.27 | 579 | 7/8/1946 | 1.10 | 1.32 |
| 45-1277 | Centralia 1 W | WA | 31 | 46.70 | -122.97 | 185 | 10/28/1949 | 1.15 | 1.51 |
| 45-7470 | Seattle EMSU | WA | 31 | 47.68 | -122.25 | 60 | 6/29/1952 | 0.96 | 1.01 |
| 45-5224 | Mc Millin Reservoir | WA | 31 | 47.13 | -122.27 | 579 | 9/17/1957 | 1.07 | 1.21 |
| 45-2675 | Everett | WA | 31 | 47.98 | -122.18 | 60 | 5/31/1958 | 1.14 | 1.14 |
| 45-0324 | Auburn | WA | 31 | 47.32 | -122.23 | 79 | 6/8/1959 | 0.87 | 1.04 |
| 45-5224 | Mc Millin Reservoir | WA | 31 | 47.13 | -122.27 | 579 | 8/26/1960 | 1.70 | 2.04 |
| 35-3340 | Goble 3 SW | OR | 32 | 45.98 | -122.92 | 530 | 6/30/1963 | 0.87 | 1.05 |
| 45-4769 | Longview | WA | 31 | 46.15 | -122.92 | 12 | 8/23/1963 | 1.05 | 1.05 |
| 45-7773 | Snoqualmie Falls | WA | 31 | 47.53 | -121.83 | 440 | 9/19/1964 | 1.17 | 1.19 |
| 45-0986 | Burlington | WA | 31 | 48.47 | -122.32 | 30 | 8/12/1965 | 1.28 | 1.50 |
| 45-6678 | Port Townsend | WA | 32 | 48.10 | -122.75 | 100 | 9/10/1967 | 0.84 | 1.02 |
| 35-6751 | Portland Intl Airport | OR | 32 | 45.58 | -122.60 | 19 | 1/11/1970 | 1.15 | 1.41 |
| 45-2675 | Everett | WA | 31 | 47.98 | -122.18 | 60 | 9/22/1972 | 0.99 | 1.13 |
| 45-1191 | Castle Rock 2 NW | WA | 31 | 46.27 | -122.92 | 39 | 9/20/1973 | 1.46 | 2.35 |
| 45-1277 | Centralia 1 W | WA | 31 | 46.70 | -122.97 | 185 | 7/8/1974 | 1.20 | 1.50 |
| 45-7470 | Seattle EMSU | WA | 31 | 47.68 | -122.25 | 60 | 8/26/1977 | 1.64 | 1.66 |
| 45-1146 | Carnation 4 NW | WA | 31 | 47.68 | -121.98 | 50 | 9/20/1977 | 1.20 | 1.30 |
| 45-4486 | Landsburg | WA | 31 | 47.38 | -121.98 | 535 | 7/9/1980 | 0.90 | 1.00 |
| 45-7473 | Sea-Tac Airport | WA | 31 | 47.45 | -122.30 | 400 | 10/6/1981 | 0.85 | 1.21 |
| 45-1146 | Carnation 4 NW | WA | 31 | 47.68 | -121.98 | 50 | 6/18/1986 | 1.00 | 1.30 |
| 45-1146 | Carnation 4 NW | WA | 31 | 47.68 | -121.98 | 50 | 9/19/1988 | 1.10 | 1.40 |
| 45-0729 | Blaine | WA | 31 | 49.00 | -122.75 | 60 | 8/15/1989 | 1.40 | 2.00 |
| | Seattle SPU RG08 | WA | 31 | | | | 9/23/1992 | 1.02 | 1.02 |
| | King County East Pine PS | WA | 31 | | | | 8/22/2004 | 1.84 | 2.50 |
| | Seattle SPU RG16 | WA | 31 | | | | 5/31/2005 | 0.92 | 0.95 |
| | Seattle SPU RG10 | WA | 31 | | | | 6/1/2005 | 1.15 | 1.28 |
| | Seattle SPU RG02 | WA | 31 | | | | 5/27/2006 | 1.09 | 1.12 |
| | Seattle SPU RG20 | WA | 31 | | | | 12/14/2006 | 1.10 | 1.13 |

Table 4 - Catalog of Short-Duration Extreme Storms for Regions 15, 151 and 142
Mountain Areas in Western Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2-HR | 6-HR |
| 45-5704 | Mud Mountain Dam | WA | 15 | 47.15 | -121.93 | 1308 | 6/10/1942 | 0.99 | 1.08 |
| 45-5704 | Mud Mountain Dam | WA | 15 | 47.15 | -121.93 | 1308 | 9/1/1943 | 0.99 | 1.11 |
| 45-1759 | Cougar 4 SW | WA | 15 | 46.02 | -122.35 | 520 | 9/21/1944 | 1.49 | 1.98 |
| 45-7709 | Skykomish 1 ENE | WA | 15 | 47.70 | -121.37 | 1030 | 5/25/1945 | 1.78 | 1.78 |
| 45-6295 | Palmer 3 ESE | WA | 15 | 47.30 | -121.85 | 920 | 5/27/1948 | 1.20 | 1.45 |
| 45-5663 | Mount Baker Lodge | WA | 15 | 48.87 | -121.67 | 4150 | 6/16/1949 | 1.53 | 1.53 |
| 45-1457 | Cinebar 2 E | WA | 15 | 46.60 | -122.48 | 1040 | 6/9/1953 | 1.51 | 1.90 |
| 45-6909 | Randle 1 E | WA | 15 | 46.53 | -121.93 | 900 | 8/28/1957 | 1.40 | 1.44 |
| 45-7657 | Silverton | WA | 15 | 48.07 | -121.57 | 1475 | 9/10/1967 | 1.40 | 2.10 |
| 35-0897 | Bonneville Dam | OR | 15 | 45.63 | -121.95 | 62 | 11/20/1970 | 1.40 | 1.45 |
| 45-6385 | White River RS | WA | 15 | 46.92 | -121.53 | 3553 | 5/10/1975 | 1.20 | 1.30 |
| 45-1233 | Cedar Lake | WA | 15 | 47.42 | -121.73 | 1560 | 9/20/1977 | 1.40 | 2.00 |
| 45-6909 | Randle 1 E | WA | 15 | 46.53 | -121.93 | 900 | 6/28/1978 | 1.30 | 1.30 |
| 45-5704 | Mud Mountain Dam | WA | 15 | 47.15 | -121.93 | 1308 | 7/9/1979 | 1.11 | 1.28 |
| 45-7657 | Silverton | WA | 15 | 48.07 | -121.57 | 1475 | 9/30/1980 | 1.80 | 2.00 |
| 45-6851 | Quilcene Dam 5 SW | WA | 142 | 47.78 | -122.98 | 1028 | 11/29/1980 | 1.40 | 1.69 |
| 45-0013 | Aberdeen 20 NNE | WA | 151 | 47.27 | -123.70 | 435 | 5/28/1982 | 2.50 | 2.50 |
| 45-5876 | Nooksack Salmon Hatchery | WA | 15 | 48.90 | -122.15 | 410 | 10/20/1992 | 1.80 | 2.30 |
| 45-1233 | Cedar Lake | WA | 15 | 47.42 | -121.73 | 1560 | 6/22/1993 | 1.40 | 1.50 |

Table 5 - Catalog of Short-Duration Extreme Storms for Region 14
East Face of Cascade Mountains

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2-HR | 6-HR |
| 45-1257 | Centerville 2 SW | WA | 14 | 45.73 | -120.95 | 1650 | 6/7/1947 | 0.80 | 0.80 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 1/17/1971 | 0.90 | 0.97 |
| 35-4003 | Hood River Exp Stn | OR | 14 | 45.68 | -121.52 | 500 | 5/20/1972 | 1.00 | 1.30 |
| 45-5659 | Mount Adams RS | WA | 14 | 46.00 | -121.53 | 1960 | 1/12/1980 | 1.30 | 1.70 |
| 45-1160 | Carson Fish Hatchery | WA | 14 | 45.87 | -121.97 | 1134 | 1/12/1980 | 1.40 | 2.00 |
| 45-2384 | Easton | WA | 14 | 47.23 | -121.18 | 2170 | 8/26/1983 | 1.80 | 1.90 |
| 45-4446 | Lake Wenatchee | WA | 14 | 47.83 | -120.78 | 2005 | 2/11/1985 | 1.10 | 1.30 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 7/16/1985 | 1.10 | 1.10 |
| 45-6472 | Peshastin Telemetering | WA | 14 | 47.57 | -120.62 | 1028 | 8/6/1991 | 0.90 | 1.00 |
| 45-2157 | Diablo Dam | WA | 14 | 48.72 | -121.15 | 891 | 7/20/1992 | 1.10 | 1.40 |
| 35-4003 | Hood River Exp Stn | OR | 14 | 45.68 | -121.52 | 500 | 9/18/1998 | 1.60 | 2.40 |
| 45-2384 | Easton | WA | 14 | 47.23 | -121.18 | 2170 | 9/9/2000 | 0.90 | 1.40 |
| 35-0571 | Bear Springs RS | OR | 14 | 45.12 | -121.53 | 3360 | 9/14/2001 | 1.00 | 1.10 |
| 45-3183 | Glenwood | WA | 14 | 46.02 | -121.28 | 1896 | 5/23/2006 | 0.90 | 1.00 |

Table 6 - Catalog of Short-Duration Extreme Storms for Transition Zone 147
Cascade Foothills in Eastern Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2-HR | 6-HR |
| 45-2505 | Ellensburg | WA | 147 | 46.97 | -120.53 | 1480 | 5/12/1943 | 0.62 | 0.74 |
| 45-9465 | Yakima Airport | WA | 147 | 46.57 | -120.53 | 1064 | 6/19/1944 | 0.90 | 0.91 |
| 45-6187 | Oroville 1 S | WA | 147 | 48.93 | -119.43 | 932 | 6/16/1947 | 1.25 | 1.25 |
| 45-5327 | Methow 2S | WA | 147 | 48.13 | -120.02 | 1165 | 8/10/1948 | 1.08 | 1.08 |
| 45-5327 | Methow 2S | WA | 147 | 48.13 | -120.02 | 1165 | 6/17/1950 | 0.89 | 0.89 |
| 45-9082 | Wenatchee AP | WA | 147 | 47.38 | -120.20 | 1229 | 8/10/1952 | 1.29 | 1.29 |
| 45-9082 | Wenatchee AP | WA | 147 | 47.38 | -120.20 | 1229 | 8/25/1956 | 1.38 | 1.73 |
| 45-5731 | Naches 10 NW | WA | 147 | 46.87 | -120.77 | 2280 | 5/5/1957 | 0.90 | 0.90 |
| 45-5327 | Methow 2S | WA | 147 | 48.13 | -120.02 | 1165 | 7/8/1958 | 1.33 | 1.33 |
| 45-9082 | Wenatchee AP | WA | 147 | 47.38 | -120.20 | 1229 | 8/23/1965 | 0.96 | 1.19 |
| 45-9082 | Wenatchee AP | WA | 147 | 47.38 | -120.20 | 1229 | 6/9/1972 | 1.05 | 1.45 |
| 35-5734 | Moro | OR | 147 | 45.47 | -120.72 | 1870 | 6/9/1972 | 0.90 | 0.90 |
| 45-9465 | Yakima Airport | WA | 147 | 46.57 | -120.53 | 1064 | 8/18/1975 | 0.98 | 1.39 |
| 35-5734 | Moro | OR | 147 | 45.47 | -120.72 | 1870 | 9/27/1981 | 0.80 | 0.80 |
| 45-5731 | Naches 10 NW | WA | 147 | 46.87 | -120.77 | 2280 | 7/7/1982 | 1.20 | 1.20 |
| 45-5731 | Naches 10 NW | WA | 147 | 46.87 | -120.77 | 2280 | 8/1/1984 | 0.80 | 0.80 |
| 35-0265 | Arlington | OR | 147 | 45.72 | -120.20 | 277 | 4/29/1992 | 0.80 | 0.80 |
| 45-2505 | Ellensburg | WA | 147 | 46.97 | -120.53 | 1480 | 7/3/1998 | 0.90 | 0.90 |

Table 7 - Catalog of Short-Duration Extreme Storms for Regions 77 and 7
Central Basin and Lowland Areas in Eastern Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2-HR | 6-HR |
| 45-6982 | Republic RS | WA | 7 | 48.63 | -118.73 | 2630 | 8/23/1941 | 1.43 | 1.54 |
| 45-9397 | Withrow | WA | 77 | 47.72 | -119.82 | 2533 | 6/13/1944 | 1.06 | 1.11 |
| 45-2030 | Dayton 1 WSW | WA | 7 | 46.30 | -118.00 | 1557 | 7/8/1946 | 0.79 | 0.83 |
| 45-8207 | Sunnyside | WA | 77 | 46.32 | -120.00 | 747 | 6/7/1947 | 1.62 | 1.83 |
| 45-3515 | Harrington 1 NW | WA | 77 | 47.48 | -118.25 | 2190 | 6/10/1948 | 1.03 | 1.13 |
| 45-9327 | Wilson Creek | WA | 77 | 47.42 | -119.12 | 1280 | 6/18/1950 | 1.50 | 1.55 |
| 45-6789 | Pullman 2 NW | WA | 7 | 46.75 | -117.18 | 2545 | 8/10/1952 | 1.77 | 2.39 |
| 45-9327 | Wilson Creek | WA | 77 | 47.42 | -119.12 | 1280 | 7/24/1955 | 0.80 | 0.94 |
| 45-8931 | Walla Walla WSO | WA | 7 | 46.03 | -118.33 | 949 | 5/8/1957 | 1.15 | 1.15 |
| 45-3883 | Ice Harbor Dam | WA | 77 | 46.23 | -118.87 | 368 | 6/5/1957 | 1.67 | 1.67 |
| 45-8931 | Walla Walla WSO | WA | 7 | 46.03 | -118.33 | 949 | 5/24/1958 | 1.60 | 1.62 |
| 45-1400 | Chief Joseph Dam | WA | 77 | 47.98 | -119.65 | 820 | 6/7/1958 | 0.71 | 0.71 |
| 45-6982 | Republic RS | WA | 7 | 48.63 | -118.73 | 2630 | 7/5/1958 | 1.10 | 1.20 |
| 10-7188 | Plummer 3 WSW | ID | 7 | 47.30 | -116.95 | 2920 | 7/7/1958 | 0.87 | 1.03 |
| 45-1767 | Coulee Dam 1 SW | WA | 77 | 47.95 | -119.00 | 1700 | 4/29/1961 | 0.85 | 0.93 |
| 45-6982 | Republic RS | WA | 7 | 48.63 | -118.73 | 2630 | 8/9/1962 | 1.26 | 1.26 |
| 45-6789 | Pullman 2 NW | WA | 7 | 46.75 | -117.18 | 2545 | 6/16/1963 | 1.47 | 1.47 |
| 45-6610 | Pomeroy | WA | 7 | 46.47 | -124.58 | 1900 | 9/13/1966 | 1.12 | 1.12 |
| 45-9397 | Withrow | WA | 77 | 47.72 | -119.82 | 2533 | 8/14/1968 | 0.94 | 1.18 |
| 45-9397 | Withrow | WA | 77 | 47.72 | -119.82 | 2533 | 12/11/1969 | 0.93 | 0.94 |
| 45-8931 | Walla Walla WSO | WA | 7 | 46.03 | -118.33 | 949 | 5/26/1971 | 1.75 | 1.82 |
| 35-8726 | Ukiah | OR | 7 | 45.13 | -118.93 | 3400 | 7/9/1975 | 2.10 | 2.10 |
| 45-7938 | Spokane Intl AP | WA | 7 | 47.62 | -117.52 | 2353 | 6/7/1977 | 0.96 | 1.10 |
| 45-9200 | Whitman Mission | WA | 7 | 46.03 | -118.45 | 632 | 8/5/1977 | 0.94 | 0.96 |
| 45-2030 | Dayton 1 WSW | WA | 7 | 46.30 | -118.00 | 1557 | 7/7/1978 | 1.20 | 1.20 |
| 45-3515 | Harrington 1 NW | WA | 77 | 47.48 | -118.25 | 2190 | 6/1/1982 | 1.00 | 1.00 |
| 45-6982 | Republic RS | WA | 7 | 48.63 | -118.73 | 2630 | 7/1/1982 | 1.10 | 1.10 |
| 45-8207 | Sunnyside | WA | 77 | 46.32 | -120.00 | 747 | 9/15/1986 | 1.15 | 1.25 |
| 45-1400 | Chief Joseph Dam | WA | 77 | 47.98 | -119.65 | 820 | 7/25/1987 | 1.00 | 1.00 |
| 45-4679 | Lind 3 NE | WA | 77 | 46.98 | -118.57 | 1630 | 8/20/1990 | 0.80 | 0.90 |
| 45-9200 | Whitman Mission | WA | 7 | 46.03 | -118.45 | 632 | 7/22/1992 | 0.80 | 0.90 |
| 45-1400 | Chief Joseph Dam | WA | 77 | 47.98 | -119.65 | 820 | 7/9/1993 | 1.10 | 1.10 |
| 35-1765 | Condon | OR | 7 | 45.22 | -120.17 | 2840 | 7/13/1993 | 1.70 | 2.00 |
| 35-3827 | Heppner | OR | 7 | 45.35 | -119.55 | 1885 | 7/19/1993 | 1.20 | 1.20 |
| 45-4679 | Lind 3 NE | WA | 77 | 46.98 | -118.57 | 1630 | 7/22/1993 | 1.40 | 1.40 |
| 35-1765 | Condon | OR | 7 | 45.22 | -120.17 | 2840 | 7/27/1998 | 1.20 | 1.40 |
| 35-9213 | Weston | OR | 7 | 45.82 | -118.42 | 1922 | 10/8/2000 | 0.70 | 0.70 |
| 45-8348 | Tekoa | WA | 7 | 47.22 | -117.08 | 2495 | 6/27/2001 | 0.80 | 0.80 |
| 10-7269 | Porthill 1 SW | ID | 7 | 48.98 | -116.50 | 1700 | 7/8/2002 | 0.80 | 1.10 |

Table 8 - Catalog of Short-Duration Extreme Storms for Region 13
Mountain Areas in Eastern Washington Eastward of Cascade Mountains

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2-HR | 6-HR |
| 45-1630 | Colville | WA | 13 | 48.53 | -117.90 | 1657 | 7/19/1950 | 1.00 | 1.00 |
| 45-1630 | Colville | WA | 13 | 48.53 | -117.90 | 1657 | 7/6/1956 | 0.82 | 0.88 |
| 45-0849 | Boundary Switchyard | WA | 13 | 48.97 | -117.35 | 2500 | 9/10/1962 | 0.99 | 1.17 |
| 45-0849 | Boundary Switchyard | WA | 13 | 48.97 | -117.35 | 2500 | 5/21/1981 | 1.10 | 1.20 |
| 45-1395 | Chewelah | WA | 13 | 48.27 | -117.72 | 1670 | 7/20/1983 | 1.00 | 1.00 |
| 45-5946 | Northport | WA | 13 | 48.90 | -117.78 | 1350 | 5/27/1987 | 1.00 | 1.10 |
| 10-1079 | Bonners Ferry | ID | 13 | 48.68 | -116.32 | 1770 | 6/15/1987 | 0.90 | 1.00 |
| 10-2845 | Dworshak Fish Hatchery | ID | 13 | 46.50 | -116.32 | 995 | 5/27/1989 | 0.80 | 0.90 |
| 45-1630 | Colville | WA | 13 | 48.53 | -117.90 | 1657 | 8/9/1989 | 1.30 | 1.50 |
| 35-8985 | Walla Walla 13 ESE | OR | 13 | 45.98 | -118.05 | 2400 | 6/6/1991 | 1.70 | 2.30 |
| 35-6636 | Pilot Rock 11 E | OR | 13 | 45.50 | -118.60 | 1920 | 8/14/1991 | 1.40 | 1.40 |
| 10-1956 | Coeur D'Alene | ID | 13 | 47.67 | -116.80 | 2133 | 6/30/1998 | 0.90 | 1.00 |
| 45-5946 | Northport | WA | 13 | 48.90 | -117.78 | 1350 | 7/11/1998 | 1.10 | 1.20 |
| 45-1630 | Colville | WA | 13 | 48.53 | -117.90 | 1657 | 8/18/2004 | 1.90 | 1.90 |

Table 9 - Catalog of Intermediate-Duration Extreme Storms for Region 5
Coastal Lowlands

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 6-HR | 18-HR |
| 45-1496 | Clearwater | WA | 5 | 47.58 | -124.30 | 80 | 11/23/1948 | 3.40 | 4.70 |
| 45-5488 | Moclips | WA | 5 | 47.22 | -124.20 | 120 | 12/11/1953 | 2.47 | 3.49 |
| 45-5549 | Montesano 3 NW | WA | 5 | 46.97 | -123.62 | 25 | 12/21/1961 | 2.46 | 3.37 |
| 45-6584 | Point Grenville | WA | 5 | 47.30 | -124.28 | 100 | 10/29/1967 | 2.98 | 4.38 |
| 45-6858 | Quillayute AP | WA | 5 | 47.93 | -124.55 | 179 | 1/25/1971 | 3.21 | 6.10 |
| 45-3333 | Grays River Hatchery | WA | 5 | 46.38 | -123.57 | 100 | 11/6/1980 | 3.20 | 4.50 |
| 45-9112 | Westport 2 S | WA | 5 | 46.87 | -124.10 | 20 | 7/1/1983 | 2.20 | 2.60 |
| 45-3333 | Grays River Hatchery | WA | 5 | 46.38 | -123.57 | 100 | 10/26/1985 | 3.10 | 4.90 |
| 45-9112 | Westport 2 S | WA | 5 | 46.87 | -124.10 | 20 | 12/4/1990 | 2.20 | 2.90 |
| 45-6858 | Quillayute AP | WA | 5 | 47.93 | -124.55 | 179 | 8/9/1995 | 2.87 | 4.13 |
| 35-0328 | Astoria AP Port | OR | 5 | 46.15 | -123.87 | 9 | 11/25/1998 | 2.49 | 4.72 |
| 45-6858 | Quillayute AP | WA | 5 | 47.93 | -124.55 | 179 | 11/28/2003 | 3.71 | 6.08 |

Table 10 - Catalog of Intermediate-Duration Extreme Storms for Regions 32 and 31
Interior Lowlands Western Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 6-HR | 18-HR |
| 45-7473 | Sea-Tac (WSO) | WA | 31 | 47.45 | -122.30 | 400 | 1/19/1943 | 1.60 | 2.49 |
| 45-6678 | Port Townsend | WA | 32 | 48.10 | -122.75 | 100 | 6/14/1946 | 1.35 | 2.21 |
| 45-7473 | Sea-Tac (WSO) | WA | 31 | 47.45 | -122.30 | 400 | 2/16/1949 | 1.50 | 1.69 |
| 45-6114 | Olympia AP | WA | 32 | 46.97 | -122.90 | 206 | 12/9/1956 | 2.13 | 3.35 |
| 45-9485 | Yelm | WA | 31 | 46.95 | -122.60 | 351 | 11/20/1959 | 1.44 | 2.58 |
| 45-2675 | Everett | WA | 31 | 47.98 | -122.18 | 60 | 10/23/1960 | 1.39 | 1.52 |
| 45-7773 | Snoqualmie Falls | WA | 31 | 47.53 | -121.83 | 440 | 10/21/1963 | 2.08 | 2.48 |
| 45-1146 | Carnation 4 NW | WA | 31 | 47.68 | -121.98 | 50 | 12/3/1968 | 1.57 | 1.95 |
| 45-4486 | Landsburg | WA | 31 | 47.38 | -121.98 | 535 | 6/23/1969 | 1.64 | 2.09 |
| 35-6751 | Portland Intl Airport | OR | 32 | 45.58 | -122.60 | 19 | 9/17/1969 | 1.91 | 2.38 |
| 45-0729 | Blaine 1 ENE | WA | 31 | 49.00 | -122.75 | 60 | 11/3/1971 | 1.60 | 3.43 |
| 45-9485 | Yelm | WA | 31 | 46.95 | -122.60 | 351 | 12/21/1972 | 1.43 | 1.78 |
| 45-6624 | Port Angeles | WA | 32 | 48.10 | -123.42 | 90 | 11/3/1978 | 1.92 | 2.55 |
| 45-7773 | Snoqualmie Falls | WA | 31 | 47.53 | -121.83 | 440 | 1/23/1982 | 2.00 | 2.90 |
| 45-7470 | Seattle EMSU | WA | 31 | 47.68 | -122.25 | 60 | 12/3/1982 | 1.56 | 2.53 |
| 45-5224 | Mc Millin Reservoir | WA | 31 | 47.13 | -122.27 | 579 | 8/29/1983 | 1.90 | 2.00 |
| 45-0729 | Blaine 1 ENE | WA | 31 | 49.00 | -122.75 | 60 | 12/29/1983 | 1.70 | 3.10 |
| 45-0729 | Blaine 1 ENE | WA | 31 | 49.00 | -122.75 | 60 | 2/15/1986 | 2.00 | 2.80 |
| 45-5224 | Mc Millin Reservoir | WA | 31 | 47.13 | -122.27 | 579 | 2/19/1991 | 1.60 | 2.50 |
| 45-0729 | Blaine 1 ENE | WA | 31 | 49.00 | -122.75 | 60 | 11/11/1995 | 1.60 | 1.70 |
| 35-6751 | Portland Intl Airport | OR | 32 | 45.58 | -122.60 | 19 | 9/15/1996 | 1.56 | 2.04 |
| 35-2348 | Dixie Mountain | OR | 32 | 45.68 | -122.92 | 1430 | 10/30/1997 | 2.10 | 2.80 |
| 45-1277 | Centralia 1 W | WA | 31 | 46.70 | -122.97 | 185 | 11/14/2001 | 2.30 | 4.40 |
| 45-2675 | Everett | WA | 31 | 47.98 | -122.18 | 60 | 11/19/2003 | 1.40 | 2.10 |
| | Seattle RG12 | WA | 31 | | | | 12/3/2007 | 2.38 | 5.26 |

Table 11 - Catalog of Intermediate-Duration Extreme Storms for Regions 15, 151 and 142 Mountain Areas in Western Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 6-HR | 18-HR |
| 45-7781 | Snoqualmie Pass | WA | 15 | 47.42 | -121.40 | 3020 | 12/4/1941 | 2.74 | 3.73 |
| 45-7919 | Spirit Lake RS | WA | 15 | 46.27 | -122.15 | 3240 | 10/24/1943 | 3.12 | 5.46 |
| 45-4999 | Marblemount RS | WA | 15 | 48.53 | -121.45 | 348 | 1/7/1945 | 2.04 | 4.12 |
| 45-7657 | Silverton | WA | 15 | 48.07 | -121.57 | 1475 | 2/7/1945 | 2.84 | 4.52 |
| 45-7781 | Snoqualmie Pass | WA | 15 | 47.42 | -121.40 | 3020 | 10/24/1945 | 3.87 | 6.00 |
| 45-7319 | Sappho 8 E | WA | 151 | 48.07 | -124.12 | 760 | 2/1/1947 | 3.32 | 4.28 |
| 35-0897 | Bonneville Dam | OR | 15 | 45.63 | -121.95 | 62 | 10/19/1947 | 3.60 | 4.79 |
| 45-6851 | Quilcene Dam 5 SW | WA | 142 | 47.78 | -122.98 | 1028 | 12/1/1948 | 2.55 | 3.95 |
| 45-1992 | Darrington RS | WA | 15 | 48.25 | -121.60 | 550 | 9/27/1953 | 2.20 | 3.32 |
| 45-4634 | Lester | WA | 15 | 47.20 | -121.48 | 1630 | 12/9/1953 | 2.15 | 3.53 |
| 45-6851 | Quilcene Dam 5 SW | WA | 142 | 47.78 | -122.98 | 1028 | 2/7/1955 | 2.64 | 3.93 |
| 45-0013 | Aberdeen 20 NNE | WA | 151 | 47.27 | -123.70 | 435 | 11/2/1955 | 3.47 | 7.14 |
| 45-7657 | Silverton | WA | 15 | 48.07 | -121.57 | 1475 | 12/9/1956 | 3.30 | 5.31 |
| 45-6295 | Palmer 3 ESE | WA | 15 | 47.30 | -121.85 | 920 | 9/26/1959 | 2.69 | 3.85 |
| 45-1064 | Camp Grisdale | WA | 151 | 47.37 | -123.60 | 820 | 11/19/1959 | 4.14 | 7.62 |
| 45-8009 | Stampede Pass | WA | 15 | 47.28 | -121.33 | 3958 | 11/22/1959 | 2.94 | 6.26 |
| 45-8009 | Stampede Pass | WA | 15 | 47.28 | -121.33 | 3958 | 11/21/1961 | 2.56 | 4.71 |
| 45-2984 | Frances | WA | 142 | 46.55 | -123.50 | 231 | 11/25/1962 | 2.72 | 4.40 |
| 45-6385 | White River RS | WA | 15 | 46.92 | -121.53 | 3553 | 11/9/1973 | 2.00 | 3.70 |
| 45-5704 | Mud Mountain Dam | WA | 15 | 47.15 | -121.93 | 1308 | 8/18/1975 | 2.13 | 3.41 |
| 45-7781 | Snoqualmie Pass | WA | 15 | 47.42 | -121.40 | 3020 | 12/1/1975 | 2.90 | 4.90 |
| 45-0013 | Aberdeen 20 NNE | WA | 151 | 47.27 | -123.70 | 435 | 12/26/1975 | 3.30 | 5.40 |
| 45-3357 | Greenwater | WA | 15 | 47.13 | -121.63 | 1730 | 12/2/1977 | 2.70 | 4.00 |
| 45-6864 | Quinault RS | WA | 151 | 47.47 | -123.85 | 220 | 2/15/1981 | 4.00 | 7.10 |
| 45-2984 | Frances | WA | 142 | 46.55 | -123.50 | 231 | 12/15/1982 | 2.90 | 4.20 |
| 45-6295 | Palmer 3 ESE | WA | 15 | 47.30 | -121.85 | 920 | 11/3/1983 | 2.40 | 3.60 |
| 45-3357 | Greenwater | WA | 15 | 47.13 | -121.63 | 1730 | 1/3/1984 | 2.10 | 2.80 |
| 45-1233 | Cedar Lake | WA | 15 | 47.42 | -121.73 | 1560 | 1/24/1984 | 2.40 | 4.10 |
| 45-1934 | Cushman Dam | WA | 142 | 47.42 | -123.22 | 760 | 1/18/1986 | 4.30 | 8.00 |
| 45-6864 | Quinault RS | WA | 151 | 47.47 | -123.85 | 220 | 11/23/1986 | 5.00 | 9.10 |
| 35-3770 | Headworks Portland Water | OR | 15 | 45.45 | -122.15 | 748 | 4/25/1989 | 2.60 | 3.30 |
| 45-7781 | Snoqualmie Pass | WA | 15 | 47.42 | -121.40 | 3020 | 11/9/1989 | 2.90 | 6.04 |
| 45-6909 | Randle 1 E | WA | 15 | 46.53 | -121.93 | 900 | 2/19/1991 | 1.80 | 2.80 |
| 45-6851 | Quilcene Dam 5 SW | WA | 142 | 47.78 | -122.98 | 1028 | 12/10/1993 | 2.70 | 5.10 |
| 45-1759 | Cougar 4 SW | WA | 15 | 46.02 | -122.35 | 520 | 10/31/1994 | 2.80 | 5.60 |
| 45-0013 | Aberdeen 20 NNE | WA | 151 | 47.27 | -123.70 | 435 | 10/31/1994 | 3.40 | 4.20 |
| 45-8715 | Upper Baker Dam | WA | 15 | 48.65 | -121.68 | 690 | 2/21/2002 | 3.30 | 5.90 |
| 45-1233 | Cedar Lake | WA | 15 | 47.42 | -121.73 | 1560 | 9/8/2003 | 2.60 | 3.10 |
| 45-5876 | Nooksack Salmon Hatchery | WA | 15 | 48.90 | -122.15 | 410 | 11/24/2004 | 2.60 | 5.80 |
| 35-0897 | Bonneville Dam | OR | 15 | 45.63 | -121.95 | 62 | 12/14/2006 | 2.30 | 3.30 |

Table 12 - Catalog of Intermediate-Duration Extreme Storms for Region 14
East Face of Cascade Mountains

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 6-HR | 18-HR |
| 45-2384 | Easton | WA | 14 | 47.23 | -121.18 | 2170 | 10/31/1942 | 2.13 | 4.39 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 7/6/1955 | 1.83 | 1.92 |
| 45-2157 | Diablo Dam | WA | 14 | 48.72 | -121.15 | 891 | 12/8/1971 | 2.50 | 3.70 |
| 45-4849 | Lucerne 2 NNW | WA | 14 | 48.23 | -120.60 | 1200 | 12/8/1971 | 1.45 | 2.23 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 1/11/1972 | 2.20 | 2.99 |
| 45-4446 | Lake Wenatchee | WA | 14 | 47.83 | -120.78 | 2005 | 1/17/1975 | 2.10 | 2.50 |
| 45-8059 | Stehekin 4 NW | WA | 14 | 48.35 | -120.72 | 1270 | 11/26/1977 | 2.60 | 5.74 |
| 45-3183 | Glenwood | WA | 14 | 46.02 | -121.28 | 1896 | 12/1/1977 | 1.65 | 2.48 |
| 45-6472 | Peshastin Telemetering | WA | 14 | 47.57 | -120.62 | 1028 | 2/6/1979 | 1.60 | 2.61 |
| 45-7342 | Satus Pass 2 SSW | WA | 14 | 45.95 | -120.67 | 2610 | 1/12/1980 | 2.10 | 2.90 |
| 45-4849 | Lucerne 2 NNW | WA | 14 | 48.23 | -120.60 | 1200 | 1/23/1982 | 1.58 | 2.46 |
| 45-5659 | Mount Adams RS | WA | 14 | 46.00 | -121.53 | 1960 | 2/20/1982 | 2.00 | 3.37 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 12/3/1982 | 2.10 | 3.30 |
| 45-3183 | Glenwood | WA | 14 | 46.02 | -121.28 | 1896 | 11/2/1988 | 1.40 | 1.98 |
| 45-2384 | Easton | WA | 14 | 47.23 | -121.18 | 2170 | 10/31/1994 | 2.10 | 3.86 |
| 45-8059 | Stehekin 4 NW | WA | 14 | 48.35 | -120.72 | 1270 | 12/29/1996 | 2.40 | 2.48 |
| 45-7342 | Satus Pass 2 SSW | WA | 14 | 45.95 | -120.67 | 2610 | 10/30/1997 | 1.70 | 2.08 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 10/20/2003 | 1.50 | 3.37 |
| 35-0571 | Bear Springs RS | OR | 14 | 45.12 | -121.53 | 3360 | 12/21/2005 | 1.60 | 2.48 |

Table 13 - Catalog of Intermediate-Duration Extreme Storms for Transition Zone 147
Cascade Foothills in Eastern Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 6-HR | 18-HR |
| 35-0265 | Arlington | OR | 147 | 45.72 | -120.20 | 277 | 1/8/1953 | 1.02 | 1.42 |
| 45-9082 | Wenatchee AP | WA | 147 | 47.38 | -120.20 | 1229 | 10/31/1973 | 1.49 | 1.68 |
| 45-9082 | Wenatchee AP | WA | 147 | 47.38 | -120.20 | 1229 | 8/18/1975 | 1.38 | 2.04 |
| 45-5731 | Naches 10 NW | WA | 147 | 46.87 | -120.77 | 2280 | 1/23/1982 | 1.00 | 1.60 |
| 45-5731 | Naches 10 NW | WA | 147 | 46.87 | -120.77 | 2280 | 12/9/1987 | 1.30 | 2.40 |
| 35-0265 | Arlington | OR | 147 | 45.72 | -120.20 | 277 | 12/27/1998 | 1.00 | 1.40 |

Table 14 - Catalog of Intermediate-Duration Extreme Storms for Regions 77 and 7
Central Basin and Lowland Areas in Eastern Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 6-HR | 18-HR |
| 10-7188 | Plummer 3 WSW | ID | 7 | 47.30 | -116.95 | 2920 | 6/6/1947 | 1.46 | 1.67 |
| 45-9327 | Wilson Creek | WA | 77 | 47.42 | -119.12 | 1280 | 6/16/1948 | 1.06 | 1.19 |
| 45-5231 | McNary Dam | WA | 77 | 45.93 | -119.28 | 361 | 10/1/1957 | 1.86 | 3.00 |
| 10-7188 | Plummer 3 WSW | ID | 7 | 47.30 | -116.95 | 2920 | 6/17/1965 | 1.42 | 2.40 |
| 45-1400 | Chief Joseph Dam | WA | 77 | 47.98 | -119.65 | 820 | 8/23/1965 | 1.02 | 1.36 |
| 45-1767 | Coulee Dam | WA | 77 | 47.95 | -119.00 | 1700 | 11/12/1973 | 1.19 | 1.34 |
| 45-8348 | Tekoa | WA | 7 | 47.22 | -117.08 | 2495 | 7/4/1978 | 1.30 | 2.00 |
| 45-6400 | Pasco | WA | 77 | 46.22 | -119.10 | 350 | 9/13/1980 | 1.30 | 1.60 |
| 45-8931 | Walla Walla WSO | WA | 7 | 46.03 | -118.33 | 949 | 10/13/1980 | 1.97 | 2.82 |
| 45-8348 | Tekoa | WA | 7 | 47.22 | -117.08 | 2495 | 8/23/1989 | 1.40 | 1.60 |
| 45-7938 | Spokane Intl AP | WA | 7 | 47.62 | -117.52 | 2353 | 7/25/1990 | 1.32 | 1.78 |
| 35-9213 | Weston | OR | 7 | 45.82 | -118.42 | 1922 | 8/16/1993 | 2.20 | 2.80 |
| 45-1690 | Connell 1 W | WA | 77 | 46.65 | -118.87 | 1020 | 5/15/1994 | 1.00 | 1.30 |
| 45-3515 | Harrington 1 NW | WA | 77 | 47.48 | -118.25 | 2190 | 5/9/2005 | 1.10 | 1.50 |

Table 15 - Catalog of Intermediate-Duration Extreme Storms for Region 13
Mountain Areas in Eastern Washington Eastward of Cascade Mountains

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 6-HR | 18-HR |
| 10-7188 | Plummer 3 WSW | ID | 7 | 47.30 | -116.95 | 2920 | 6/6/1947 | 1.46 | 1.67 |
| 45-9327 | Wilson Creek | WA | 77 | 47.42 | -119.12 | 1280 | 6/16/1948 | 1.06 | 1.19 |
| 45-5231 | McNary Dam | WA | 77 | 45.93 | -119.28 | 361 | 10/1/1957 | 1.86 | 3.00 |
| 10-7188 | Plummer 3 WSW | ID | 7 | 47.30 | -116.95 | 2920 | 6/17/1965 | 1.42 | 2.40 |
| 45-1400 | Chief Joseph Dam | WA | 77 | 47.98 | -119.65 | 820 | 8/23/1965 | 1.02 | 1.36 |
| 45-1767 | Coulee Dam | WA | 77 | 47.95 | -119.00 | 1700 | 11/12/1973 | 1.19 | 1.34 |
| 45-8348 | Tekoa | WA | 7 | 47.22 | -117.08 | 2495 | 7/4/1978 | 1.30 | 2.00 |
| 45-6400 | Pasco | WA | 77 | 46.22 | -119.10 | 350 | 9/13/1980 | 1.30 | 1.60 |
| 45-8931 | Walla Walla WSO | WA | 7 | 46.03 | -118.33 | 949 | 10/13/1980 | 1.97 | 2.82 |
| 45-8348 | Tekoa | WA | 7 | 47.22 | -117.08 | 2495 | 8/23/1989 | 1.40 | 1.60 |
| 45-7938 | Spokane Intl AP | WA | 7 | 47.62 | -117.52 | 2353 | 7/25/1990 | 1.32 | 1.78 |
| 35-9213 | Weston | OR | 7 | 45.82 | -118.42 | 1922 | 8/16/1993 | 2.20 | 2.80 |
| 45-1690 | Connell 1 W | WA | 77 | 46.65 | -118.87 | 1020 | 5/15/1994 | 1.00 | 1.30 |

Table 16 - Catalog of Long-Duration Extreme Storms for Region 5 - Coastal Lowlands

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 24-HR | 72-HR |
| 45-1496 | Clearwater | WA | 5 | 47.58 | -124.30 | 80 | 12/3/1943 | 8.41 | 10.87 |
| 45-8332 | Tatoosh Island WB | WA | 5 | 48.38 | -124.73 | 100 | 10/23/1944 | 5.33 | 6.53 |
| 45-3333 | Grays River Hatchery | WA | 5 | 46.38 | -123.57 | 100 | 1/14/1958 | 6.64 | 8.83 |
| 45-5549 | Montesano 3 NW | WA | 5 | 46.97 | -123.62 | 25 | 11/18/1962 | 5.40 | 7.09 |
| 45-6858 | Quillayute AP | WA | 5 | 47.93 | -124.55 | 179 | 1/18/1968 | 8.32 | 12.32 |
| 45-1496 | Clearwater | WA | 5 | 47.58 | -124.30 | 80 | 1/25/1971 | 7.90 | 10.20 |
| 45-1496 | Clearwater | WA | 5 | 47.58 | -124.30 | 80 | 7/11/1972 | 8.90 | 10.90 |
| 45-5549 | Montesano 3 NW | WA | 5 | 46.97 | -123.62 | 25 | 2/27/1980 | 5.00 | 7.40 |
| 45-1496 | Clearwater | WA | 5 | 47.58 | -124.30 | 80 | 2/13/1982 | 9.30 | 14.50 |
| 35-0328 | Astoria AP Port | OR | 5 | 46.15 | -123.87 | 9 | 1/9/1990 | 5.14 | 6.33 |
| 45-9112 | Westport 2 S | WA | 5 | 46.87 | -124.10 | 20 | 11/24/1990 | 5.40 | 6.90 |
| 45-5549 | Montesano 1 S | WA | 5 | 46.97 | -123.62 | 25 | 12/10/1993 | 5.40 | 6.70 |
| 45-3333 | Grays River Hatchery | WA | 5 | 46.38 | -123.57 | 100 | 12/27/1994 | 7.70 | 10.50 |

Table 17 - Catalog of Long-Duration Extreme Storms for Regions 32 and 31
Interior Lowlands Western Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 24-HR | 72-HR |
| 45-7473 | Seattle WB City | WA | 31 | 47.45 | -122.30 | 400 | 2/6/1945 | 3.00 | 3.55 |
| 45-0986 | Burlington | WA | 31 | 48.47 | -122.32 | 30 | 10/24/1945 | 4.91 | 6.85 |
| 45-0986 | Burlington | WA | 31 | 48.47 | -122.32 | 30 | 2/15/1949 | 3.42 | 3.79 |
| 45-0729 | Blaine 1 ENE | WA | 31 | 49.00 | -122.75 | 60 | 11/3/1955 | 3.63 | 4.38 |
| 45-0324 | Auburn | WA | 31 | 47.32 | -122.23 | 79 | 11/20/1959 | 3.63 | 4.77 |
| 45-6624 | Port Angeles | WA | 32 | 48.10 | -123.42 | 90 | 1/14/1961 | 3.12 | 3.19 |
| 45-4769 | Longview | WA | 31 | 46.15 | -122.92 | 12 | 11/19/1962 | 5.41 | 5.91 |
| 45-1191 | Castle Rock 2 NW | WA | 31 | 46.27 | -122.92 | 39 | 11/23/1964 | 4.62 | 6.68 |
| 45-7773 | Snoqualmie Falls | WA | 31 | 47.53 | -121.83 | 440 | 1/18/1967 | 4.72 | 5.94 |
| 45-7773 | Snoqualmie Falls | WA | 31 | 47.53 | -121.83 | 440 | 3/5/1972 | 4.90 | 5.20 |
| 45-4769 | Longview | WA | 31 | 46.15 | -122.92 | 12 | 12/2/1977 | 4.70 | 5.50 |
| 45-7473 | Sea-Tac Airport | WA | 31 | 47.45 | -122.30 | 400 | 10/6/1981 | 3.71 | 4.33 |
| 45-7470 | Seattle EMSU | WA | 31 | 47.68 | -122.25 | 60 | 1/18/1986 | 4.48 | 5.37 |
| 45-4769 | Longview | WA | 31 | 46.15 | -122.92 | 12 | 2/23/1986 | 4.70 | 5.30 |
| 45-5224 | Mc Millin Reservoir | WA | 31 | 47.13 | -122.27 | 579 | 11/24/1986 | 3.80 | 4.90 |
| 45-7773 | Snoqualmie Falls | WA | 31 | 47.53 | -121.83 | 440 | 1/9/1990 | 4.90 | 6.70 |
| 45-0986 | Burlington | WA | 31 | 48.47 | -122.32 | 30 | 11/9/1990 | 3.00 | 4.10 |
| 45-1277 | Centralia 1 W | WA | 31 | 46.70 | -122.97 | 185 | 11/24/1990 | 5.10 | 5.80 |
| 35-2348 | Dixie Mountain | OR | 32 | 45.68 | -122.92 | 1430 | 4/5/1991 | 4.00 | 6.10 |
| 35-6751 | Portland Intl Airport | OR | 32 | 45.58 | -122.60 | 19 | 10/27/1994 | 4.44 | 5.10 |
| 45-1277 | Centralia 1 W | WA | 31 | 46.70 | -122.97 | 185 | 2/8/1996 | 4.00 | 6.60 |
| 35-6751 | Portland Intl Airport | OR | 32 | 45.58 | -122.60 | 19 | 11/19/1996 | 3.98 | 4.56 |
| | Seattle RG03 | WA | 31 | | | | 12/29/1996 | 2.83 | 4.43 |
| 45-5224 | Mc Millin Reservoir | WA | 31 | 47.13 | -122.27 | 579 | 11/25/1998 | 3.60 | 4.30 |
| | Seattle RG18 | WA | 31 | | | | 10/20/2003 | 4.01 | 4.26 |
| 35-6751 | Portland Intl Airport | OR | 32 | 45.58 | -122.60 | 19 | 11/6/2006 | 2.59 | 5.13 |
| | Seattle RG12 | WA | 31 | | | | 12/3/2007 | 5.61 | 7.56 |

Table 18 - Catalog of Long-Duration Extreme Storms for Regions 15, 151 and 142 Mountain Areas in Western Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 24-HR | 72-HR |
| 45-6892 | Rainier Carbon River | WA | 15 | 47.00 | -121.92 | 1735 | 11/17/1946 | 4.30 | 5.71 |
| 45-2493 | Electron Headworks | WA | 15 | 46.90 | -122.03 | 1730 | 12/10/1946 | 4.77 | 7.69 |
| 45-1992 | Darrington RS | WA | 15 | 48.25 | -121.60 | 550 | 11/26/1949 | 4.98 | 8.30 |
| 45-0013 | Aberdeen 20 NNE | WA | 151 | 47.27 | -123.70 | 435 | 11/3/1955 | 8.39 | 11.76 |
| 45-6851 | Quilcene Dam 5 SW | WA | 142 | 47.78 | -122.98 | 1028 | 1/17/1959 | 5.80 | 12.66 |
| 45-7709 | Skykomish 1 ENE | WA | 15 | 47.70 | -121.37 | 1030 | 12/14/1959 | 7.70 | 9.86 |
| 45-6896 | Rainier Ohanapecosh | WA | 15 | 46.73 | -121.57 | 1950 | 11/19/1962 | 7.78 | 9.70 |
| 45-6295 | Palmer 3 ESE | WA | 15 | 47.30 | -121.85 | 920 | 1/28/1965 | 5.14 | 9.46 |
| 45-3160 | Glacier RS | WA | 15 | 48.88 | -121.95 | 935 | 3/5/1972 | 4.90 | 5.10 |
| 45-8009 | Stampede Pass | WA | 15 | 47.28 | -121.33 | 3958 | 12/1/1975 | 6.84 | 14.96 |
| 45-1457 | Cinebar 2 E | WA | 15 | 46.60 | -122.48 | 1040 | 12/2/1977 | 6.80 | 8.60 |
| 45-3160 | Glacier RS | WA | 15 | 48.88 | -121.95 | 935 | 12/14/1979 | 5.70 | 7.34 |
| 45-8715 | Upper Baker Dam | WA | 15 | 48.65 | -121.68 | 690 | 11/21/1980 | 5.80 | 7.30 |
| 45-3357 | Greenwater | WA | 15 | 47.13 | -121.63 | 1730 | 1/23/1982 | 5.30 | 6.90 |
| 45-6851 | Quilcene Dam 5 SW | WA | 142 | 47.78 | -122.98 | 1028 | 10/22/1982 | 7.90 | 9.80 |
| 45-7657 | Silverton | WA | 15 | 48.07 | -121.57 | 1475 | 12/3/1982 | 7.70 | 8.40 |
| 45-5876 | Nooksack Salmon Hatchery | WA | 15 | 48.90 | -122.15 | 410 | 1/10/1983 | 6.30 | 9.60 |
| 45-3357 | Greenwater | WA | 15 | 47.13 | -121.63 | 1730 | 1/24/1984 | 4.50 | 7.00 |
| 45-1992 | Darrington RS | WA | 15 | 48.25 | -121.60 | 550 | 1/18/1986 | 6.60 | 9.20 |
| 45-2984 | Frances | WA | 142 | 46.55 | -123.50 | 231 | 1/18/1986 | 5.20 | 7.80 |
| 45-4999 | Marblemount RS | WA | 15 | 48.53 | -121.45 | 348 | 2/24/1986 | 6.20 | 8.50 |
| 45-5704 | Mud Mountain Dam | WA | 15 | 47.15 | -121.93 | 1308 | 11/24/1986 | 4.20 | 5.10 |
| 45-2984 | Frances | WA | 142 | 46.55 | -123.50 | 231 | 3/3/1987 | 6.20 | 9.10 |
| 45-1457 | Cinebar 2 E | WA | 15 | 46.60 | -122.48 | 1040 | 1/9/1990 | 5.00 | 7.20 |
| 45-5876 | Nooksack Salmon Hatchery | WA | 15 | 48.90 | -122.15 | 410 | 2/10/1990 | 6.70 | 9.80 |
| 45-4999 | Marblemount RS | WA | 15 | 48.53 | -121.45 | 348 | 11/10/1990 | 6.20 | 9.50 |
| 45-6864 | Quinault RS | WA | 151 | 47.47 | -123.85 | 220 | 11/10/1990 | 13.50 | 17.60 |
| 45-1233 | Cedar Lake | WA | 15 | 47.42 | -121.73 | 1560 | 11/24/1990 | 6.40 | 9.10 |
| 35-3705 | Haskins Dam | OR | 142 | 45.30 | -123.35 | 756 | 4/5/1991 | 5.60 | 9.00 |
| 45-1934 | Cushman Dam | WA | 142 | 47.42 | -123.22 | 760 | 11/20/1994 | 8.20 | 14.90 |
| 35-1033 | Brightwood 1 WNW | OR | 15 | 45.38 | -122.03 | 978 | 11/27/1994 | 7.50 | 8.80 |
| 45-7319 | Sappho 8 E | WA | 151 | 48.07 | -124.12 | 760 | 11/8/1995 | 6.40 | 9.30 |
| 45-4764 | Longmire Rainier NPS | WA | 15 | 46.75 | -121.82 | 2762 | 11/27/1995 | 6.40 | 10.60 |
| 45-2984 | Frances | WA | 142 | 46.55 | -123.50 | 231 | 4/23/1996 | 6.20 | 7.70 |
| 35-0897 | Bonneville Dam | OR | 15 | 45.63 | -121.95 | 62 | 11/19/1996 | 5.90 | 8.10 |
| 45-1934 | Cushman Dam | WA | 142 | 47.42 | -123.22 | 760 | 3/19/1997 | 9.20 | 15.00 |
| 45-6851 | Quilcene Dam 5 SW | WA | 142 | 47.78 | -122.98 | 1028 | 1/29/1999 | 7.40 | 9.80 |
| 45-8715 | Upper Baker Dam | WA | 15 | 48.65 | -121.68 | 690 | 10/16/2003 | 6.80 | 8.70 |
| 45-8009 | Stampede Pass | WA | 15 | 47.28 | -121.33 | 3958 | 11/6/2006 | 8.79 | 14.06 |
| 45-2984 | Frances | WA | 142 | 46.55 | -123.50 | 231 | 11/6/2006 | 4.90 | 9.20 |
| 35-4824 | Lees Camp | OR | 151 | 45.58 | -123.52 | 655 | 11/6/2006 | 13.70 | 23.40 |

Table 19 - Catalog of Long-Duration Extreme Storms for Region 14
East Face of Cascade Mountains

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 24-HR | 72-HR |
| 45-2157 | Diablo Dam | WA | 14 | 48.72 | -121.15 | 891 | 10/24/1945 | 6.42 | 9.23 |
| 45-8688 | Underwood 4 W | WA | 14 | 45.73 | -121.60 | 1260 | 12/11/1946 | 4.04 | 7.29 |
| 35-4003 | Hood River Exp Stn | OR | 14 | 45.68 | -121.52 | 500 | 1/6/1948 | 3.26 | 4.48 |
| 45-2157 | Diablo Dam | WA | 14 | 48.72 | -121.15 | 891 | 2/16/1949 | 7.80 | 9.71 |
| 45-2157 | Diablo Dam | WA | 14 | 48.72 | -121.15 | 891 | 2/9/1951 | 6.47 | 12.99 |
| 45-1257 | Centerville 2 SW | WA | 14 | 45.73 | -120.95 | 1650 | 1/9/1953 | 2.36 | 2.76 |
| 45-7342 | Satus Pass 2 SSW | WA | 14 | 45.95 | -120.67 | 2610 | 11/24/1960 | 3.25 | 4.43 |
| 45-4849 | Lucerne 2 NNW | WA | 14 | 48.23 | -120.60 | 1200 | 11/19/1962 | 3.05 | 3.43 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 2/27/1972 | 3.80 | 6.00 |
| 45-7342 | Satus Pass 2 SSW | WA | 14 | 45.95 | -120.67 | 2610 | 1/15/1974 | 3.60 | 5.20 |
| 45-4849 | Lucerne 2 NNW | WA | 14 | 48.23 | -120.60 | 1200 | 12/2/1975 | 3.17 | 6.64 |
| 45-7342 | Satus Pass 2 SSW | WA | 14 | 45.95 | -120.67 | 2610 | 12/13/1977 | 3.30 | 5.00 |
| 45-5133 | Mazama | WA | 14 | 48.60 | -120.43 | 2170 | 1/12/1980 | 3.20 | 3.60 |
| 45-8059 | Stehekin 4 NW | WA | 14 | 48.35 | -120.72 | 1270 | 1/23/1982 | 5.00 | 6.60 |
| 45-7342 | Satus Pass 2 SSW | WA | 14 | 45.95 | -120.67 | 2610 | 12/10/1987 | 3.90 | 4.40 |
| 45-4446 | Lake Wenatchee | WA | 14 | 47.83 | -120.78 | 2005 | 1/9/1990 | 5.30 | 7.60 |
| 45-2384 | Easton | WA | 14 | 47.23 | -121.18 | 2170 | 11/24/1990 | 6.40 | 10.20 |
| 45-3183 | Glenwood | WA | 14 | 46.02 | -121.28 | 1896 | 10/27/1994 | 3.80 | 4.20 |
| 45-2384 | Easton | WA | 14 | 47.23 | -121.18 | 2170 | 2/8/1996 | 4.10 | 8.90 |
| 35-4008 | Hood River Tucker Bridge | OR | 14 | 45.65 | -121.53 | 383 | 11/19/1996 | 4.70 | 6.60 |
| 45-7342 | Satus Pass 2 SSW | WA | 14 | 45.95 | -120.67 | 2610 | 12/28/1998 | 4.10 | 4.60 |
| 45-5659 | Mount Adams RS | WA | 14 | 46.00 | -121.53 | 1960 | 11/6/2006 | 3.90 | 7.50 |
| 45-6472 | Peshastin Telemetering | WA | 14 | 47.57 | -120.62 | 1028 | 11/6/2006 | 3.20 | 4.90 |

Table 20 - Catalog of Long-Duration Extreme Storms for Transition Zone 147
Cascade Foothills in Eastern Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 24-HR | 72-HR |
| 45-5327 | Methow 2 S | WA | 147 | 48.13 | -120.02 | 1165 | 5/28/1948 | 2.02 | 2.32 |
| 45-6187 | Oroville 1 S | WA | 147 | 48.93 | -119.43 | 932 | 11/16/1950 | 1.96 | 2.02 |
| 45-5731 | Naches 10 NW | WA | 147 | 46.87 | -120.77 | 2280 | 1/14/1956 | 1.43 | 1.59 |
| 35-0265 | Arlington | OR | 147 | 45.72 | -120.20 | 277 | 12/22/1964 | 2.18 | 4.51 |
| 45-2505 | Ellensburg | WA | 147 | 46.97 | -120.53 | 1480 | 12/10/1987 | 1.80 | 1.80 |
| 35-0265 | Arlington | OR | 147 | 45.72 | -120.20 | 277 | 4/21/1988 | 1.70 | 2.20 |
| 45-2505 | Ellensburg | WA | 147 | 46.97 | -120.53 | 1480 | 11/18/1996 | 1.90 | 1.90 |

Table 21 - Catalog of Long-Duration Extreme Storms for Regions 77 and 7
Central Basin and Lowland Areas in Eastern Washington

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 24-HR | 72-HR |
| 45-4679 | Lind 3 NE | WA | 77 | 46.98 | -118.57 | 1630 | 6/25/1942 | 1.53 | 1.77 |
| 45-7956 | Sprague | WA | 7 | 47.30 | -117.98 | 1970 | 9/21/1945 | 1.55 | 2.33 |
| 45-6789 | Pullman 2 NW | WA | 7 | 46.75 | -117.18 | 2545 | 9/15/1947 | 2.10 | 2.59 |
| 45-1767 | Coulee Dam 1 SW | WA | 77 | 47.95 | -119.00 | 1700 | 5/28/1948 | 1.66 | 1.82 |
| 45-5231 | McNary Dam | WA | 77 | 45.93 | -119.28 | 361 | 10/2/1957 | 3.15 | 3.20 |
| 45-8931 | Walla Walla WSO | WA | 7 | 46.03 | -118.33 | 949 | 10/14/1980 | 3.08 | 3.62 |
| 45-1400 | Chief Joseph Dam | WA | 77 | 47.98 | -119.65 | 820 | 9/19/1986 | 1.50 | 1.70 |
| 45-6982 | Republic RS | WA | 7 | 48.63 | -118.73 | 2630 | 7/27/1988 | 2.00 | 2.00 |
| 45-2030 | Dayton 1 WSW | WA | 7 | 46.30 | -118.00 | 1557 | 11/1/1994 | 2.20 | 2.40 |
| 45-9200 | Whitman Mission | WA | 7 | 46.03 | -118.45 | 632 | 11/19/1996 | 2.00 | 2.40 |
| 45-6982 | Republic RS | WA | 7 | 48.63 | -118.73 | 2630 | 5/27/1998 | 2.50 | 2.80 |
| 45-7938 | Spokane Intl AP | WA | 7 | 47.62 | -117.52 | 2353 | 4/5/2000 | 1.53 | 1.73 |

Table 22 - Catalog of Long -Duration Extreme Storms for Region 13
Mountain Areas in Eastern Washington Eastward of Cascade Mountains

| NOAA STATION ID | STATION NAME | STATE | REGION | LAT | LONG | ELEV (ft) | STORM DATE | PRECIPITATION (in) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 24-HR | 72-HR |
| 35-8985 | Walla Walla 13 ESE | OR | 13 | 45.98 | -118.05 | 2400 | 12/28/1945 | 3.95 | 4.71 |
| 10-1079 | Bonners Ferry | ID | 13 | 48.68 | -116.32 | 1770 | 11/18/1946 | 2.78 | 4.11 |
| 45-2197 | Dixie 4 SE | WA | 13 | 46.08 | -118.10 | 2250 | 11/23/1964 | 2.70 | 3.00 |
| 45-2037 | Dayton 9 SE | WA | 13 | 46.22 | -117.85 | 2343 | 12/24/1964 | 3.01 | 4.55 |
| 45-2037 | Dayton 9 SE | WA | 13 | 46.22 | -117.85 | 2343 | 1/2/1966 | 2.53 | 3.69 |
| 10-2845 | Dworshak Fish Hatchery | ID | 13 | 46.50 | -116.32 | 995 | 12/1/1977 | 2.30 | 2.40 |
| 45-0849 | Boundary Switchyard | WA | 13 | 48.97 | -117.35 | 2500 | 2/15/1986 | 3.10 | 3.20 |
| 35-4622 | La Grande | OR | 13 | 45.32 | -118.07 | 2755 | 2/23/1986 | 2.00 | 2.80 |
| 45-5946 | Northport | WA | 13 | 48.90 | -117.78 | 1350 | 6/13/1992 | 2.30 | 2.50 |
| 10-6586 | Ola | ID | 13 | 44.17 | -116.27 | 3075 | 12/27/1996 | 3.10 | 5.00 |
| 45-1395 | Chewelah | WA | 13 | 48.27 | -117.72 | 1670 | 5/26/1998 | 2.70 | 3.40 |
| 10-2845 | Dworshak Fish Hatchery | ID | 13 | 46.50 | -116.32 | 995 | 11/25/1999 | 2.50 | 3.10 |
| 35-8985 | Walla Walla 13 ESE | OR | 13 | 45.98 | -118.05 | 2400 | 10/1/2000 | 4.30 | 4.50 |

# APPENDIX B
# DIMENSIONLESS DEPTH-DURATION CURVES

## OVERVIEW

This appendix contains listing of the ordinates of dimensionless depth-duration curves for use in developing short, intermediate and long-duration candidate design storms for large watersheds. See Section 4.3 for a discussion of the procedures for developing candidate design storms for large watersheds.

Table 23 – Listing of Ordinates of Dimensionless Depth-Duration Curves for Developing Short-Duration Candidate Design Storms for Large Watersheds

| TIME (minutes) | CLIMATIC REGIONS | | |
|---|---|---|---|
| | Western WA | 14 – 147 – 13 | 77 – 7 |
| 0 | 0.000 | 0.000 | 0.000 |
| 5 | 0.224 | 0.272 | 0.302 |
| 10 | 0.364 | 0.436 | 0.532 |
| 15 | 0.499 | 0.565 | 0.649 |
| 20 | 0.567 | 0.626 | 0.730 |
| 25 | 0.630 | 0.687 | 0.807 |
| 30 | 0.685 | 0.739 | 0.875 |
| 45 | 0.831 | 0.837 | 0.993 |
| 60 | 0.924 | 0.902 | 1.000 |
| 75 | 0.957 | 0.970 | 1.000 |
| 90 | 0.972 | 1.000 | 1.000 |
| 105 | 0.986 | 1.000 | 1.000 |
| 120 | 1.000 | 1.000 | 1.000 |
| 180 | 1.139 | 1.091 | 1.035 |
| 240 | 1.193 | 1.111 | 1.040 |
| 300 | 1.255 | 1.125 | 1.055 |
| 360 | 1.256 | 1.180 | 1.085 |

Table 24 – Listing of Ordinates of Dimensionless Depth-Duration Curves
for Developing Intermediate-Duration Candidate Design Storms for Large Watersheds

| TIME (hours) | CLIMATIC REGIONS | | | | | |
|---|---|---|---|---|---|---|
| | 5 | 151 – 142<br>15 – 154 | 31 – 32 | 14 | 147<br>77 – 7 | 13 |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.25 | 0.132 | 0.132 | 0.139 | 0.127 | 0.157 | 0.145 |
| 0.50 | 0.204 | 0.204 | 0.212 | 0.200 | 0.240 | 0.228 |
| 0.75 | 0.268 | 0.268 | 0.273 | 0.266 | 0.320 | 0.306 |
| 1.00 | 0.324 | 0.324 | 0.330 | 0.327 | 0.402 | 0.381 |
| 1.50 | 0.420 | 0.420 | 0.428 | 0.420 | 0.502 | 0.504 |
| 2.00 | 0.508 | 0.508 | 0.520 | 0.498 | 0.560 | 0.596 |
| 3.00 | 0.671 | 0.671 | 0.704 | 0.672 | 0.717 | 0.730 |
| 4.00 | 0.787 | 0.787 | 0.818 | 0.830 | 0.852 | 0.861 |
| 5.00 | 0.917 | 0.917 | 0.939 | 0.940 | 0.926 | 0.946 |
| 6.00 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 9.00 | 1.291 | 1.314 | 1.291 | 1.324 | 1.287 | 1.295 |
| 12.00 | 1.507 | 1.501 | 1.507 | 1.571 | 1.435 | 1.485 |
| 15.00 | 1.597 | 1.671 | 1.597 | 1.686 | 1.500 | 1.540 |
| 18.00 | 1.667 | 1.854 | 1.667 | 1.883 | 1.520 | 1.595 |

Table 25 – Listing of Ordinates of Dimensionless Depth-Duration Curves
for Developing Long-Duration Candidate Design Storms for Large Watersheds

| TIME (hours) | CLIMATIC REGIONS | | | | | |
|---|---|---|---|---|---|---|
| | 5 | 151 – 142<br>15 – 154 | 31 – 32 | 14 | 147<br>77 – 7 | 13 |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.25 | 0.043 | 0.037 | 0.047 | 0.052 | 0.067 | 0.071 |
| 0.50 | 0.070 | 0.058 | 0.071 | 0.084 | 0.100 | 0.112 |
| 0.75 | 0.090 | 0.078 | 0.094 | 0.114 | 0.127 | 0.143 |
| 1.00 | 0.107 | 0.096 | 0.117 | 0.139 | 0.149 | 0.167 |
| 1.50 | 0.139 | 0.130 | 0.158 | 0.178 | 0.199 | 0.208 |
| 2.00 | 0.170 | 0.163 | 0.194 | 0.209 | 0.248 | 0.245 |
| 3.00 | 0.235 | 0.229 | 0.262 | 0.274 | 0.310 | 0.325 |
| 4.00 | 0.299 | 0.290 | 0.320 | 0.337 | 0.374 | 0.405 |
| 5.00 | 0.362 | 0.336 | 0.373 | 0.402 | 0.440 | 0.448 |
| 6.00 | 0.414 | 0.385 | 0.429 | 0.455 | 0.505 | 0.490 |
| 9.00 | 0.558 | 0.521 | 0.578 | 0.564 | 0.649 | 0.650 |
| 12.00 | 0.702 | 0.667 | 0.713 | 0.706 | 0.777 | 0.776 |
| 18.00 | 0.870 | 0.873 | 0.901 | 0.888 | 0.974 | 0.915 |
| 24.00 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 30.00 | 1.117 | 1.155 | 1.100 | 1.170 | 1.076 | 1.124 |
| 36.00 | 1.203 | 1.281 | 1.149 | 1.280 | 1.112 | 1.234 |
| 42.00 | 1.275 | 1.347 | 1.197 | 1.380 | 1.149 | 1.278 |
| 48.00 | 1.342 | 1.403 | 1.247 | 1.460 | 1.149 | 1.326 |
| 54.00 | 1.379 | 1.469 | 1.292 | 1.520 | 1.154 | 1.369 |
| 60.00 | 1.425 | 1.501 | 1.349 | 1.580 | 1.239 | 1.378 |
| 66.00 | 1.457 | 1.556 | 1.363 | 1.634 | 1.256 | 1.412 |
| 72.00 | 1.480 | 1.630 | 1.390 | 1.678 | 1.256 | 1.464 |

# REGIONAL PRECIPITATION-FREQUENCY ANALYSIS AND SPATIAL MAPPING OF PRECIPITATION FOR 24-HOUR AND 2-HOUR DURATIONS IN WESTERN WASHINGTON

WA-RD 544.1

March 2002

**Washington State Department of Transportation**

Washington State Transportation Commission
Planning and Capital Program Management

# REGIONAL PRECIPITATION-FREQUENCY ANALYSIS AND SPATIAL MAPPING OF PRECIPITATION FOR 24-HOUR AND 2-HOUR DURATIONS IN WESTERN WASHINGTON

Prepared for:

**Washington State Department of Transportation**

By:

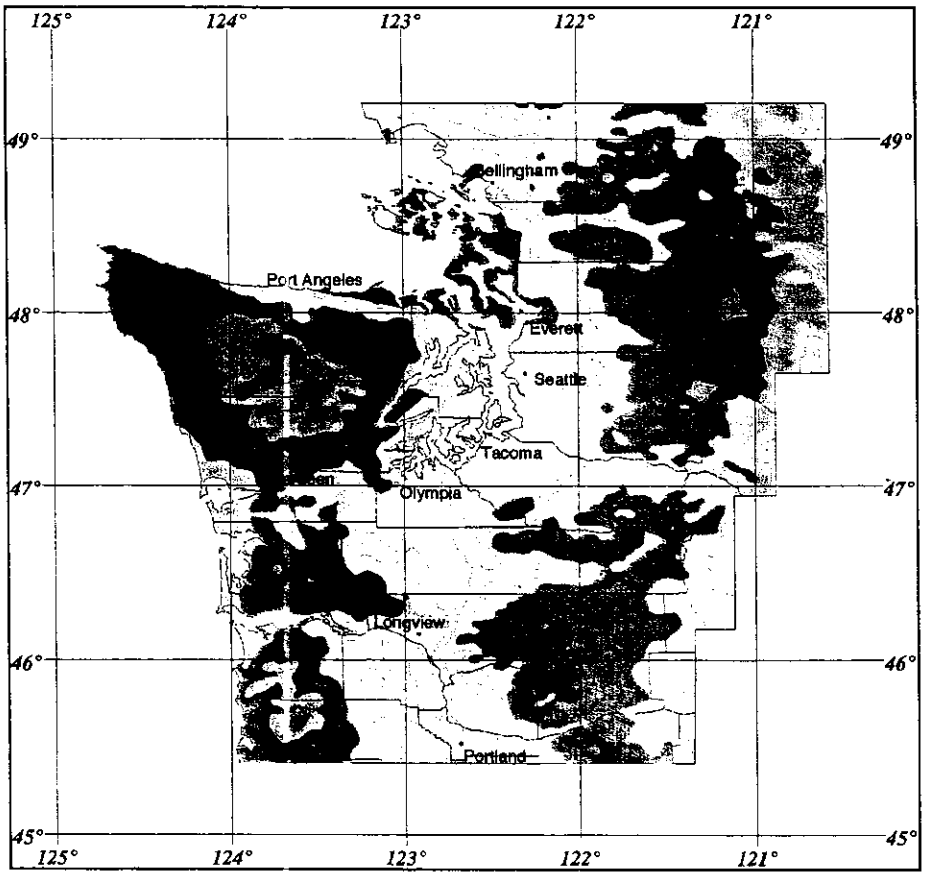

MG Schaefer Ph.D. P.E. MGS Engineering Consultants
BL Barker P.E. MGS Engineering Consultants
GH Taylor CCM Oregon Climate Service
JR Wallis Ph.D. Yale University


March 2002


MGS Engineering Consultants, Inc. Oregon Climate Service

WA STATE DOT LIBRARY
3 3166 0003 6523 9

# REGIONAL PRECIPITATION-FREQUENCY ANALYSIS AND SPATIAL MAPPING OF PRECIPITATION FOR 24-HOUR AND 2-HOUR DURATIONS IN WESTERN WASHINGTON




**10-Year 24-Hour Precipitation**

## Washington State Department of Transportation

March 2002

MGS Engineering Consultants, Inc.

Oregon Climate Service

# REGIONAL PRECIPITATION-FREQUENCY ANALYSIS AND SPATIAL MAPPING OF PRECIPITATION FOR 24-HOUR AND 2-HOUR DURATIONS IN WESTERN WASHINGTON


## EXECUTIVE SUMMARY

Regional frequency analyses were conducted for precipitation annual maxima in western Washington for durations of 24-hours and 2-hours. A total of 430 precipitation gages in Washington, southern British Columbia and northern Oregon were included in the study representing 15,124 and 4,797 station-years of record for the 24-hour and 2-hour durations, respectively. A regional analysis methodology was utilized that pools data from climatologically similar areas to increase the dataset and improve the reliability of precipitation-frequency estimates. The regional analysis methodology included L-moment statistics, and an index-flood type approach for scaling the annual maxima data. L-moment statistics were used to: characterize the variability, skewness and kurtosis of the data; measure heterogeneity in proposed homogeneous sub-regions; and assist in identification of an appropriate regional probability distribution.

It was found that the study area could be described by seven climatic regions. These seven climatic regions were geographic areas that had similar topographic and climatological characteristics and were subjected to similar meteorological conditions during storm events. This included three coastal regions, two interior lowland regions and two Cascade Mountain regions. In particular, the need was recognized to distinguish between windward and leeward areas in both mountain and lowland areas. Separate regional analyses were conducted for each of the seven climatic regions for each of the two durations. Within each climatic region, precipitation gages were assigned to groups where the gage sites had similar magnitudes of mean annual precipitation. A total of 32 sub-regions were formed by this process and were found to be acceptably homogeneous. Predictor equations were then developed to describe the variability of the L-moment ratios, L-Cv and L-Skewness, between the sub-regions and within and/or across climatic region boundaries. The sub-region L-moment ratio plots for L-Skewness and L-Kurtosis revealed the data to be near or slightly more kurtotic than the Generalized Extreme Value distribution. The four-parameter Kappa distribution was chosen to describe the regional magnitude-frequency relationship for both the 24-hour and 2-hour durations.

Spatial mapping techniques were employed for mapping of the precipitation-frequency information. This included spatial mapping of at-site means, L-moment ratio values of L-Cv and L-Skewness, and mapping of precipitation for selected recurrence intervals at both the 24-hour and 2-hour durations. Procedures were employed to minimize differences between mapped values and observed station values in a manner that was consistent with the regional behavior of the data and also recognized uncertainties due to natural sampling variability.

Color-shaded isopluvial maps were developed for the 2-year, 10-year, 25-year, 50-year, and 100-year precipitation at both the 24-hour and 2-hour durations. An isopluvial map was also developed for 6-month, 24-hour precipitation, which is useful for water-quality treatment design applications. Electronic gridded datasets were provided for WSDOT use in creation of GIS applications that utilize precipitation-frequency information.

A catalog of extreme storms was assembled that lists precipitation events in western Washington that exceeded a 20-year return period. The information from the storm catalog was used to conduct seasonality analyses. The seasonality analyses were used to identify the frequency of occurrence of extreme storms by month. In particular, the seasonality analyses identified those months that were the most likely and least likely for an extreme event to occur. This information is useful in rainfall-runoff modeling and can be used by WSDOT staff in conducting hydrologic analyses throughout western Washington.

# TABLE OF CONTENTS


| *SUBJECT* | *PAGE* |
|---|---|
| OVERVIEW | 1 |
| STUDY AREA | 1 |
| CLIMATIC AND METEOROLOGIC CHARACTERISTICS OF STUDY AREA | 3 |
| Annual Precipitation | 3 |
| Weather Systems and Sources of Atmospheric Moisture | 3 |
| DATA SOURCES | 3 |
| Precipitation Gage Types, Methods of Measurement and Reporting | 4 |
| Number of Gages and Gage Types | 4 |
| DATA SCREENING AND QUALITY CHECKING | 7 |
| Stationarity and Serial Independence | 7 |
| REGIONAL ANALYSIS METHODOLOGY | 7 |
| Description of Climatic/Geographic Regions | 8 |
| Regional Growth Curve | 10 |
| FORMING HOMOGENEOUS SUB-REGIONS | 10 |
| Heterogeneity Measures of Proposed Homogeneous Sub-Regions | 11 |
| Acceptance of Proposed Homogeneous Sub-Regions | 11 |
| Systematic Variation of L-Cv and L-Skewness with Mean Annual Precipitation | 12 |
| ANALYSES OF 24-HOUR DURATION ANNUAL MAXIMA | 13 |
| Regional Solutions for L-Moment Ratios, L-Cv and L-Skewness | 13 |
| Heterogeneity Measures, 24-Hour Duration | 17 |
| Identification of Regional Probability Distribution, 24-Hour Duration | 18 |

# TABLE OF CONTENTS


ANALYSES OF 2-HOUR DURATION ANNUAL MAXIMA 19

Regional Solutions for L-Moment Ratios, L-Cv and L-Skewness 20

Heterogeneity Measures, 2-Hour Duration 22

Identification of Regional Probability Distribution, 2-Hour Duration 22

PRECIPITATION MAGNITUDE-FREQUENCY ESTIMATES FOR GAGED SITES 23

SPATIAL MAPPING OF PRECIPITATION-FREQUENCY INFORMATION 26

Mean Annual Precipitation 26

SPATIAL MAPPING OF AT-SITE MEANS 26

Quantitative Assessment of Success Achieved in Spatial Mapping of At-Site Means 29

SPATIAL MAPPING OF REGIONAL L-MOMENT STATISTICAL PARAMETERS 30

PRODUCTION OF ISOPLUVIAL MAPS 30

Precipitation Magnitude-Frequency Estimates for Moderate to Large Size Watersheds 31

Uncertainty Bounds for 100-Year Values 31

ELECTRONIC FILES
LISTING AT-SITE AND REGIONAL PARAMETERS FOR ALL GAGED SITES 33

SEASONALITY OF EXTREME STORMS 33

CATALOG OF EXTREME STORMS 35

REFERENCES 36

APPENDIX A - STATION CATALOGS
AND ELECTRONIC FILES OF PROJECT DELIVERABLES A-1

APPENDIX B - ISOPLUVIAL MAPS FOR SELECTED RECURRENCE INTERVALS B-1

APPENDIX C - SEASONALITY OF 24-HOUR AND 2-HOUR EXTREME STORMS C-1

APPENDIX D - CATALOGS OF EXTREME STORMS
FOR 24-HOUR AND 2-HOUR DURATIONS D-1

APPENDIX E - L-MOMENT STATISTICS E-1

APPENDIX F - SELECTED DEFINITIONS F-1

# REGIONAL PRECIPITATION-FREQUENCY ANALYSIS AND SPATIAL MAPPING OF PRECIPITATION FOR 24-HOUR AND 2-HOUR DURATIONS IN WESTERN WASHINGTON

March 2002

## OVERVIEW

This report documents the findings of regional precipitation-frequency analyses of 24-hour and 2-hour precipitation annual maxima for western Washington. It also describes the procedures used for spatial mapping of the precipitation-frequency estimates for selected recurrence intervals.

This study is an update of the information contained in the precipitation-frequency atlas published by the National Weather Service in 1973 (NOAA Atlas 2[16]). Data collection for the NWS study ended in 1966, and this study includes the 34-years of record collected since 1966. These additional data provide a precipitation database with more than double the record length than was available in the original NWS study.

Since the original study, major advances have been made in the methods for statistical analysis of precipitation annual maxima, and for spatial mapping of precipitation in complex terrain. Specifically, L-Moment statistical analysis techniques[7,9] conducted within a regional framework have greatly improved the reliability of precipitation magnitude-frequency estimates, particularly for rare storm events. Development of the PRISM model[3] incorporating digital terrain data has also improved the spatial mapping of precipitation and increased the reliability of estimating precipitation in the broad areas between precipitation measurement stations. These methodologies are particularly effective in areas with high topographic and climatic variability such as in western Washington, where mean annual precipitation varies from less than 20-inches to over 200-inches. Both of these methodologies have been utilized in conducting the precipitation-frequency analyses and in developing the isopluvial maps for selected recurrence intervals.

## STUDY AREA

While western Washington is the area of interest, the study area was expanded to provide additional data in border areas. Accordingly, the study area included areas in southwestern British Columbia, northwestern Oregon, and areas in the Cascade Mountains in eastern Washington (Figure 1). Specifically, the study area is bounded on the North at latitude 49°30′ N, bounded to the south by latitude 45°00′ N, and bounded to the east by the contour line of 20-inches mean annual precipitation, approximately longitude 120°00′ W. Addition of precipitation stations in the boundary areas also provided data from areas climatologically similar to data-sparse areas in Washington such as the windward and leeward faces of the Olympic Mountains, Willapa Hills, and the Cascade Mountains.

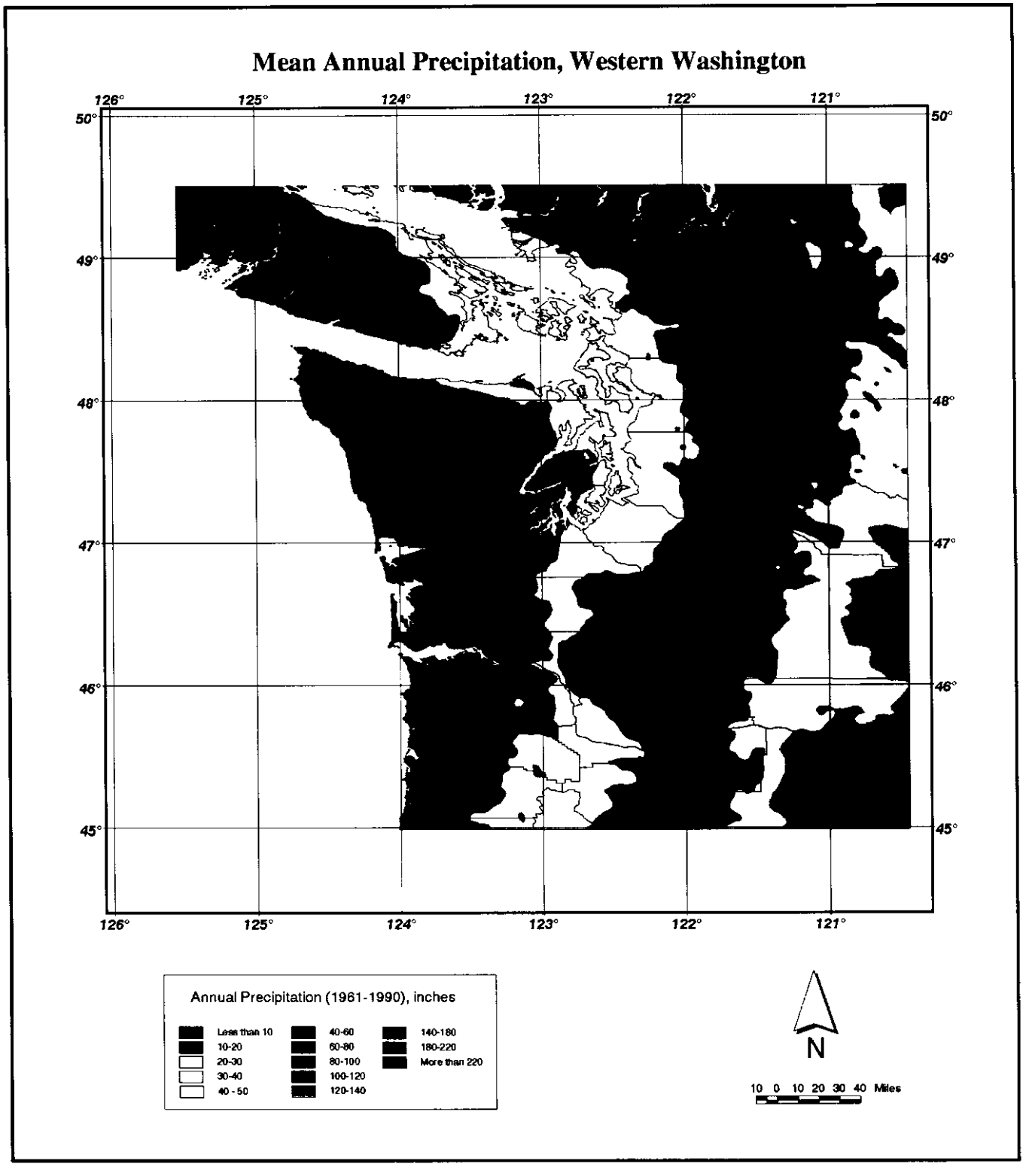



Figure 1 – Mean Annual Precipitation[20,21] for Western Washington Study Area

## CLIMATIC AND METEOROLOGIC CHARACTERISTICS OF STUDY AREA

### Annual Precipitation

Mean annual precipitation within the study area varies dramatically from the coast to the eastern slopes of the Cascade Mountains (Figure 1). Mean Annual Precipitation[20] (MAP) ranges from a high of over 240-inches in the Olympic Mountains, to a low near 18-inches in the Olympic rain shadow area near Sequim, and to 20-inches in the foothills of the Cascades in eastern Washington.

### Weather Systems and Sources of Atmospheric Moisture

In general, two ingredients are needed for precipitation to occur, a source of atmospheric moisture and a meteorological mechanism to release that moisture. There is also a greater potential for extreme precipitation events when the source of moisture originates in areas with warmer temperatures and higher dewpoints. There are three generalized geographic areas that are sources of atmospheric moisture to the study area and have differing characteristic temperatures and dewpoints. These source areas include: the Gulf of Alaska; the Pacific Ocean north of the Canadian border; and the Pacific Ocean from as far south as latitude 20°N near the Hawaiian Islands.

Storm systems[16,18,19] moving in a southeasterly direction out of the Gulf of Alaska primarily affect northern portions of the study area and generally contain cooler temperatures and dewpoints. Storm systems originating over the Pacific Ocean are the most common and those that originate from southerly latitudes near the Hawaiian Islands have been responsible for many of the largest long-duration precipitation events experienced in the winter months. Synoptic-scale cyclonic weather systems and associated fronts generally provide the mechanism for producing precipitation annual maxima at the 24-hour and longer durations. Precipitation is enhanced in mountain areas as atmospheric moisture is lifted over the Olympic, Coastal and Cascade Mountains. This orographic component of precipitation has the greatest effect at 24-hour and longer time scales, and can significantly enhance the total accumulation of precipitation over several days. Precipitation annual maxima at the 24-hour duration occur predominately in the fall and winter seasons in western Washington.

Precipitation annual maxima at the 2-hour duration may occur as a result of several different storm mechanisms. They may occur due to low-to-moderate convective activity associated with a large-scale synoptic weather system in the fall or winter season. In this case, the 2-hour annual maxima are embedded within a much longer duration storm event. They may also occur due to more intense convective activity that may, or may not, be associated with an organized weather system. In this latter case, the 2-hour annual maxima are often associated with "thunderstorms" in the spring and summer, which are short-duration localized storm events with limited areal coverage.

## DATA SOURCES

A precipitation annual maximum is the greatest precipitation amount in a 12-month period for a specified duration at a given measurement site. The water-year, October 1st to September 30th is the 12-month period used for determining precipitation annual maxima for the 24-hour and 2-hour durations for these analyses.

Precipitation annual maxima and associated storm dates were obtained from precipitation records from a variety of sources. The majority of the data were obtained from the electronic files of the National Climatic Data Center (NCDC). Data for southwestern British Columbia were obtained from the Canadian Atmospheric Environment Services Agency (AES). Data from Snotel gages in mountains areas were obtained from electronic files from the Natural Resources Conservation Service (NRCS). Several counties in Washington also provided data for urban areas, including: King, Kitsap, Snohomish, Thurston and Clark Counties.

**Precipitation Gage Types, Methods of Measurement and Reporting**
Precipitation is measured by a variety of devices and reported by a number of different agencies in the United States and Canada. Descriptions of the gage types and reporting methods are summarized below.

*Daily Gages* – Daily gages in US and Canada are standardized devices comprised of simple vertical cylinders open to the atmosphere. A variety of shields for protection from the wind are used in both countries, with shields being more common now than in the past. Precipitation is measured once each day at a specified time and represents the precipitation for the previous 24-hours.

*Automated Gages* – Automated gages such as weighing buckets, Fisher-Porter tipping buckets, and other types of tipping buckets can provide information about precipitation intensity on various time scales. The standards in both the US and Canada are for reporting on either hourly or 15-minute intervals. Weighing bucket gages with paper strip charts came on-line around 1940-1945 in the US and many were installed in Canada in the 1950's and 1960's. Tipping bucket gages and automated reporting systems were installed at many sites beginning in the 1970's. These gages are often given the generic term hourly gages to distinguish them from daily gages.

*Snotel Gages* – Snotel gages are a type of automated gage commonly used in mountain areas. They have external heating systems and are designed for cold weather operation. Precipitation that falls as snow is converted to liquid water for measurement. Snotel gages typically report precipitation on a daily basis on a midnight-to-midnight reporting schedule.

**Number of Gages and Gage Types**
The number of gages and gage types used in the regional analyses are summarized in Tables 1a,b. Both daily and hourly precipitation gages are co-located at many NCDC sites in the US. This occurred at 61 stations in Washington and Oregon. To avoid duplication, the record from the gage with the longest record was utilized in the analyses for the 24-hour duration. When both the daily and hourly records were of similar length, the record from the hourly gage was selected. The precipitation station networks are shown in Figures 2a,b for the 24-hour and 2-hour durations, respectively.

Table 1a – Number and Type of Gages Utilized for Analyses of 24-Hour Annual Maxima

| STATION LOCATION | DAILY GAGE | HOURLY GAGE | SNOTEL GAGE |
|---|---|---|---|
| British Columbia | 56 | 6 | 0 |
| Washington | 146 | 78 | 44 |
| Oregon | 44 | 31 | 11 |
| Municipal Gages | 14 | 0 | 0 |
| **TOTAL** | **260** | **115** | **55** |

61 NCDC stations have co-located daily and hourly gages

Table 1b – Number and Type of Gages Utilized for Analyses of 2-Hour Annual Maxima

| STATION LOCATION | DAILY GAGE | HOURLY GAGE | SNOTEL GAGE |
|---|---|---|---|
| British Columbia | 0 | 24 | 0 |
| Washington | 0 | 78 | 0 |
| Oregon | 0 | 31 | 0 |
| Municipal Gages | 0 | 3 | 0 |
| **TOTAL** | **0** | **146** | **0** |

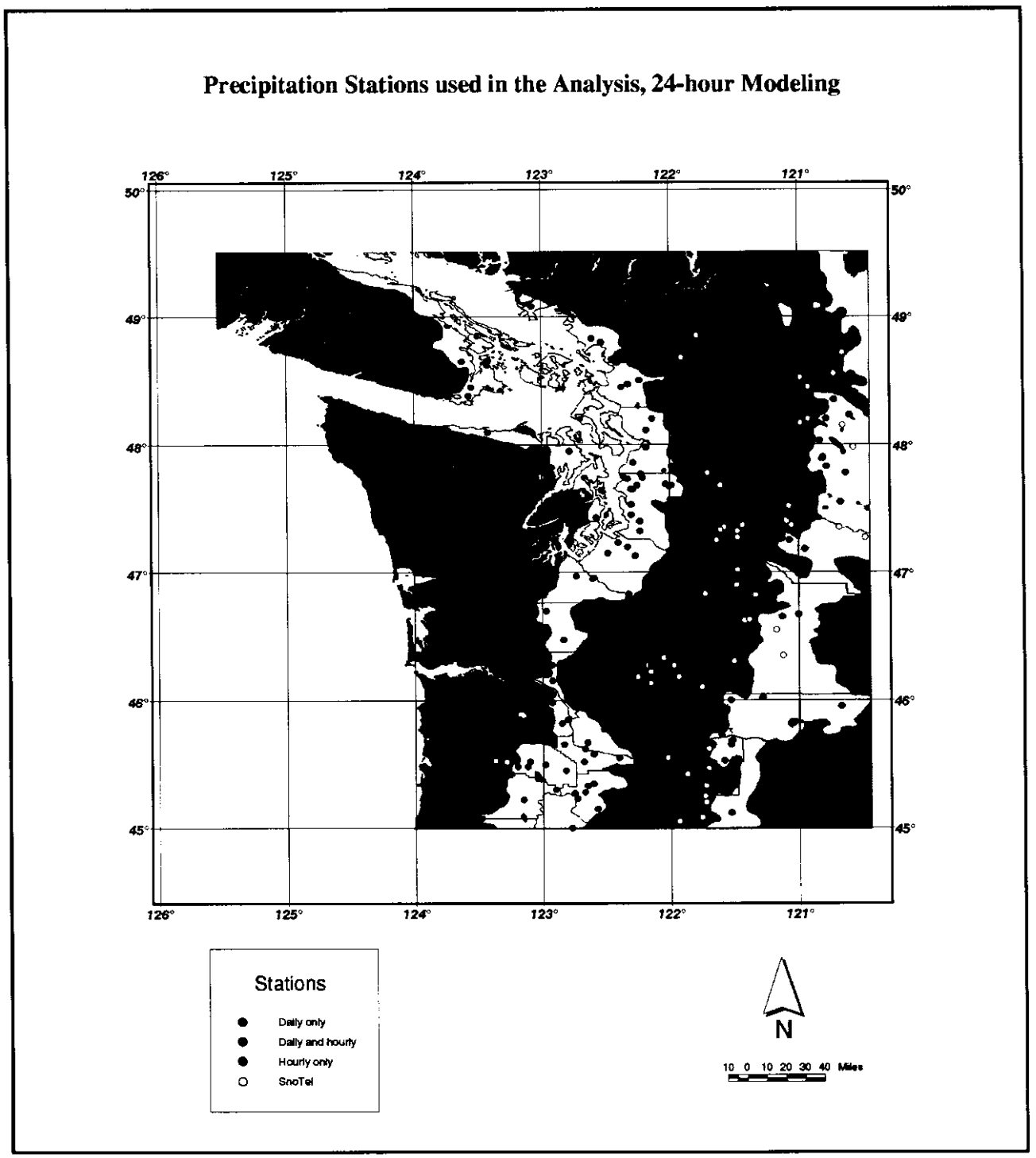



Figure 2a – Precipitation Gaging Network for Analysis of 24-Hour Annual Maxima

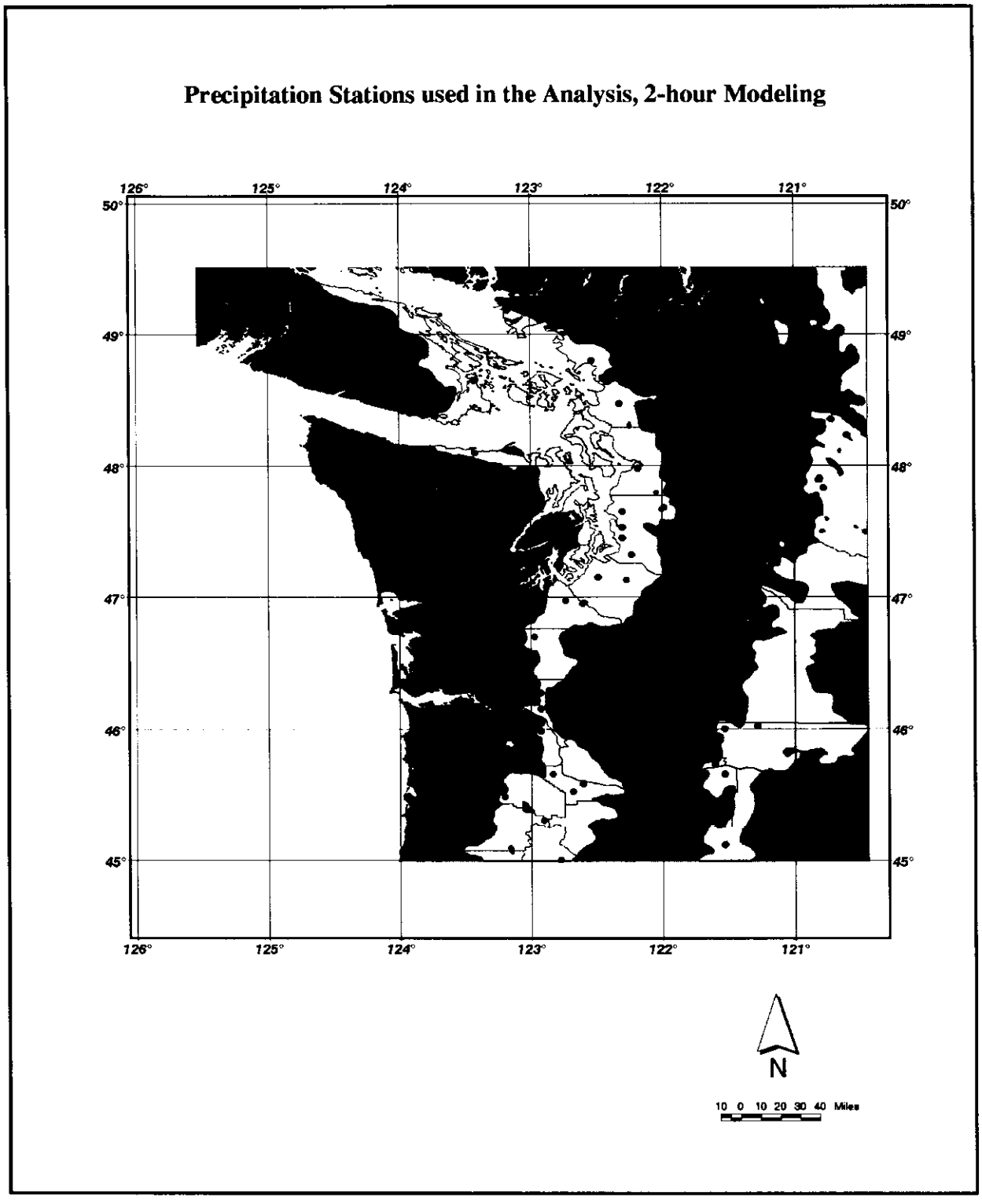



Figure 2b – Precipitation Gaging Network for Analysis of 2-Hour Annual Maxima

## DATA SCREENING AND QUALITY CHECKING

Extensive efforts were made in screening and quality checking the annual maxima data. Quality checking was needed to eliminate false annual maxima associated with a variety of data measurement, reporting, and transcription errors, particularly incomplete reporting during some years. The record for all sites and climatic-years was checked for completeness. In addition, all records were scanned for anomalously small or large precipitation amounts and the Hosking and Wallis[9,10] measure of discordancy [9,10] was also used to identify gages whose sample statistics were markedly different from the majority of gages in a given region. Suspicious gages and data were checked to verify the validity of records. Nearby sites were also checked to corroborate the magnitude and date of occurrence of any anomalously small or large precipitation annual maxima. Data that were clearly erroneous were removed from the datasets.

### Stationarity and Serial Independence

Two underlying assumptions inherent in frequency analyses are the data are stationary over the period of observation and prediction, and the data at a given site (gage) are serially independent. As part of the data screening process, standard statistical tests for stationarity and serial independence were conducted. Inter-station correlation analyses were also conducted to assess the relative amount of correlation between annual maxima data at nearby gages.

To meet the stationarity criterion, the data must be free from trends during the period of observation. For each duration, this was confirmed by standard linear regression techniques where the station data were first rescaled by division by the at-site mean and then regressed against the year of occurrence minus 1900. This approach allowed comparisons to be made among all gages and to interpret the relative magnitude of any trend over the past century. The average values of the slope parameter were +0.20%, and +0.15% for the 24-hour, and 2-hour durations, respectively. The regression results for the collective group of gages were tested against a null hypothesis of zero slope (stationarity). The null hypothesis could not be rejected at the 5% level and the data at both durations were accepted as stationary.

To confirm independence of the annual maxima data, serial correlation coefficients were computed for the data at each gage for each duration. The regression results for the collective group of gages at each duration were tested against a null hypothesis of zero serial correlation (independence). The null hypothesis could not be rejected at the 5% level. As expected, the annual maxima data were found to be serially independent.

## REGIONAL FREQUENCY ANALYSIS METHODOLOGY

The cornerstone of a regional frequency analysis is that data from sites within a homogeneous region can be pooled to improve the reliability of the magnitude-frequency estimates for all sites. A homogeneous region may be a geographic area delineated on a map or it may be a collection of sites having similar characteristics pertinent to the phenomenon being investigated.

Early in the study it was recognized that the climatic and topographic diversity in the study area would likely preclude the use of large geographic areas that would meet statistical criteria for homogeneity. It was decided to employ climatic/geographic regions that had basic similarities in the climatic and topographic setting. It was anticipated that these regions might require further sub-division to meet homogeneity criteria for use in regional frequency analysis.

**Description of Climatic/Geographic Regions**
Identification of climatologically similar regions meant delineating geographic areas that had similar climatological and topographical characteristics. To assist in this effort, a literature review was conducted to examine region designations utilized in prior studies. This included a review of NOAA Atlas 2[16], studies of extreme precipitation in the Pacific Northwest (NWS[18,19]), and prior regional frequency analyses conducted in coastal mountain areas (Schaefer[23,25,26]).

Based on information in those studies and the spatial characteristics of mean annual precipitation, seven climatic/geographic regions were identified (Figure 3). In particular, the map of mean annual precipitation (Figure 1) developed by Daly using the PRISM[3] model provided the basic mapping information for delineating the boundaries of the climatic regions. This map is based on the 1961-1990 time period, which is the most recent NOAA 30-year decadal-based climate tracking period. The magnitude and gradient of mean annual precipitation were the primary measures used to define the boundaries between the regions. Those regions include:

**Coastal Lowlands** (Region 5) – The lowlands along the west coast of Washington, Oregon and Vancouver Island that are open to the Pacific Ocean. The eastern boundary is either a generalized contour line of 1,000 feet elevation, or the ridgeline of mean annual precipitation that separates the coastal lowlands from the interior lowlands, such as within the Aberdeen-Montesano gap.

**Coastal Mountains West** (Region 151) – The windward faces of the Olympic Mountains, Willapa Hills, Black Hills, Coastal Mountains in Oregon, and Vancouver Island Mountains in British Columbia above a generalized contour line of 1,000 feet elevation. These areas are bounded to the west by the 1,000 feet contour line, and bounded to the east by the ridgeline of mean annual precipitation near the crestline of the mountain barrier.

**Coastal Mountains East** (Region 142) – The leeward faces of the Olympic Mountains, Willapa Hills, Black Hills, Coastal Mountains in Oregon, and Vancouver Island Mountains in British Columbia above a generalized contour line of 1,000 feet elevation. These areas are bounded to the west by the ridgeline of mean annual precipitation near the crestline of the mountain barrier, and bounded to the east by the 1,000 feet contour line.

**Interior Lowlands West** (Region 32) – The interior lowlands below a generalized contour line of 1,000 feet elevation bounded to the east by the trough-line of mean annual precipitation through the Strait of Juan De Fuca, Puget Sound Lowlands and Willamette Valley. This is a zone of low orography where mean annual precipitation generally decreases from west to east.

**Interior Lowlands East** (Region 31) – The interior lowlands below a generalized contour line of 1,000 feet elevation bounded to the west by the trough-line of mean annual precipitation through the Strait of Juan De Fuca, Puget Sound Lowlands and Willamette Valley. This is a zone of low orography where mean annual precipitation generally increases from west to east.

**Cascade Mountains West** (Region 15) – The windward face of the Cascade Mountains in Washington, Oregon, and British Columbia above a generalized contour line of 1,000 feet elevation. This region is bounded to the east by the ridgeline of mean annual precipitation near the Cascade crest.

**Cascade Mountains East** (Region 14) – The leeward face of the Cascade Mountains in Washington, Oregon, and British Columbia above the 20-inch isopluvial of mean annual precipitation. This region is bounded to the west by the ridgeline of mean annual precipitation near the Cascade crest.

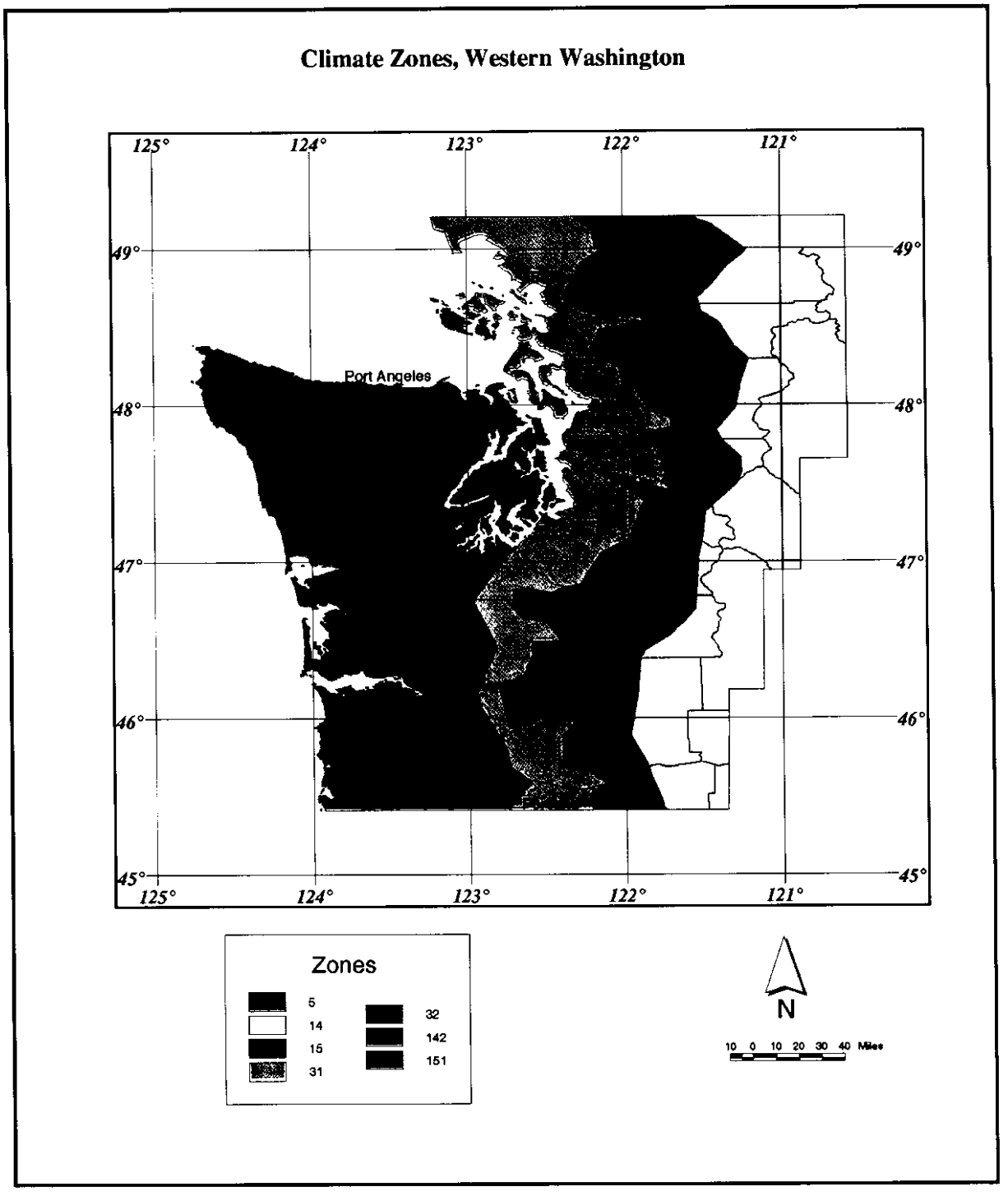



Figure 3 – Delineation of Climatic Regions for Western Washington Study Area

## REGIONAL GROWTH CURVE

Implicit in the definition of a homogeneous region is the condition that all sites can be described by one probability distribution having common distribution parameters after the site data are rescaled by their at-site mean. Thus, all sites have a common regional magnitude-frequency curve (regional growth curve, Figure 4) that becomes site-specific after scaling by the at-site mean of the data from the specific site of interest. Thus,

$$Q_i(F) = \hat{\mu}_i \, q(F) \tag{1}$$

where $Q_i(F)$ is the at-site inverse Cumulative Distribution Function (CDF), $\hat{\mu}_i$ is the estimate of the population at-site mean, and $q(F)$ is the regional growth curve, regional inverse CDF. This is often called an index-flood approach to regional frequency analyses and was first proposed by Dalrymple[2] and expanded by Wallis[30,31].

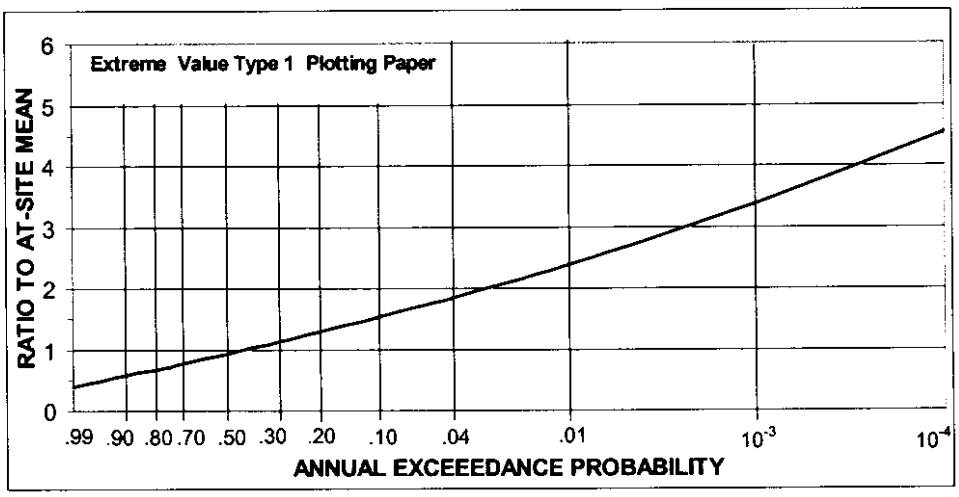



Figure 4 – Example of Regional Growth Curve

## FORMING HOMOGENEOUS SUB-REGIONS

It was anticipated that the climatic regions defined here would require sub-division to meet homogeneity criteria. The methodology used herein for forming and testing proposed homogeneous sub-regions follows the procedures recommended by Hosking and Wallis[9,10].

The basic approach is to propose homogeneous sub-regions (grouping of sites/gages) based on the similarity of the physical/meteorological characteristics of the sites. L-moments (Hosking[7,9], Appendix E) are then used to estimate the variability and skewness of the pooled regional data and to test for heterogeneity as a basis for accepting or rejecting the proposed sub-region formulation.

In general, proposed homogeneous sub-regions can be formed by utilizing some measure(s) of physical and/or climatological characteristics for assigning sites/gages to sub-regions. Candidates for physical features[16,18,19] include such measures as: site elevation; elevation averaged over some grid size; localized topographic slope; macro topographic slope averaged over some grid size; distance from the coast or source of moisture; distance to sheltering mountains or ridgelines; and latitude or longitude. Candidate climatological characteristics include such measures as: mean annual precipitation; precipitation during a given season; seasonality of extreme storms; and seasonal temperature/dewpoint indices.

A review of the topographic and climatological characteristics in each region shows that the seven climatic regions already had similarities regarding several of the physical and climatological measures listed above. As such, only one additional measure, mean annual precipitation (MAP) was needed for grouping of sites/gages into homogeneous sub-regions within a given climatic region. Homogeneous sub-regions were therefore formed with gages/sites within a small range of MAP.

**Heterogeneity Measures of Proposed Homogeneous Sub-Regions**

Heterogeneity measures have been developed by Hosking and Wallis[9,10] as indicators of the amount of heterogeneity in the L-moment ratios for a collection of sites/gages. The statistics H1 and H2 measure the relative variability of observed L-Cv and L-Skewness sample statistics, respectively, for gages/sites in a sub-region. Specifically, these measures compare the observed variability to that expected from a large sample drawn from a homogeneous region from the Kappa distribution[12] having weighted average L-moment ratios that were observed in the sub-region. Initial recommendations from Hosking and Wallis[9,10] were that regions with H1 and H2 values less than 1.00 were acceptably homogeneous. Values of H1 and H2 between 1.00 and 2.00 were possibly heterogeneous. Values greater than 2.00 indicated definite heterogeneity and that redefinition of the region and/or reassignment of sites/gages should be considered.

These heterogeneity criteria measure statistical heterogeneity from known distributions and do not account for variability that arises from other sources. Most cooperative precipitation measurement networks include gages operated by various organizations and individuals that provide a varied level of quality control. Therefore, precipitation measurements often contain additional variability due to: gages being moved during the many years of operation; frequent change of operators and level of diligence in timely measurement; missing data arising from inconsistent reporting; lack of attention to measurement precision; and localized site and wind condition changes over time due to building construction or growth of trees in the vicinity of the gage. Recognizing this additional variability, Wallis[29] has suggested that for precipitation annual maxima, H1 values less than 2.00 may be considered acceptably homogeneous and H1 values greater than 3.00 would be indicative of heterogeneity. Both the H1 and H2 measures will be used later to assess the relative heterogeneity in proposed sub-regions.

**Acceptance of Proposed Homogeneous Sub-Regions**

When a proposed sub-region is found to satisfy homogeneity criteria, the regional L-moment ratios are then used to conduct goodness-of-fit tests (Hosking and Wallis[9,10]) to assist in selecting a suitable probability distribution, and to estimate the parameters of the regional distribution. Examples of this type of approach are described by Schaefer in his study of Washington State[23], southern British Columbia[25], and the Sierra Mountains in California[26]. The basic approach adapted to this study is summarized below:

**<u>Adopted Methodology</u>**

1) Form proposed homogeneous sub-regions by assigning gages within a climatic region to groups within a small range of mean annual precipitation;
2) Compute L-moment sample statistics for gages within the proposed homogeneous sub-regions;
3) Use L-moment heterogeneity criteria to test proposed homogeneous sub-regions;
4) Develop a mathematical predictor for describing the behavior of regional L-Cv and L-skewness values with mean annual precipitation across the climatic region;
5) Conduct goodness-of-fit tests to identify a suitable probability distribution for regional growth curve;
6) Solve for the distribution parameters of the selected probability distribution for each sub-region using the regional values of L-Cv and L-skewness (from Step 4).

**Systematic Variation of L-Cv and L-Skewness with Mean Annual Precipitation**
As described previously, climatic regions were comprised of numerous homogeneous sub-regions. A mathematical relationship was therefore needed to link the sub-regions and provide estimation of L-moment ratios L-Cv and L-Skewness across a climatic region. The relationships were developed in a manner to provide continuity with adjacent climatic regions. This approach had the additional benefit of eliminating or minimizing discontinuities at the boundaries between the climatic regions. Recognizing that the sub-regions were formed as groupings of gages within a small range of mean annual precipitation (MAP), it was found that MAP was a suitable explanatory variable. The predictor equations took the general forms:

$$\textit{L-Moment Ratios} = \alpha\, e^{-\beta(MAP)} + \delta \qquad \text{(2a)}$$

$$\textit{L-Moment Ratios} = \alpha + \beta(LN[MAP]) \qquad \text{(2b)}$$

where: alpha ($\alpha$), beta ($\beta$), and delta ($\delta$) are parameters specific to a given climatic region or group of climatic regions, and delta is a limiting value at large values of mean annual precipitation.

## ANALYSES OF 24-HOUR DURATION ANNUAL MAXIMA

Homogeneous sub-regions were formed as collections of gages within small ranges of mean annual precipitation (MAP) within each of the climatic regions. The range of MAP was chosen so that about 8 to 12 gages, 400 to 500 station-years of record, were included in each sub-region with each gage having at least 15 years of record. This resulted in a total of 32 sub-regions for the 24-hour duration (Table 2). Record lengths at precipitation measurement stations varied from a minimum of 15-years to over 100-years, with nearly 50% of the stations having record lengths in excess of 50-years. Figure 5 depicts the number of stations within various ranges of record length.

Table 2 – Number of Sub-Regions, Gages and Station-Years of Record for 24-Hour Duration Annual Maxima

| CLIMATIC REGION | NUMBER OF SUB-REGIONS | DAILY GAGES | HOURLY GAGES | SNOTEL GAGES | STATION-YEARS OF RECORD |
|---|---|---|---|---|---|
| 5 | 3 | 18 | 9 | 0 | 1,328 |
| 151 | 2 | 8 | 6 | 0 | 715 |
| 142 | 3 | 20 | 6 | 1 | 1,263 |
| 32 | 6 | 39 | 17 | 0 | 2,838 |
| 31 | 7 | 45 | 16 | 0 | 3,474 |
| 15 | 6 | 24 | 28 | 19 | 2,925 |
| 14 | 5 | 28 | 13 | 22 | 2,581 |
| **TOTAL** | **32** | **182** | **95** | **42** | **15,124** |

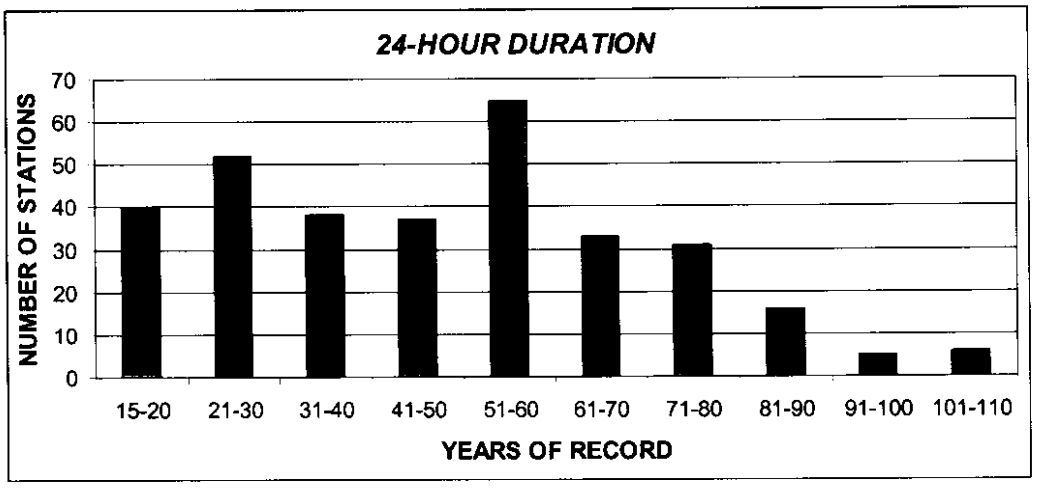



Figure 5 – Histogram of Record Lengths at Stations for 24-Hour Annual Maxima

### Regional Solutions for L-Moment Ratios, L-Cv and L-Skewness

Regional predictor equations for L-moment ratios were developed for groupings of sub-regions in the climatic regions using forms of the regression equations shown in Equations 2a and 2b. It was found that a single predictor equation could often be developed applicable to adjacent climatic regions (Tables 3a,b). For those climatic regions where an exponential decay predictor equation was appropriate (Equation 2a), delta values were first estimated based on regional L-moment ratio values computed from those sub-regions with the largest sub-region values of mean annual precipitation.

For the case of climatic regions 15 and 14, where the boundary is near the crest of the Cascade Mountains, sub-region L-moment ratio values were also computed for gages near the Cascade crest. The sub-region and boundary L-moment ratio values were used to assist in estimation of the delta parameter, which provided continuity between mountain regions 15 and 14.

A least squares solution was used to determine the alpha and beta parameters. Standardized root mean square error (RMSE) was also computed for the predictor equation for each region(s) to provide a measure of the goodness-of-fit of the predictor equation. The resultant predictor equations for L-Cv are listed in Tables 3a,b and graphically depicted in Figures 6a,b,c,d.

Few precipitation gages exist at high elevations in the Olympic Mountains. Extrapolation is required in this area to provide L-moment ratio values applicable to locations with mean annual precipitation exceeding about 140-inches. The regression parameters for high mountain areas in region 142, on the leeward face of the Olympic Mountains, were based on the behavior of L-moment ratio values for gages with the greatest mean annual precipitation on the windward face of the Olympics. This approach provided continuity across the crest of the Olympics for very high values of mean annual precipitation as seen in Figures 5a,b and 6a,b.

Table 3a – Predictor Equations for L-Cv for 24-Hour Annual Maxima

| $L\text{-}Cv = \alpha + \beta * LN(MAP)$ | | | | |
|---|---|---|---|---|
| **REGIONS** | **APPLICABILITY** | **ALPHA** | **BETA** | **STANDARDIZED RMSE** |
| 5 - 151 | ALL | 0.0925 | 0.0130 | 5.3% |
| 32 - 142 | MAP ≥ 75-inches | 0.0925 | 0.0130 | 3.2% |
| 31 - 15 | MAP ≥ 60-inches | 0.1276 | 0.0054 | 3.5% |

Table 3b – Predictor Equations for L-Cv for 24-Hour Annual Maxima

| $L\text{-}Cv = \alpha * EXP[-\beta * MAP] + \delta$ | | | | | |
|---|---|---|---|---|---|
| **REGIONS** | **APPLICABILITY** | **ALPHA** | **BETA** | **DELTA** | **STANDARDIZED RMSE** |
| 32 - 142 | MAP < 75-inches | 0.2500 | 0.0845 | 0.1480 | 3.2% |
| 31 - 15 | MAP < 60-inches | 0.2500 | 0.0845 | 0.1480 | 3.5% |
| 14 | ALL | 0.1100 | 0.0330 | 0.1550 | 3.3% |

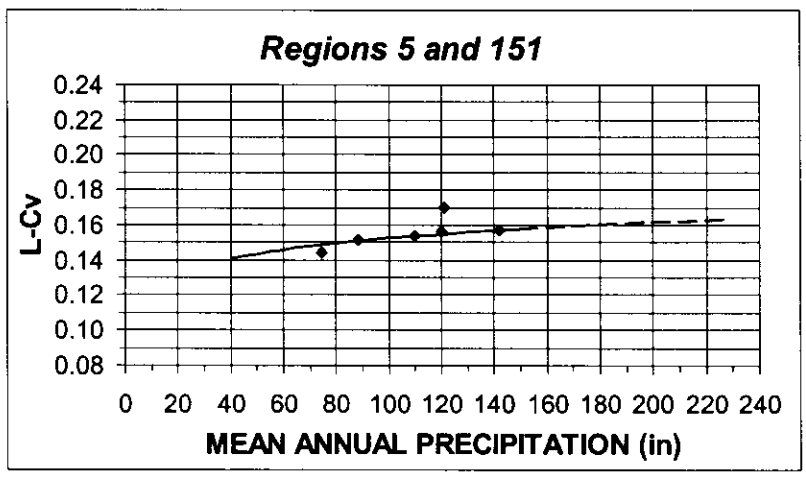



Figure 6a – Predictor Equation Solutions of Observed L-Cv for Climatic Regions 5 and 151 for 24-Hour Duration

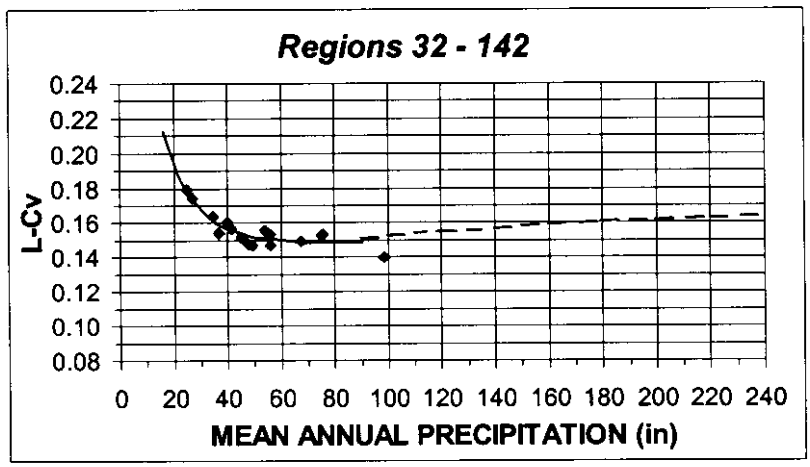



Figure 6b – Predictor Equation Solutions of Observed L-Cv for Climatic Regions 32 and 142 for 24-Hour Duration

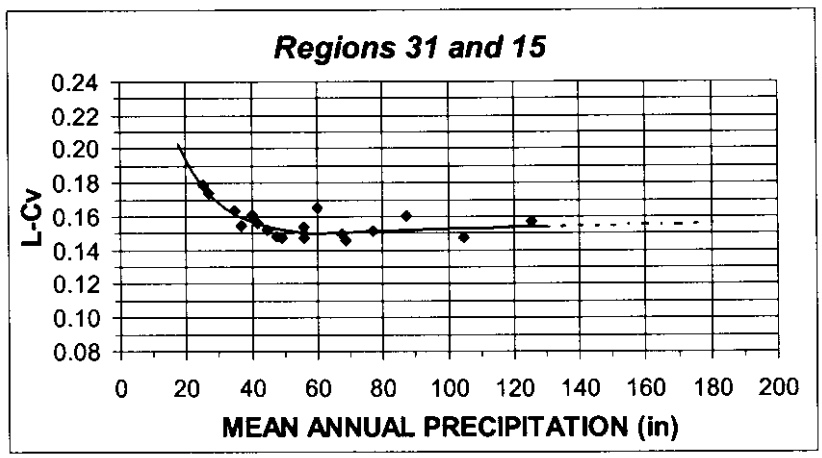



Figure 6c – Predictor Equation Solutions of Observed L-Cv for Climatic Regions 31 and 15 for 24-Hour Duration

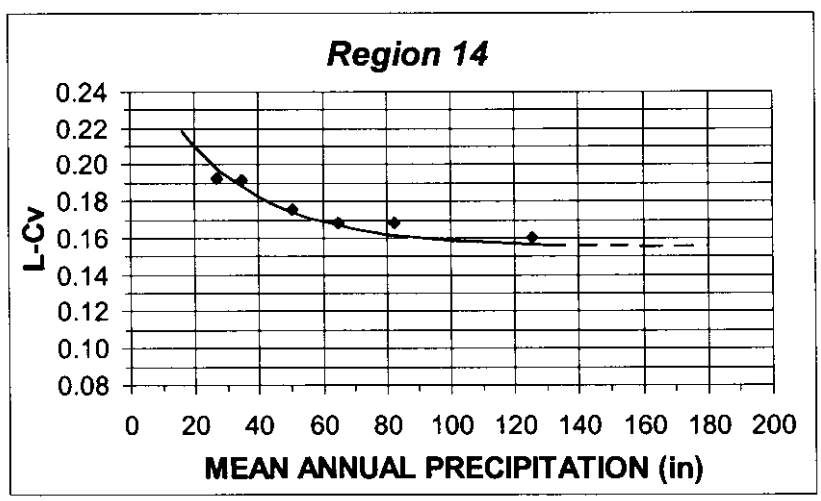



Figure 6d – Predictor Equation Solution of Observed L-Cv for Climatic Region 14 for 24-Hour Duration

Skewness measures are highly variable for the record lengths commonly available for precipitation-frequency analysis. This greater sampling variability is exhibited in larger RMSE values for the predictor equations for L-Skewness (Tables 4a,b). Regional predictor equations for L-Skewness were developed in the same manner as that described above for L-Cv. The predictor equations for L-Skewness are listed in Tables 4a,b and graphically depicted in Figures 7a,b,c,d.

Table 4a – Predictor Equations for L-Skewness for 24-Hour Annual Maxima

| $L\text{-}Skewness = \alpha + \beta * LN(MAP)$ | | | | |
|---|---|---|---|---|
| **REGIONS** | **APPLICABILITY** | **ALPHA** | **BETA** | **STANDARDIZED RMSE** |
| 5 - 151 | MAP < 150-inches | 0.0930 | 0.0130 | 13.7% |
| 5 - 151 | MAP ≥ 150-inches | 0.1580 | 0.0000 | 13.7% |
| 32 - 142 | 70-inches ≤ MAP < 150-inches | 0.0930 | 0.0130 | 14.2% |
| 32 - 142 | MAP ≥ 150-inches | 0.1580 | 0.0000 | 14.2% |

Table 4b – Predictor Equations for L-Skewness for 24-Hour Annual Maxima

| $L\text{-}Skewness = \alpha * EXP[-\beta * MAP] + \delta$ | | | | | |
|---|---|---|---|---|---|
| **REGIONS** | **APPLICABILITY** | **ALPHA** | **BETA** | **DELTA** | **STANDARDIZED RMSE** |
| 32 - 142 | MAP < 70-inches | 0.1500 | 0.0400 | 0.1400 | 14.2% |
| 31 - 15 | ALL | 0.1300 | 0.0400 | 0.1580 | 9.8% |
| 14 | ALL | 0.1300 | 0.0400 | 0.1580 | 10.5% |

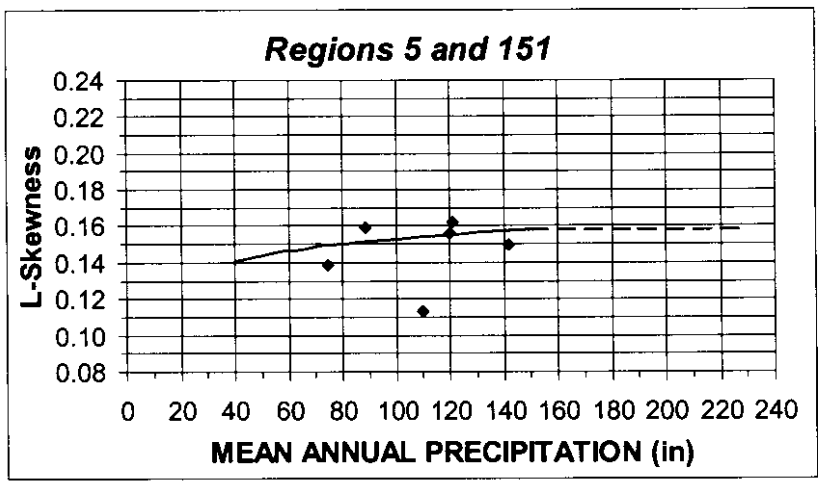



Figure 7a – Predictor Equation Solutions of Observed L-Skewness for Climatic Regions 5 and 151 for 24-Hour Duration

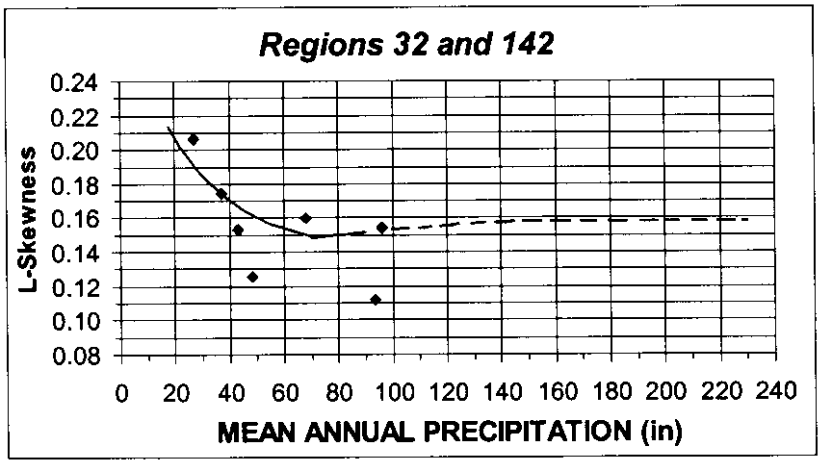



Figure 7b – Predictor Equation Solutions of Observed L-Skewness for Climatic Regions 142 and 32 for 24-Hour Duration

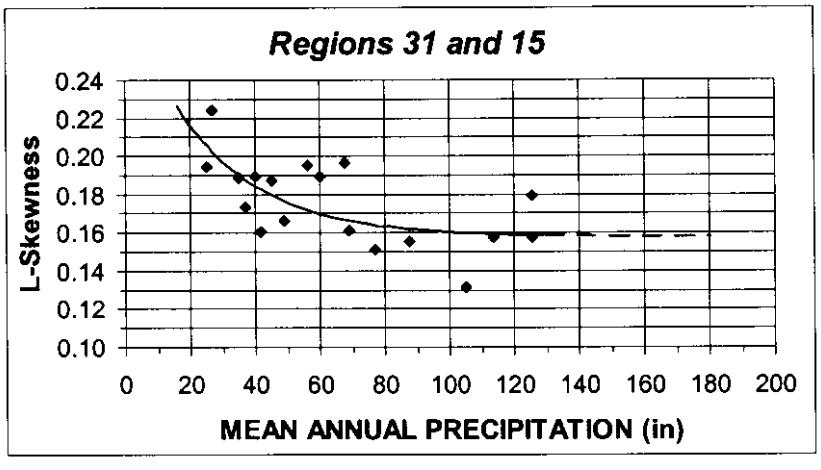



Figure 7c – Predictor Equation Solutions of Observed L-Skewness for Climatic Regions 31 and 15 for 24-Hour Duration

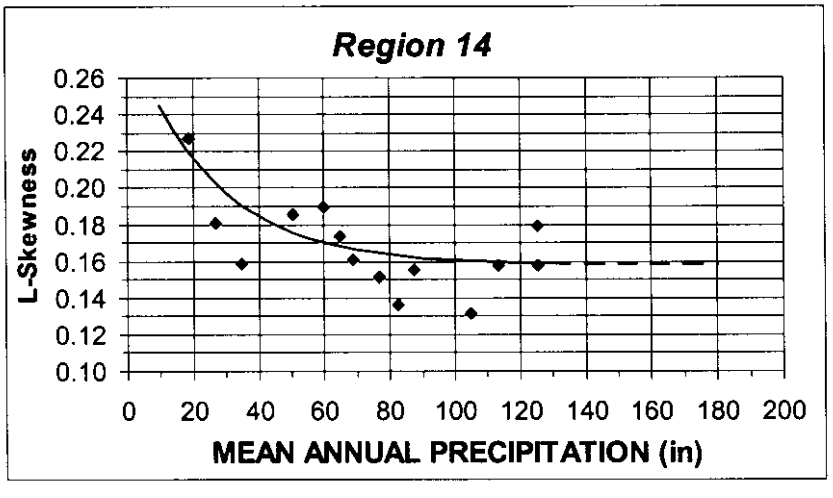



Figure 7d – Predictor Equation Solutions of Observed L-Skewness for Climatic Region 14 for 24-Hour Duration

**Heterogeneity Measures, 24-Hour Duration**

Heterogeneity measures H1 and H2 (Hosking and Wallis[9,10]) were used to judge the relative heterogeneity in the proposed sub-regions for L-Cv and L-Skewness, respectively. Computation of H1 and H2 values for the various sub-regions indicated the majority of sub-regions were acceptably homogeneous (Table 5). In those cases where computed heterogeneity measures exceeded acceptance criteria, the excursions were generally of a minor amount. Only one sub-region on the windward face of the Olympics had large excursions beyond the acceptance criteria. In summary, mean annual precipitation was an excellent explanatory variable for describing the variability of L-Cv and L-Skewness across the study area.

Table 5 – Results of Heterogeneity and Goodness-of-Fit Tests for 24-Hour Duration

| CLIMATIC REGIONS | NUMBER OF SUB-REGIONS | HOMOGENEOUS SUB-REGIONS H1 ≤ 2.00 | HOMOGENEOUS SUB-REGIONS H2 ≤ 1.00 | SUB-REGIONS ACCEPTING GEV DISTRIBUTION |
|---|---|---|---|---|
| 5 - 151 | 5 | 3 | 4 | 5 |
| 142 - 32 | 9 | 6 | 7 | 8 |
| 31 -15 | 13 | 13 | 11 | 13 |
| 14 | 5 | 4 | 4 | 3 |
| **TOTAL** | **32** | **26** | **26** | **29** |

**Identification of Regional Probability Distribution, 24-Hour Duration**

One of the primary tasks in the regional analyses was to identify the best probability distribution for describing the behavior of the annual maxima data. Accordingly, a goodness-of-fit test statistic (Hosking and Wallis[9,10]) was computed for each sub-region for use in identifying the best three-parameter distribution. Using the L-moment based test statistic, the Generalized Extreme Value (GEV) distribution[9,27] was identified most frequently as the best three-parameter probability model (Table 5).

A plot of regional L-Skewness and L-Kurtosis values for the 32 sub-regions at the 24-hour duration in shown in Figure 8. Nearness to the GEV distribution is clearly evident and consistent with the goodness-of-fit test results listed in Table 5.

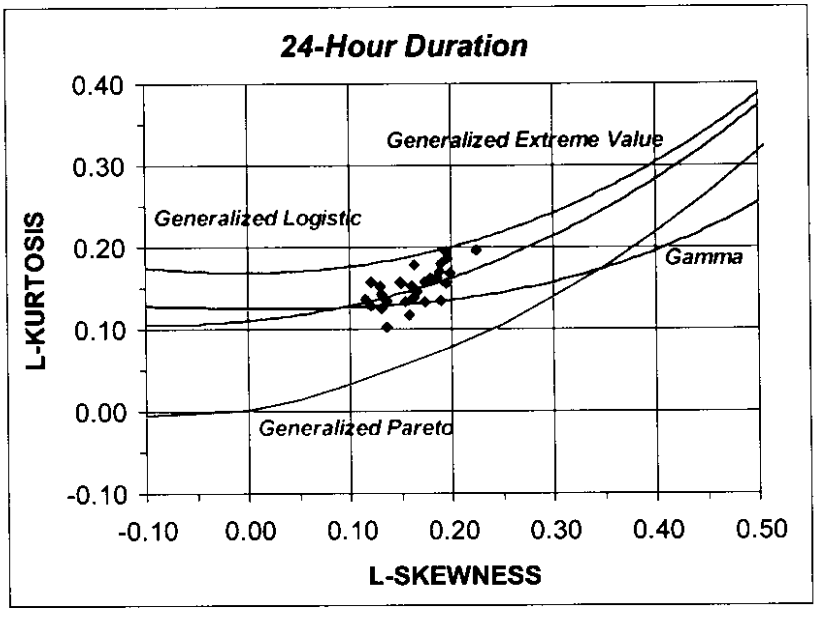



Figure 8 – L-Moment Ratio Plot for Sub-Regions for 24-Hour Duration

The GEV is a very suitable distribution for estimation of precipitation quantiles out to the 500-year recurrence interval. If quantile estimates are desired for events more extreme than the 500-year recurrence interval, it would be worthwhile to refine the selection of the regional probability distribution. Given this consideration, it was decided to utilize the four-parameter Kappa[9,12] distribution, which can mimic the GEV and produce a variety of regional growth curves immediately around the GEV. The inverse form of the Kappa distribution is:

$$q(F) = \xi + \frac{\alpha}{\kappa}\left\{1 - \left(\frac{1-F^h}{h}\right)^{\kappa}\right\} \tag{3}$$

where: $\xi$, $\alpha$, $\kappa$, and $h$ are location, scale and shape parameters respectively.

An $h$ value of zero leads to the GEV distribution, an $h$ value of 1 produces the Generalized Pareto (GP) and an $h$ value of -1 produces the Generalized Logistic (GL) distribution. Thus, positive values of $h$ produce regional growth curves that are flatter than the GEV, and negative values of $h$ produce steeper regional growth curves. Minor adjustments of $h$ near a zero value (GEV) allow fine-tuning of the regional growth curves. This minor adjustment of the $h$ value only becomes important for the estimation of very rare quantiles.

To solve for an appropriate $h$ value, a hierarchical approach (Fiorentino[4]) was taken wherein the shape parameter $h$ was computed as the average value from the group of sub-region solutions. An average value of -0.057 was computed with a standard error of estimation of approximately $\pm$ 0.045. Based on this information, a nominal $h$ value of -0.05 was adopted. This produces a regional growth curve slightly steeper than the GEV for very rare events and essentially matches the GEV out to the 100-year recurrence interval.

## ANALYSES OF 2-HOUR DURATION ANNUAL MAXIMA

As in the analysis of 24-hour annual maxima, homogeneous sub-regions at the 2-hour duration were formed as collections of gages within small ranges of mean annual precipitation (MAP) within each of the climatic regions. The range of MAP was chosen so that about 6 to 10 gages, 200 to 350 station-years of record, were included in each sub-region with each gage having at least 15-years of record. This resulted in a total of 15 sub-regions for the 2-hour duration (Table 6). Record lengths at precipitation measurement stations varied from a minimum of 15-years to near 60-years, with nearly 50% of the stations having record lengths in excess of 40-years. Figure 9 depicts the number of stations within various ranges of record length.

Table 6 – Number of Sub-Regions, Gages and Station-Years of Record for 2-Hour Duration Annual Maxima

| CLIMATIC REGIONS | NUMBER OF SUB-REGIONS | DAILY GAGES | HOURLY GAGES | SNOTEL GAGES | STATION-YEARS OF RECORD |
|---|---|---|---|---|---|
| 5 - 151 | 2 | 0 | 19 | 0 | 721 |
| 142 - 32 | 4 | 0 | 27 | 0 | 1,101 |
| 31 - 15 | 7 | 0 | 63 | 0 | 2,424 |
| 14 | 2 | 0 | 15 | 0 | 551 |
| **TOTAL** | **15** | **0** | **124** | **0** | **4,797** |

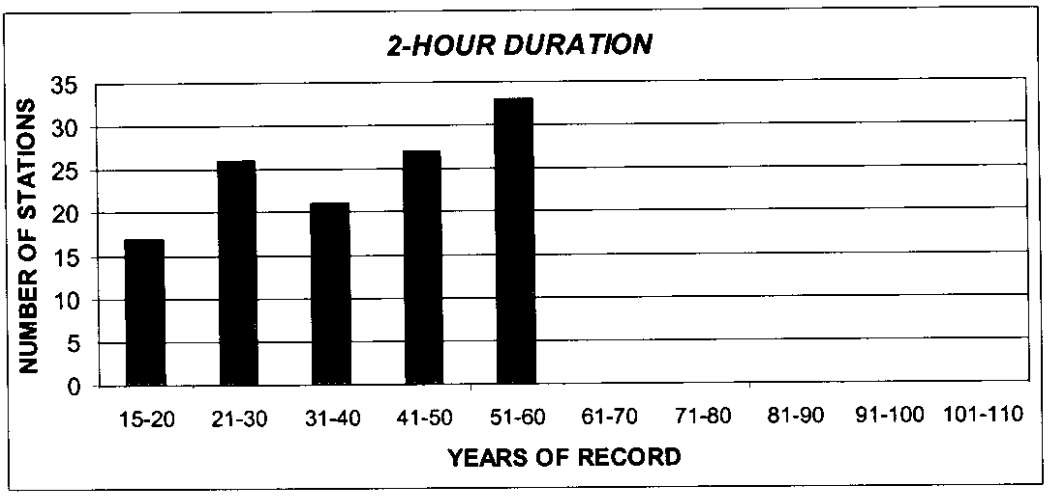



Figure 9 – Histogram of Station Record Lengths for 2-Hour Annual Maxima

**Regional Solutions for L-Moment Ratios, L-Cv and L-Skewness**

Regional predictor equations for L-moment ratios at the 2-hour duration were developed in the same manner as that for the 24-hour duration. The resultant predictor equations for L-Cv are listed in Table 7 and graphically depicted in Figures 10a,b,c. The predictor equation for L-Skewness is listed in Table 8 and graphically depicted in Figure 11.

Table 7 – Predictor Equations for L-Cv for 2-Hour Annual Maxima

| $L\text{-}Cv = \alpha * EXP[-\beta * MAP] + \delta$ | | | | | |
|---|---|---|---|---|---|
| **REGIONS** | **APPLICABILITY** | **ALPHA** | **BETA** | **DELTA** | **STANDARDIZED RMSE** |
| 5 - 151 | ALL | 0.0850 | 0.0200 | 0.1200 | 4.6% |
| 142 - 32 | ALL | 0.0500 | 0.0250 | 0.1200 | 7.9% |
| 31 - 15 | ALL | 0.0850 | 0.0200 | 0.1200 | 4.6% |
| 14 | ALL | 0.0850 | 0.0200 | 0.1200 | 1.9% |

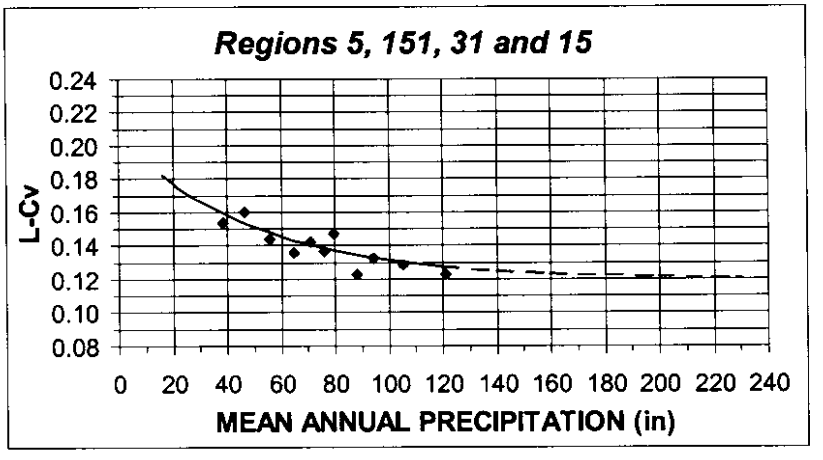



Figure 10a – Predictor Equation Solutions of Observed L-Cv for Climatic Regions 5, 151, 31 and 15 for 2-Hour Duration

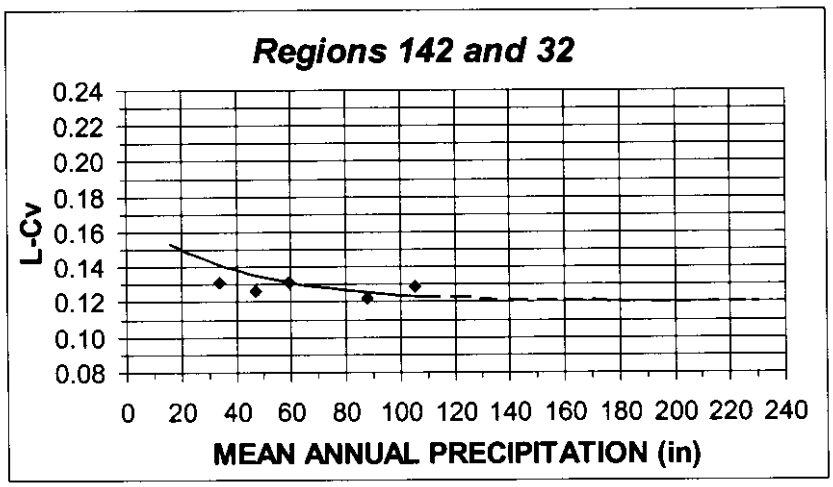



Figure 10b – Predictor Equation Solutions of Observed L-Cv for Climatic Regions 142 and 32 for 2-Hour Duration

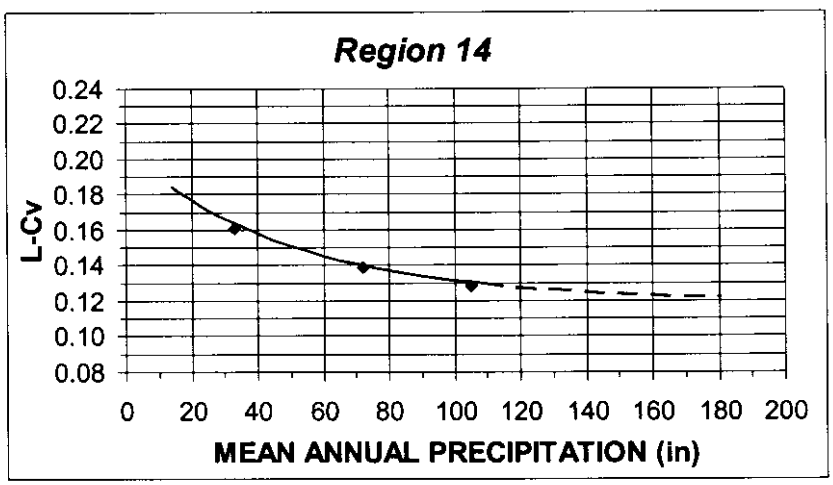



Figure 10c – Predictor Equation Solution of Observed L-Cv for Climatic Region 14 for 2-Hour Duration

Table 8 – Predictor Equations for L-Skewness for 2-Hour Annual Maxima

| $L\text{-}Skewness = \alpha * EXP[-\beta * MAP] + \delta$ | | | | | |
|---|---|---|---|---|---|
| **REGIONS** | **APPLICABILITY** | **ALPHA** | **BETA** | **DELTA** | **STANDARDIZED RMSE** |
| ALL | ALL | 0.1800 | 0.0250 | 0.1700 | 15.7% |

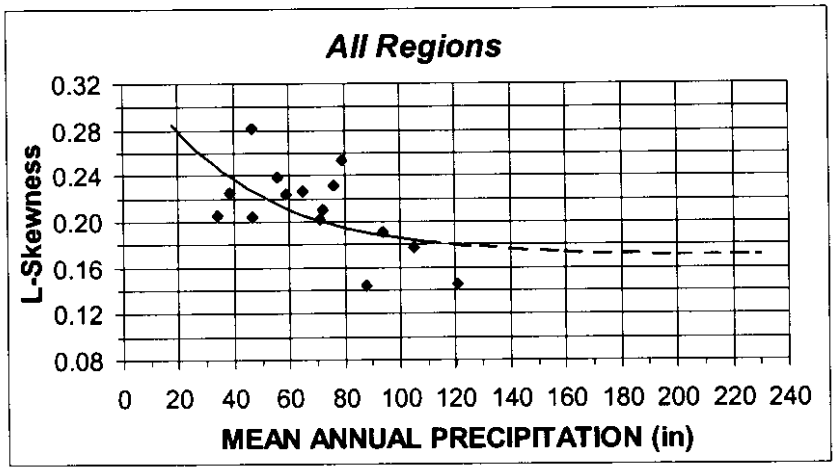



Figure 11 – Predictor Equation Solutions of Observed L-Skewness for All Climatic Regions for 2-Hour Duration

The suitability of the general form of the L-moment predictor equation (Equation 2a) is not as apparent in Figure 11 as was the case for other climatic regions. The naturally high variability of sample L-skewness values makes it more difficult to discern the underlying behavior of the data. However, the general form of the solution curve is consistent with behavior seen at the 24-hour duration and the behavior seen in other regional precipitation studies where the L-skewness values converge to some limiting value for sites with very high mean annual precipitation.

**Heterogeneity Measures, 2-Hour Duration**

Heterogeneity measures H1 and H2 (Hosking and Wallis[9,10]) were used to judge the relative heterogeneity in the proposed sub-regions for L-Cv and L-Skewness, respectively. Computation of H1 and H2 values for the various sub-regions indicated the majority of sub-regions were acceptably homogeneous (Table 9). In those cases where computed heterogeneity measures exceeded acceptance criteria, the excursions were generally of a minor amount. Only one sub-region on the windward face of the Olympics had large excursions beyond the acceptance criteria. In summary, mean annual precipitation was an excellent explanatory variable for describing the variability of L-Cv and L-Skewness across the study area.

Table 9 – Results of Heterogeneity and Goodness-of-Fit Tests for 2-Hour Duration

| CLIMATIC REGIONS | NUMBER OF SUB-REGIONS | HOMOGENEOUS SUB-REGIONS H1 ≤ 2.00 | HOMOGENEOUS SUB-REGIONS H2 ≤ 1.00 | SUB-REGIONS ACCEPTING GEV DISTRIBUTION |
|---|---|---|---|---|
| 5 - 151 | 2 | 1 | 1 | 2 |
| 142 - 32 | 4 | 4 | 2 | 4 |
| 31 -15 | 7 | 5 | 7 | 6 |
| 14 | 2 | 2 | 2 | 1 |
| **TOTAL** | **15** | **12** | **12** | **13** |

**Identification of Regional Probability Distribution, 2-Hour Duration**

The Generalized Extreme Value (GEV) distribution was identified most frequently as the best three-parameter probability model (Table 9) using the L-moment based test statistic for goodness-of-fit. A plot of regional L-Skewness and L-Kurtosis values for the 15 sub-regions at the 2-hour duration in shown in Figure 12. It is seen that the majority of data pairs plot nearest the GEV distribution, with the centroid being slightly above, slightly more kurtotic, than the GEV distribution.

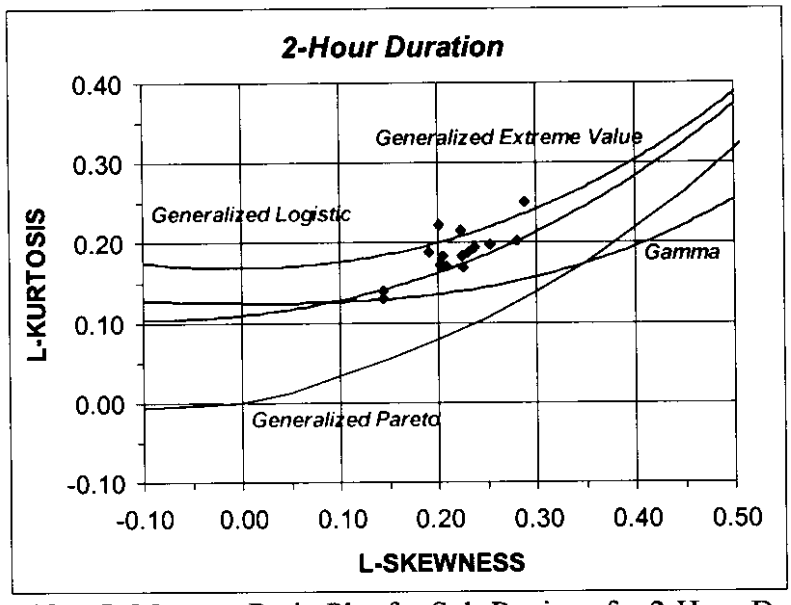


Figure 12 – L-Moment Ratio Plot for Sub-Regions for 2-Hour Duration

As was the case for the 24-hour duration, the GEV is a suitable distribution for estimation of precipitation quantiles out to the 500-year recurrence interval. If quantile estimates are desired for events more extreme than the 500-year recurrence interval, it would be worthwhile to utilize the four-parameter Kappa distribution and to refine the selection of the *h* parameter. To solve for an appropriate *h* value, a hierarchical approach (Fiorentino[4]) was taken wherein the shape parameter *h* was computed as the median value from the group of sub-region solutions. A median value of -0.150 was computed with a standard error of estimation of approximately $\pm$ 0.093. Based on this information, a nominal *h* value of -0.15 was adopted. This produces a regional growth curve slightly steeper than the GEV for very rare events and essentially matches the GEV distribution up to the 100-year recurrence interval.

## PRECIPITATION MAGNITUDE-FREQUENCY ESTIMATES FOR GAGED SITES

The first step in developing a site-specific precipitation magnitude-frequency curve is to compute the regional growth curve. The findings described in the previous sections provide the information necessary for developing the regional growth curve for the 24-hour and 2-hour durations. Specifically, the first three parameters of the Kappa distribution ($\xi$, $\alpha$, and $\kappa$) are solved (Hosking and Wallis[9,12]) using a mean of unity and the applicable regional values of L-Cv and L-Skewness as indicated in Tables 3a,b and 4a,b. The fourth parameter (*h*) of the Kappa distribution is set to the regional average value applicable to the selected duration. Equation 3 is then used to describe the regional growth curve. The site-specific precipitation-frequency curve is obtained by scaling the regional growth curve by the at-site mean.

For gaged sites, the at-site mean ($\hat{\mu}$) can be computed from the gage mean ($\bar{x}$) based on the correction factors ($C_{nop}$) in Table 10. A correction factor (Weiss[32]) is needed to adjust the gage sample mean to account for precipitation measurement and reporting on a fixed time interval rather than on the desired continuous basis. The at-site mean is computed from the gage mean as:

$$\hat{\mu} = C_{nop}(\bar{x}) \tag{4}$$

Table 10 – Correction Factors ($C_{nop}$) to Adjust Gage Sample Statistics

| GAGE TYPE | DURATION | |
|---|---|---|
| | 2-Hour | 24-Hour |
| Daily Gage<br>Snotel Gage | n/a | 1.13 |
| Automated Gage<br>Hourly Reporting | 1.04 | 1.00 |
| Automated Gage<br>15-Minute Reporting | 1.00 | 1.00 |

This procedure can be explained by an example using an existing gaged site. The Seattle-Tacoma Airport gage is located in the Interior Lowlands West, climatic Region 31. The mean annual precipitation for the site is 37.9-inches. For the 24-hour duration, the regional value of L-Cv is 0.159, which is obtained from Equation 2a and parameter values from Table 3b. The regional value of L-Skewness is 0.187, which is obtained from Equation 2a and parameter values from Table 4b. The regional value of the $h$ parameter is -0.05 for the 24-hour duration. Using a mean value of unity, the solution for the four parameters of the Kappa distribution[12,15], yields:

$$\xi = 0.8716, \quad \alpha = 0.2166, \quad \kappa = -0.0394, \quad \text{and} \quad h = -0.05.$$

Use of Equation 3 yields the regional growth curve depicted in Figure 13a. Seattle-Tacoma Airport has an hourly gage with a gage mean of 2.10-inches for the 24-hour duration for 60-years of record. Use of Equation 4 with a correction factor of 1.00 yields an at-site mean value of 2.10-inches for the 24-hour duration. The at-site precipitation magnitude-frequency curve is obtained by scaling the regional growth curve by the at-site mean and is depicted in Figure 13b. The observed 24-hour annual maxima for the Seattle-Tacoma Airport site for the period from 1940-2000 are also depicted in Figure 12b for a comparison of the regional solution and the sample data.

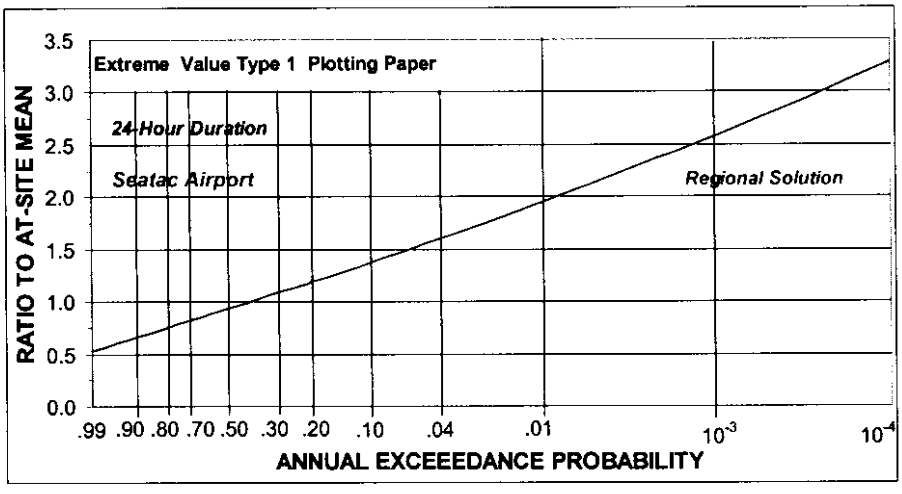



Figure 13a – Regional Growth Curve for Seattle-Tacoma Airport for 24-Hour Duration

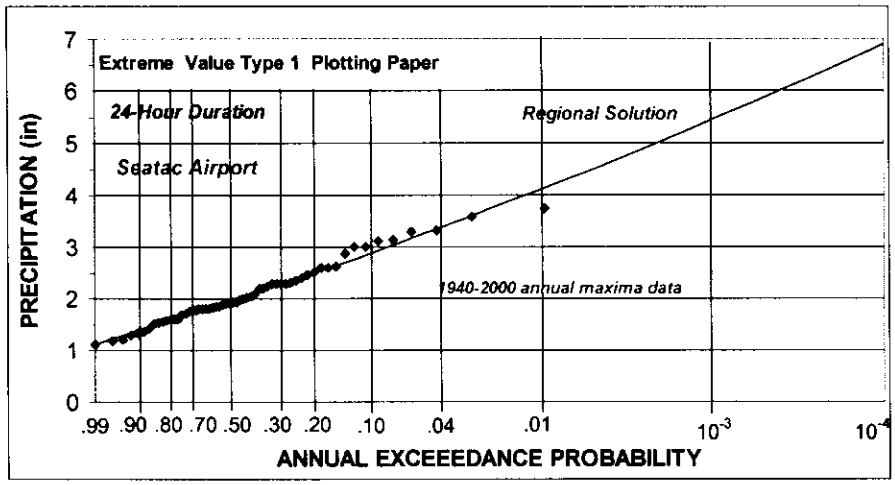



Figure 13b – Precipitation Magnitude-Frequency Curve for Seattle-Tacoma Airport for 24-Hour Duration

## SPATIAL MAPPING OF PRECIPITATION-FREQUENCY INFORMATION

Products from the PRISM model[3] operated by Oregon Climate Service were used in conducting spatial mapping of precipitation for selected recurrence intervals. Gridded datasets and isopluvial maps were prepared for the 2-year, 10-year, 25-year, 50-year and 100-year recurrence intervals for the 24-hour and 2-hour durations. A gridded dataset and isopluvial map was also prepared for the 6-month (twice/year) recurrence interval for the 24-hour duration, which is needed for some water quality applications. Precipitation estimates for the 6-month and 2-year recurrence intervals were converted from annual maxima to partial duration series equivalents using the conversion developed by Langbein[15,27]. This was done to improve the frequency estimates for common events and to be consistent with past mapping products produced by the National Weather Service[16].

The spatial mapping of precipitation for selected recurrence intervals is dependent upon the production of two key components in addition to the regional precipitation-frequency information. The first component required is the spatial mapping of at-site means (station mean values, also called mean annual maxima). Grid-cell values of at-site means are used to scale dimensionless magnitude-frequency relationships to obtain precipitation estimates for the recurrence interval of interest. The second component required is the spatial mapping of regional statistical parameters. This provides L-moment ratio statistics applicable to each grid-cell in the study area domain, which are used to determine the probability distribution parameters for describing the magnitude-frequency relationship applicable to each grid-cell. Thus, the spatial mapping of at-site means and the spatial mapping of regional statistical parameters are the primary work products needed for isopluvial mapping.

### Mean Annual Precipitation

The gridded dataset of mean annual precipitation provides a basis for spatial mapping of both at-site means and L-moment statistics and is therefore an important element of this project. An analysis of mean annual precipitation for the period from 1961 to 1990 has been completed for the study area by Oregon Climate Service using the PRISM model[3,20]. The resultant map has been utilized in this study and provides digital values of mean annual precipitation on a gridded latitude-longitude system with a nominal resolution of 1.25 minutes per grid-cell for the study area (about 1.4 $mi^2$). This resolution yields a study area domain that is a matrix of 216 rows by 336 columns, 72,576 grid-cells.

## SPATIAL MAPPING OF AT-SITE MEANS

Spatial mapping of at-site means encompasses a number of separate tasks that address the spatial behavior of at-site means and seeks to minimize differences between mapped values and sample values computed at precipitation measurement stations. This typically involves first developing relationships between at-site means computed at precipitation measurement stations and climatic/physiographic factors. These relationships are then used to populate the grid-cells in the study area domain with the values predicted from the regression equation based on the climatic/physiographic factors representative of each grid-cell. Residuals are then computed for each of the station at-site means that quantify the magnitude of difference between mapped values and station values. This allows analyses to be conducted of the residuals to identify if there is a coherent spatial pattern to the magnitude and sign of the residuals. When coherent residual patterns are encountered, they are used to adjust the original estimates. Lastly, standard bias and root mean square error measures are computed to quantify the overall goodness-of-fit of the mapped values relative to the observations at the gages. The completed maps of the at-site means for the 24-hour and 2-hour durations are shown in Figures 14a,b, respectively.

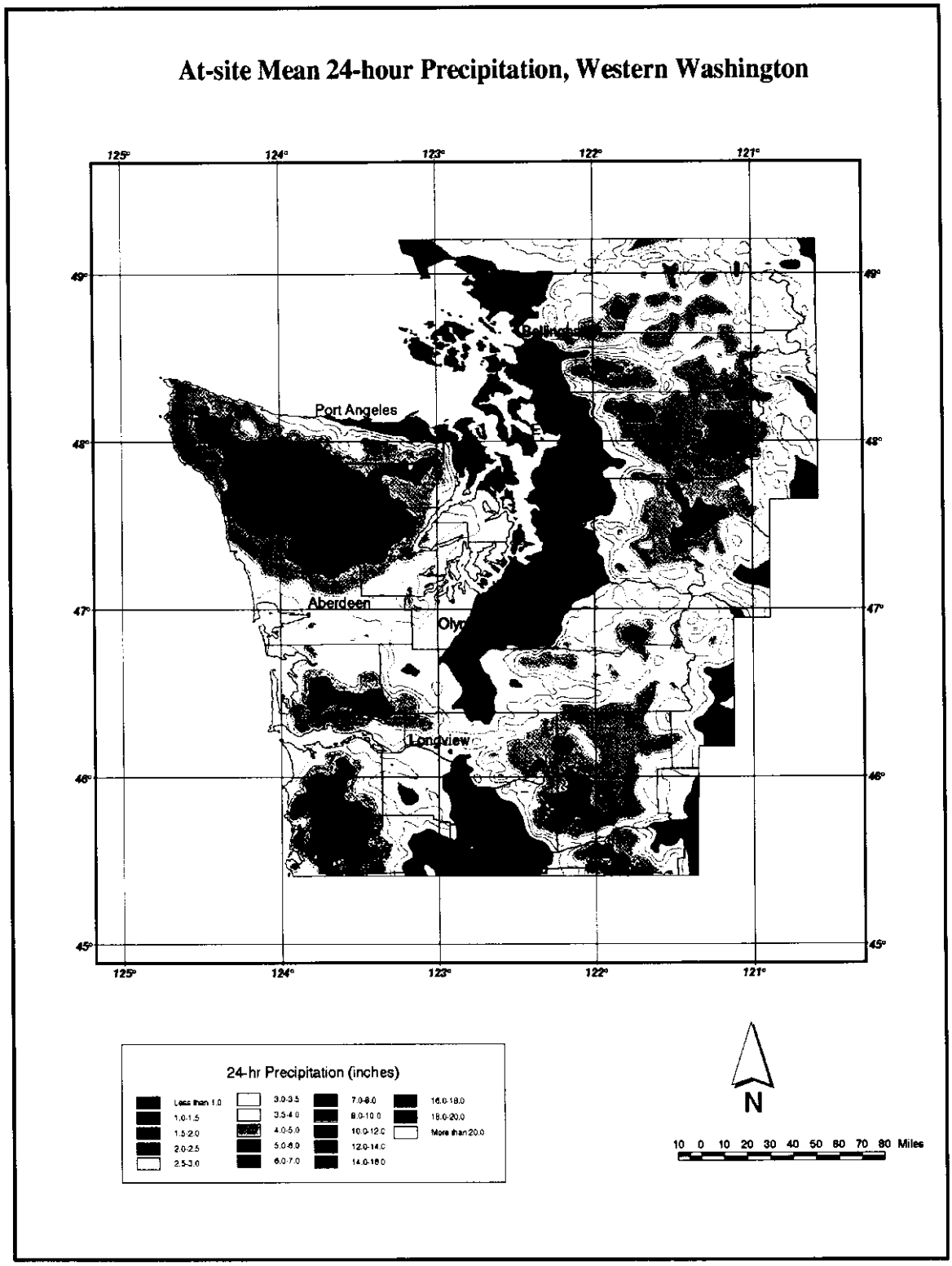



Figure 14a – Map of At-Site Means for 24-Hour Duration for Western Washington

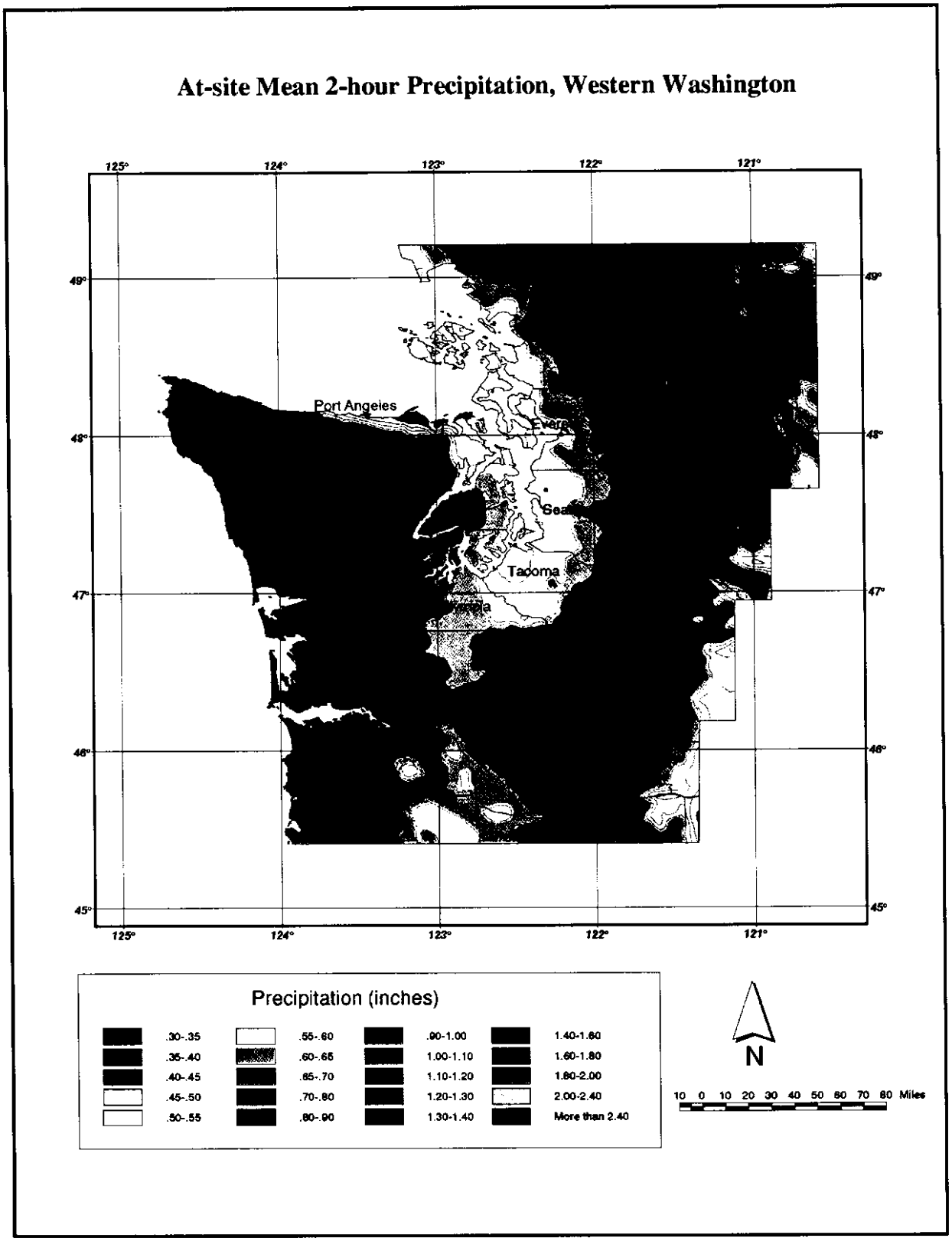



Figure 14b – Map of At-Site Means for 2-Hour Duration for Western Washington

**Quantitative Assessment of Success Achieved in Spatial Mapping of At-Site Means**
A quantitative measure was needed to assess the relative success of the spatial mapping procedures in capturing the spatial behavior of the at-site means. This is a difficult task in all studies of this type because the true values of the at-site means are unknown. The logical standard for comparison is the station sample value of at-site mean. However, sample values of the station at-site mean will differ from the true population values due to sampling variability, and other natural and man-related variability associated with precipitation measurement and recording.

We chose to approach this problem by framing the question as - how do the observed station values compare with the final mapped values? Given this question, the bias and root mean square error (RMSE) computations can be expressed in standardized units using the mapped values as the predicted value. This equates to computing bias and RMSE for the standardized residuals ($SR_2$) as:

$$SR_2 = (S - P_2) / P_2 \qquad (5)$$

where: $S$ is the observed station value of the at-site mean (in); and $P_2$ is the mapped value of the station at-site-mean (in).

The computed standardized residuals are listed in Tables 11a,b. It is seen that the final mapped values of the at-site means are nearly unbiased. If the RMSE values for the stations are representative of the at-site mean maps taken as a whole, then the final maps of at-site means have a standard error of estimate that is near 5%. The RMSE of the final mapped values are generally similar in magnitude to that expected from natural sampling variability and, thus, are as low as can reasonably be expected.

Table 11a –Bias and Root Mean Square Error of Standardized Residuals for Final Mapped Values of At-Site Means for 24-Hour Duration

| REGION | FINAL MAPPED VALUES | |
|---|---|---|
| | *Bias* | *RMSE* |
| **COASTAL AREAS** | | |
| Region 5 | +1.04% | 5.26% |
| Region 151 | -0. 68% | 2.92% |
| Region 142 | -1.47% | 5.07% |
| | | |
| **INTERIOR LOWLAND AREAS** | | |
| Region 32 | +0. 56% | 6.63% |
| Region 31 | +0.41% | 4.42% |
| | | |
| **CASCADE MOUNTAIN AREAS** | | |
| Region 15 | +0.02% | 4.01% |
| Region 14 | +0.17% | 6.27% |
| | | |
| **ALL REGIONS** | +0.18% | 5.21% |

Table 11b – Bias and Root Mean Square Error of Standardized Residuals for Final Mapped Values of At-Site Means for 2-Hour Duration

| REGION | FINAL MAPPED VALUES | |
|---|---|---|
| | *Bias* | *RMSE* |
| **COASTAL AREAS** | | |
| Region 5 | +0.61% | 1.55% |
| Region 151 | -1.58% | 5.77% |
| Region 142 | +2.75% | 5.57% |
| | | |
| **INTERIOR LOWLAND AREAS** | | |
| Region 32 | +0. 35% | 3.66% |
| Region 31 | +0.24% | 2.95% |
| | | |
| **CASCADE MOUNTAIN AREAS** | | |
| Region 15 | +0.55% | 4.12% |
| Region 14 | -0.85% | 4.70% |
| | | |
| **ALL REGIONS** | +0.21% | 3.96% |

## SPATIAL MAPPING OF REGIONAL L-MOMENT STATISTICAL PARAMETERS

In order to compute precipitation estimates for the selected recurrence intervals, the appropriate value of L-Cv and L-skewness must be obtained for each grid-cell. This was accomplished by populating the grid-cells in the study area domain utilizing the functional relationships for L-Cv and L-skewness (Tables 3a,b and 4a,b) developed in the regional precipitation-frequency analysis.

A smoothing filter was then employed along regional boundaries to provide a smooth transition of L-moment ratio values across boundaries. In general, these were minor adjustments with changes of only a few percent, as particular care had previously been taken in the precipitation-frequency study to minimize differences at regional boundaries.

Separate gridded data files were prepared for L-Cv and L-skewness for each of the two durations, and are included as electronic files with this report (Appendix A).

## PRODUCTION OF ISOPLUVIAL MAPS

Production of the isopluvial maps was accomplished by incorporation of the information described in the prior sections. For each grid-cell, the applicable value of the at-site mean and L-moment ratios L-Cv and L-skewness were used to solve the distribution parameters for the four-parameter Kappa distribution[9,12]. The distribution parameters were then used with Equation 3 to compute the expected value of the precipitation for the desired recurrence interval. This procedure was repeated for each grid-cell until the domain for the study area was populated. The resultant precipitation field was then contoured to yield isopluvials for selected values of precipitation.

An example of an isopluvial map produced by this process is depicted in Figure 15, which shows a color-shaded map of 24-hour 100-year precipitation. Isopluvial maps for the other selected recurrence intervals for the 24-hour and 2-hour durations are contained in Appendix B.

**Precipitation Magnitude-Frequency Estimates for Moderate to Large Size Watersheds**
The precipitation magnitude-frequency information contained in the gridded datasets and depicted on the isopluvial maps corresponds to 10-mi$^2$ and 1-mi$^2$ precipitation for the 24-hour and 2-hour durations, respectively. Estimation of precipitation volumes for larger watersheds for a selected recurrence interval requires the application of areal reduction factors[16,18,19]. Areal reduction factors would be obtained from analyses of historical storms. The topic of areal reduction factors, depth-area-duration analyses, and estimation of precipitation for moderate to large size watersheds is beyond the scope of this report. It is mentioned here to alert the reader that precipitation values from the gridded datasets and isopluvial maps need to be scaled by areal reduction factors to obtain estimates of precipitation volumes for moderate to large watersheds.

**Uncertainty Bounds for 100-Year Values**
The accuracy of estimation of 100-year precipitation annual maxima at a given location is dependent upon the success obtained in estimating the at-site mean, and L-moment ratios L-Cv and L-skewness, and the similarity between the chosen probability model (Kappa distribution) and the actual model mother-nature is using, which is unknown.

In general, uncertainties associated with the estimation of L-moment ratios L-Cv and L-skewness result in standard errors of estimation of about 5% at the 100-year recurrence interval. These relatively low levels of uncertainty are attributable to the very large datasets that were used to estimate the L-moment ratios and identify a suitable probability model. Interaction of these standard errors of estimation with that due to estimation of the at-site mean (Tables 11a,b) yield the standard errors of estimation shown in Table 12. The range in standard errors of estimation for a given duration is primarily due to the region-to-region variation of the standard errors for estimation of the at-site mean for the recurrence intervals cited in Table 12.

The values in Table 12 should be considered approximate as detailed studies for computation of uncertainty bounds have not been conducted. Further, these values represent regional averages. Values applicable to a given location may be somewhat smaller or larger than that indicated in Table 12.

Table 12 – Range of Standard Errors of Estimation for Selected Recurrence Intervals

| DURATION | STANDARD ERROR OF ESTIMATION FOR PRECIPITATION | |
|---|---|---|
| | 10-YEAR | 100-YEAR |
| 2-HOUR | 4% - 7% | 6% - 9% |
| 24-HOUR | 5% - 8% | 7% - 10% |

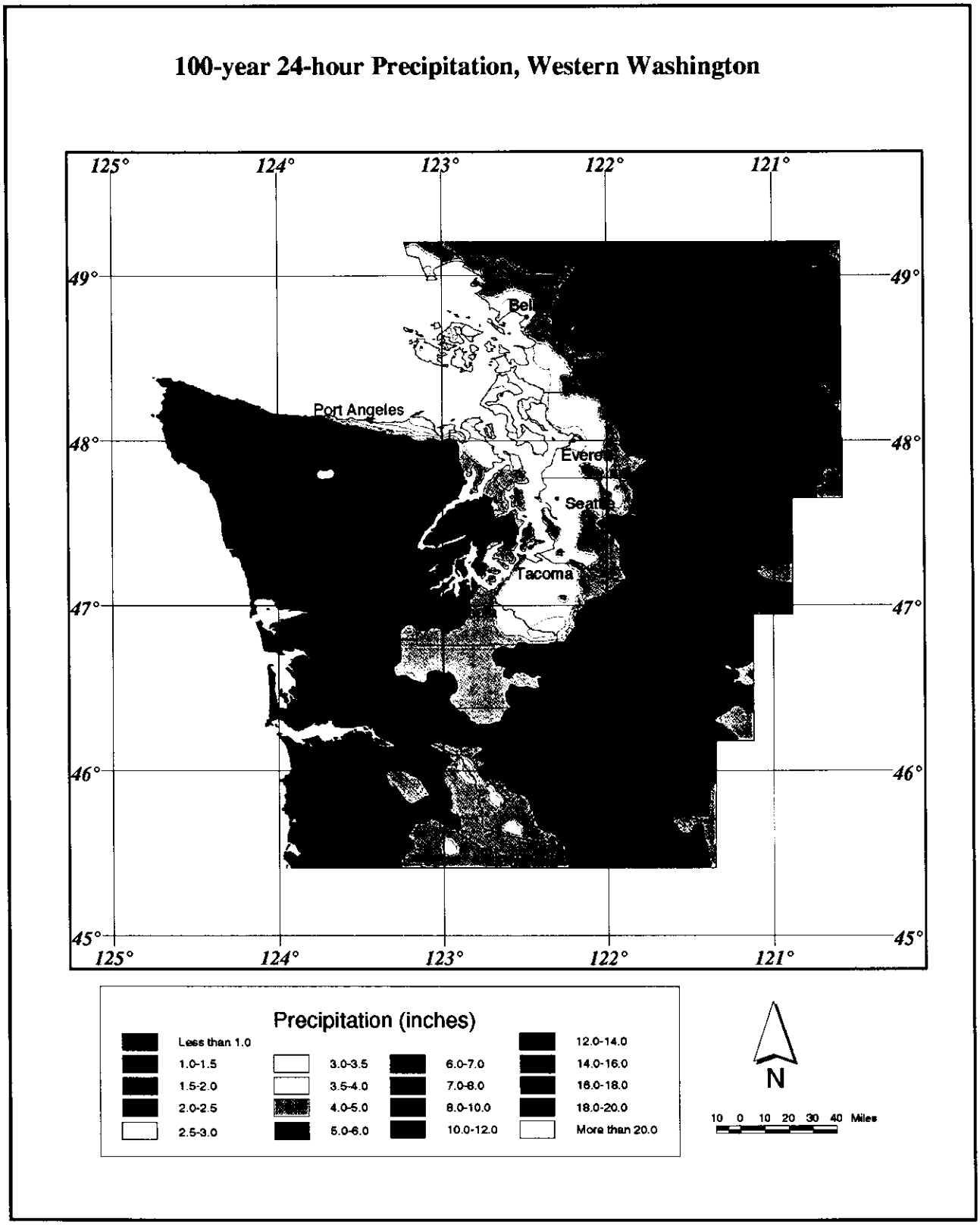



Figure 15 – Isopluvial Map of 24-Hour Precipitation for 100-Year Recurrence Interval for Western Washington

## ELECTRONIC FILES

## LISTING AT-SITE AND REGIONAL PARAMETERS FOR ALL GAGED SITES

Appendix A includes station catalogs for the stations/gages used in the study. It also references a compact disc (CD) containing ASCII text files and Excel spreadsheets listing the precipitation estimates for selected recurrence intervals. Specifically, the files contain the station identification number, station name, type of gage, climatic region number, latitude, longitude, elevation, mean annual precipitation, sample value of at-site mean, mapped value of at-site mean, regional values of L-Cv, L-skewness, *h* parameter for the Kappa distribution, and estimated 6-month, 2-year, 10-year, 25-year, 50-year, 100-year, and 500-year precipitation.

## SEASONALITY OF EXTREME STORMS

The seasonality of extreme storms can be a valuable tool for application of the precipitation-frequency information in rainfall-runoff modeling. Specifically, information on the seasonality of storms is helpful in decision-making for setting watershed conditions antecedent to the storm. The seasonality of extreme storms was investigated by constructing frequency histograms of the storm dates for rare 24-hour and 2-hour precipitation amounts for each of the seven climatic regions. Extreme storms were taken to be precipitation amounts with annual exceedance probabilities less than 0.05 (rarer than a 20-year event). Precipitation amounts/gages with duplicate storm dates (generally dates within 7 calendar days) were removed before constructing the frequency histograms for each climatic region. The results of the seasonality analyses are discussed briefly below and additional frequency histograms are presented in Appendix C.

Well-defined seasonal patterns are apparent for the 24-hour and 2-hour durations. In western Washington, storms which are extreme at the 24-hour duration occur predominantly in the fall and winter months (Figure 16). These storms are the result of synoptic scale cyclonic weather systems and associated fronts. These storms remain organized and penetrate a considerable distance inland from the coast, as the eastern slopes of the Cascade Mountains also exhibit a distinctive fall-winter seasonal pattern.

Storms which are extreme at the 2-hour duration exhibit greater seasonal variability. In lowland areas, storms that are extreme at the 2-hour duration occur both in the warm season and in the fall and winter period (Figure 17a). Some of these events are localized events having limited areal coverage with precipitation occurring over a relatively short period of time. Other events are embedded in longer duration cool season storm events and are associated with large-scale weather systems having more widespread areal coverage. As the precipitation amounts become more rare and increase in magnitude, there is a greater likelihood that they are associated with a localized event and have temporal characteristics of a thunderstorm. These more rare events are more likely to occur in the warm season as a result of convective storm activity. (Figure 17b).

In coastal and mountain areas, the seasonality of extreme 2-hour storms covers the period from late-spring through winter. Moderately large 2-hour precipitation amounts are often embedded within longer duration storms associated with large-scale weather systems. For these sites, there is a greater percentage of storms at the 2-hour duration that occur in the fall and winter period (Figure 18).

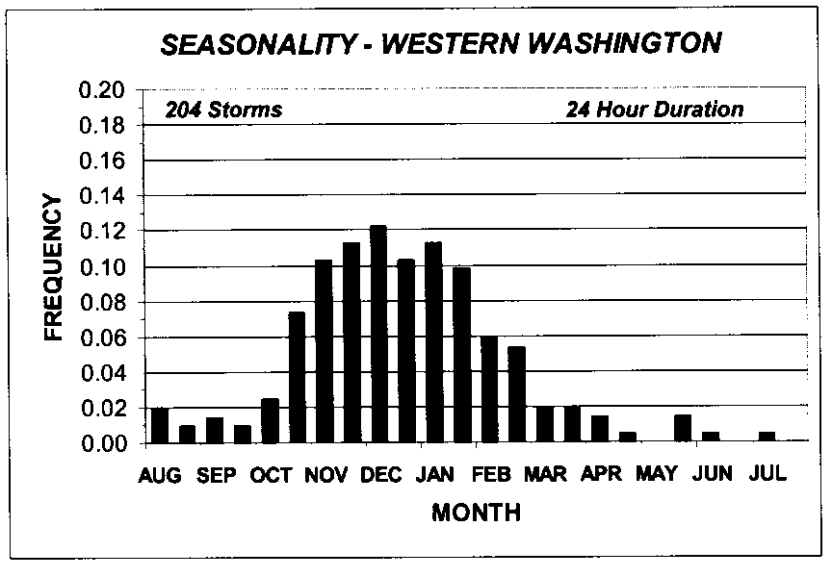



Figure 16 – Seasonality of Extreme Storms for All Climatic Regions for 24-Hour Duration

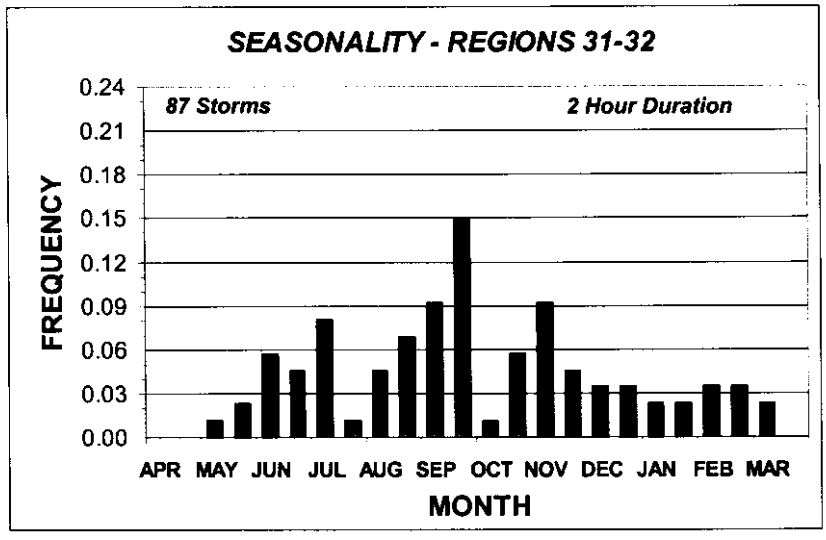



Figure 17a – Seasonality of Extreme Storms in Lowland Climatic Regions 31 and 32 for 2-Hour Duration

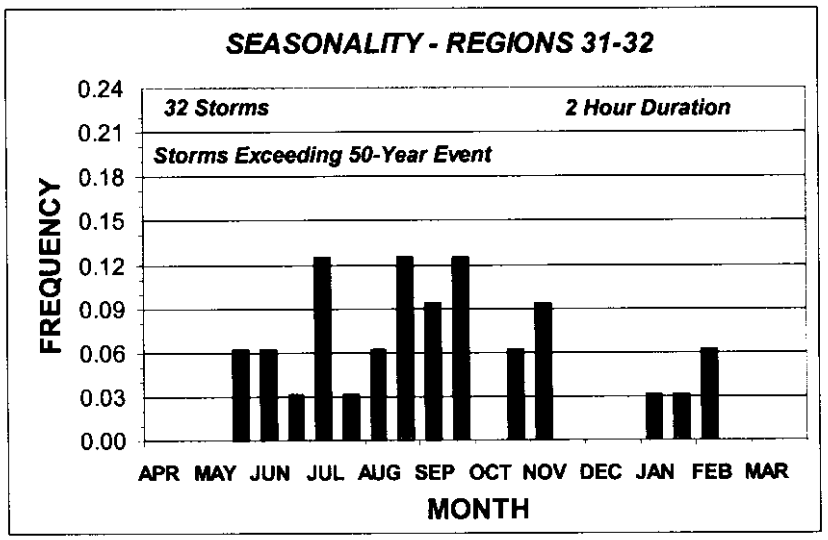



Figure 17b – Seasonality of Extreme Storms that Exceed 50-Year Event in Lowland Climatic Regions 31 and 32 for 2-Hour Duration

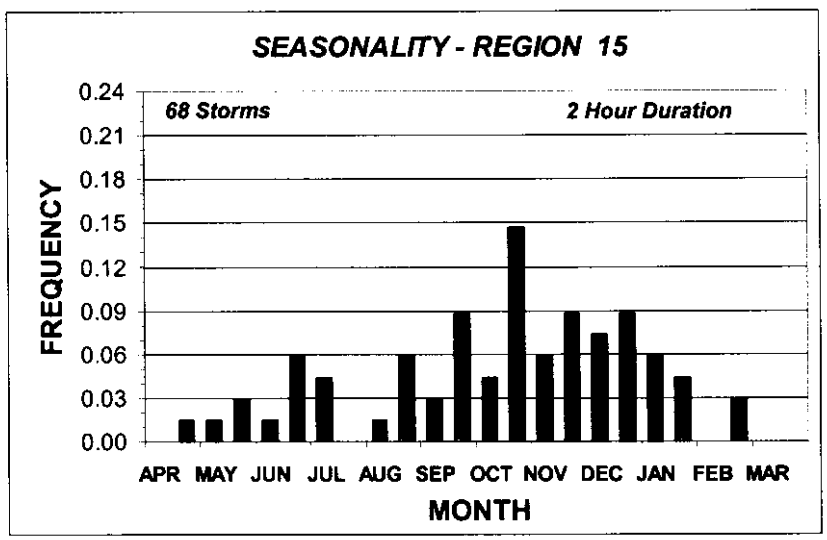



Figure 18 – Seasonality of Extreme Storms for Climatic Region 15 Windward Face of Cascade Mountains for 2-Hour Duration

## CATALOG OF EXTREME STORMS

A catalog of extreme storms is contained in Appendix D. The catalog lists those storm events at the 24-hour and 2-hour durations where the annual exceedance probabilities were less than 0.05 (rarer than a 20-year event). These are the same storm events/storm dates as used in the seasonality analysis. The temporal patterns from these storms would be logical candidates for single event rainfall-runoff modeling of extreme storms.

## REFERENCES


1. Cunnane C, Unbiased Plotting Positions - A Review, Journal of Hydrology, 37, 205-222, 1978.
2. Dalrymple D, Flood Frequency Analysis, USGS, Water Supply Paper 1543-A, 1960.
3. Daly C, PRISM, Parameter-Elevation Regression on Independent Slopes Model, Oregon State University, Oregon Climate Service, 1994.
4. Fiorentino MS, Gabrielle S, Rossi F and Versace P, Hierarchical Approach for Regional Frequency Analysis, *Regional Frequency Analysis*, Edited by VP Singh, pp35-49, Reidel, Norwell Massachusetts, 1979.
5. Gringorten II, A Plotting Rule for Extreme Probability Paper, Journal of Geophysical Research, 68(3), 813-814, 1963.
6. Helsel DR and Hirsch RM, Statistical Methods in Water Resources, Elsevier Studies in Environmental Science 49, NY, 1992.
7. Hosking JRM, L-Moments: Analysis and Estimation of Distributions using Linear Combinations of Order Statistics, Journal Royal Statistical Society, Ser B, 52, pp105-124, 1990.
8. Hosking JRM, and Wallis JR, A Comparison of Unbiased and Plotting Position Estimators of L-Moments, Water Resources Research, Vol 31, pp2019-2025, 1995.
9. Hosking JRM, and Wallis JR, Regional Frequency Analysis - An Approach Based on L-Moments, Cambridge Press, 1997.
10. Hosking JRM, and Wallis JR, Some Statistics Useful in Regional Frequency Analysis, Water Resources Research, Vol 29, No. 2, pp271-281, Feb 1993.
11. Hosking JRM, and Wallis JR, The Effect of Inter-Site Dependence on Regional Flood Frequency Analysis, Water Resources Research, Vol 24, pp588-600, 1988.
12. Hosking JRM, The Four Parameter KAPPA Distribution, IBM Research Report RC13412, IBM Research Yorktown Heights NY, 1988.
13. Hosking JRM, The Theory of Probability Weighted Moments, IBM Research ReportRC12210, October 1986.
14. Kuczera G, Combining Site-Specific and Regional Information: An Empirical Bayes Approach, Water Resources Research, Volume 18, No. 2, pp306-314, April 1982.
15. Langbein WB, Annual Floods and the Partial Duration Flood Series, Transaction American Geophysical Union, Vol 30, pp879-881, 1949.
16. Miller JF, Frederick RH and Tracey RS, NOAA ATLAS 2, Precipitation - Frequency Atlas of the Western United States, U.S. Dept. of Commerce, NOAA, National Weather Service, Washington DC, 1973.
17. National Research Council, Estimating Probabilities of Extreme Floods, Methods and Recommended Research, National Academy Press, Washington DC, 1988.
18. NWS, National Weather Service, Hydrometeorological Report 43, Probable Maximum Precipitation for the Pacific Northwest, U.S. Department of Commerce, NOAA, U.S. Weather Bureau, Washington DC, 1966

19. NWS, National Weather Service, Hydrometeorological Report 57, Probable Maximum Precipitation for the Pacific Northwest, U.S. Department of Commerce, NOAA, U.S. Weather Bureau, Washington,D.C., October 1994.

20. Oregon Climate Service, Mean Annual Precipitation Maps for Western United States, prepared with PRISM Model for NRCS, Corvallis Oregon, 1997.

21. Oregon Climate Service, Mean Annual Precipitation Map for Southern British Columbia, prepared with PRISM Model for Environment Canada, Corvallis Oregon, 2000.

22. Potter KW, Research on Flood Frequency Analysis, 1983-1986, U.S. National Report, International Union of Geodesy and Geophysics, 25(2), pp113-118, 1987.

23. Schaefer MG, Regional Analyses of Precipitation Annual Maxima in Washington State, Water Resources Research, Vol.26, No.1, pp119-132, January,1990.

24. Schaefer MG, Characteristics of Extreme Precipitation Events in Washington State, Washington State Dept. of Ecology, Report 89-51, October 1989.

25. Schaefer MG, Magnitude-Frequency Characteristics of Precipitation Annual Maxima in Southern British Columbia, MGS Engineering Consultants, Inc., prepared for BChydro Power Supply and Engineering, December 1997.

26. Schaefer MG and Barker BL, Precipitation Magnitude-Frequency Characteristics for the American River Watershed, prepared for US Army Corps of Engineers, Hydrologic Engineering Center, MGS Engineering Consultants, January 2000.

27. Stedinger JR, Vogel RM, and Foufoula-Georgiou E, Frequency Analysis of Extreme Events, Chapter 18, *Handbook of Hydrology*, McGraw Hill, 1992.

28. US Weather Bureau, Mean Annual Precipitation in Washington 1930-1957, Seattle Office National Weather Service. 1965.

29. Wallis JR, Personal Communication, April, 1997.

30. Wallis JR, Risk and Uncertainties in the Evaluation of Flood Events for the Design of Hydraulic Structures, in *Pienne e Siccita*, edited by E. Guggino, G. Rossi, and E. Todini, pp3-36, Fondazione Politecnica del Mediterranes, Catania, Italy, 1980.

31. Wallis JR, Hydrologic Problems Connected with Oil-Shale Development, Environmental Systems and Management, S. Rinaldi, Editor, North Holland, Amsterdam, pp. 85-102, 1982.

32. Weiss LL, Ratio of True to Fixed Interval Maximum Rainfall, Journal Hydraulics, ASCE, 90(HY1), pp77-82, 1964.

# Appendix A

## STATION CATALOGS

## AND

## ELECTRONIC FILES OF PROJECT DELIVERABLES

## OVERVIEW

This appendix includes station catalogs for the stations/gages used in the study for analysis of precipitation annual maxima at the 24-hour and 2-hour durations. These listings include the station identification number, station name, type of gage, climatic region number, latitude, longitude, elevation, and mean annual precipitation. A compact disc (CD) is also included as part of this appendix that contains electronic files for all of the project deliverables. Two items of particular interest are: a listing of precipitation magnitude-frequency estimates for each of the stations for the 6-month, 2-year, 10-year, 25-year, 50-year, 100-year, and 500-year recurrence intervals; and gridded datasets of precipitation-frequency values for the recurrence intervals listed above, that can be imported into GIS software .

The CD contains files with the following contents:

- catalog of stations
- precipitation annual maxima for all gages
- catalog of extreme storms
- gridded datasets for 24-hour and 2-hour mean annual maxima (at-site means)
- gridded datasets of L-moment ratios L-Cv and L-Skewness for 24-hour and 2-hour durations
- gridded datasets of precipitation estimates for selected recurrence intervals
- precipitation magnitude-frequency estimates for selected recurrence intervals for each station
- final report and supporting graphics

Table A1 – Station Catalog of Gages Used in Analyses of Precipitation Annual Maxima at 24-Hour Duration

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1100030 | ABBOTSFORD A | BC | 49.0333 | 122.3667 | 190 | 1944 | 1996 | 53 | 31 | DY | 57.8 |
| 45-0008 | ABERDEEN | WA | 46.9500 | 123.8167 | 10 | 1897 | 2000 | 104 | 5 | DY | 83.5 |
| 45-0013 | ABERDEEN 20 NNE | WA | 47.2667 | 123.7000 | 435 | 1931 | 2000 | 70 | 151 | DY | 131.0 |
| 45-0013 | ABERDEEN 20 NNE | WA | 47.2667 | 123.7000 | 435 | 1940 | 2000 | 61 | 151 | HR | 131.0 |
| 1100120 | AGASSIZ CDA | BC | 49.2500 | 121.7667 | 49 | 1889 | 1995 | 107 | 14 | DY | 67.6 |
| 1030180 | ALBERNI BEAVER CREEK | BC | 49.3667 | 124.9333 | 298 | 1894 | 1959 | 66 | 142 | DY | 97.2 |
| 45-0094 | ALDER DAM CAMP | WA | 46.8000 | 122.3167 | 1300 | 1948 | 1954 | 7 | 15 | DY | 50.2 |
| SN-0564 | ALDERWOOD WATER DIST | WA | 47.8600 | 122.2839 | 620 | 1988 | 2000 | 13 | 31 | DY | 40.2 |
| 1020270 | ALERT BAY | BC | 50.5833 | 126.9333 | 193 | 1924 | 1994 | 71 | 142 | DY | 67.5 |
| 1100360 | ALOUETTE LAKE | BC | 49.2833 | 122.4833 | 383 | 1924 | 1982 | 59 | 15 | DY | 102.5 |
| 1100370 | ALOUETTE POWER HOUSE | BC | 49.3667 | 122.3167 | 298 | 1935 | 1949 | 15 | 15 | DY | 109.3 |
| 21B48S | ALPINE MEADOWS | WA | 47.7833 | 121.7000 | 3500 | 1995 | 1999 | 5 | 15 | DY | 101.5 |
| 45-0176 | ANACORTES | WA | 48.5000 | 122.6000 | 20 | 1897 | 2000 | 104 | 31 | DY | 27.2 |
| 45-0242 | ARIEL DAM | WA | 45.9667 | 122.5667 | 220 | 1934 | 1972 | 39 | 31 | DY | 67.3 |
| 45-0257 | ARLINGTON | WA | 48.2000 | 122.1333 | 100 | 1936 | 2000 | 65 | 31 | DY | 47.0 |
| 35-0318 | ASTOR EXPERIMENT STN | OR | 46.1500 | 123.8167 | 49 | 1948 | 1973 | 26 | 5 | DY | 83.0 |
| 35-0324 | ASTORIA | OR | 46.1833 | 123.8333 | 200 | 1948 | 1960 | 13 | 5 | DY | 80.7 |
| 35-0328 | ASTORIA AP PORT OF | OR | 46.1500 | 123.8667 | 9 | 1953 | 2000 | 48 | 5 | DY | 77.3 |
| 35-0328 | ASTORIA AP PORT OF | OR | 46.1500 | 123.8667 | 9 | 1953 | 2000 | 48 | 5 | HR | 77.3 |
| 45-0324 | AUBURN | WA | 47.3167 | 122.2333 | 79 | 1954 | 1977 | 24 | 31 | HR | 38.5 |
| 35-0343 | AURORA | OR | 45.2333 | 122.7333 | 72 | 1951 | 1969 | 19 | 31 | DY | 40.7 |
| 45-0400 | BALDY MOUNTAIN | WA | 46.1000 | 122.7000 | 2190 | 1983 | 1989 | 7 | 15 | HR | 90.2 |
| 1030605 | BAMFIELD EAST | BC | 48.8333 | 125.1167 | 13 | 1959 | 1995 | 37 | 5 | DY | 115.2 |
| 45-0456 | BARING | WA | 47.7667 | 121.4833 | 760 | 1970 | 2000 | 31 | 15 | DY | 103.2 |
| 45-0482 | BATTLE GROUND | WA | 45.7667 | 122.5167 | 284 | 1930 | 2000 | 71 | 31 | DY | 50.3 |
| 1010720 | BEAR CREEK | BC | 48.5000 | 124.0000 | 1151 | 1910 | 1996 | 87 | 151 | DY | 122.5 |
| 35-0571 | BEAR SPRINGS RS | OR | 45.1167 | 121.5333 | 3360 | 1961 | 2000 | 40 | 14 | HR | 28.5 |
| 35-0595 | BEAVERTON 2 SSW | OR | 45.4500 | 122.8167 | 270 | 1973 | 2000 | 28 | 32 | DY | 40.2 |
| 45-0587 | BELLINGHAM 3 SSW | WA | 48.7167 | 122.5167 | 15 | 1911 | 2000 | 90 | 31 | DY | 38.0 |
| 45-0574 | BELLINGHAM CAA AP | WA | 48.8000 | 122.5333 | 147 | 1941 | 1952 | 12 | 31 | HR | 39.4 |
| 45-0574 | BELLINGHAM FCWOS AP | WA | 48.8000 | 122.5333 | 149 | 1950 | 2000 | 51 | 31 | DY | 39.4 |
| 45-0729 | BLAINE | WA | 49.0000 | 122.7500 | 60 | 1941 | 2000 | 60 | 31 | DY | 45.6 |
| 45-0729 | BLAINE | WA | 49.0000 | 122.7500 | 60 | 1941 | 2000 | 60 | 31 | HR | 45.6 |
| 21D33S | BLAZED ALDER | OR | 45.4167 | 121.8667 | 3650 | 1981 | 2000 | 20 | 15 | DY | 114.6 |
| 20B02S | BLEWETT PASS | WA | 47.3500 | 120.6833 | 4270 | 1982 | 1999 | 18 | 14 | DY | 33.4 |
| 1020885 | BLIND CHANNEL | BC | 50.4167 | 125.5000 | 9 | 1956 | 1993 | 38 | 142 | DY | 92.4 |
| KI-04U | BOEING CREEK | WA | 47.7508 | 122.3593 | 450 | 1990 | 2000 | 11 | 31 | DY | 37.8 |
| 35-0897 | BONNEVILLE DAM | OR | 45.6333 | 121.9500 | 62 | 1948 | 2000 | 53 | 15 | DY | 78.1 |
| 35-0897 | BONNEVILLE DAM | OR | 45.6333 | 121.9500 | 62 | 1940 | 2000 | 61 | 15 | HR | 78.1 |
| 45-0826 | BOTHELL 2 N | WA | 47.7667 | 122.2167 | 112 | 1948 | 1959 | 12 | 31 | DY | 39.0 |
| 45-0872 | BREMERTON | WA | 47.5667 | 122.6667 | 110 | 1899 | 2000 | 102 | 32 | DY | 51.9 |
| 35-1028 | BRIGHTWOOD | OR | 45.3667 | 122.0167 | 1070 | 1959 | 1982 | 24 | 15 | DY | 89.9 |
| 35-1033 | BRIGHTWOOD 1 WNW | OR | 45.3833 | 122.0333 | 978 | 1971 | 2000 | 30 | 15 | HR | 79.1 |
| 45-0917 | BROOKLYN | WA | 46.7833 | 123.5000 | 190 | 1928 | 1974 | 47 | 32 | DY | 81.3 |
| 45-0945 | BUCKLEY 1 NE | WA | 47.1667 | 122.0000 | 685 | 1913 | 2000 | 88 | 31 | DY | 50.5 |
| 45-0969 | BUMPING LAKE | WA | 46.8667 | 121.3000 | 3442 | 1910 | 1967 | 58 | 14 | DY | 51.7 |
| 21C38S | BUMPING RIDGE | WA | 46.8167 | 121.3333 | 4600 | 1979 | 1999 | 21 | 14 | DY | 50.4 |
| 1101140 | BUNTZEN LAKE | BC | 49.3833 | 122.8667 | 32 | 1924 | 1983 | 60 | 15 | DY | 131.7 |
| 45-0986 | BURLINGTON | WA | 48.4667 | 122.3167 | 30 | 1941 | 2000 | 60 | 31 | HR | 36.5 |
| 1101200 | BURQUITLAM VANCOUVER | BC | 49.2500 | 122.8833 | 400 | 1926 | 1995 | 70 | 31 | DY | 69.0 |
| 35-1222 | BUXTON | OR | 45.6833 | 123.1833 | 355 | 1948 | 2000 | 53 | 32 | HR | 55.2 |
| 35-1227 | BUXTON MOUNTAINDALE | OR | 45.6833 | 123.0667 | 360 | 1948 | 1975 | 28 | 32 | HR | 53.5 |
| 1021230 | CAMERON LAKE | BC | 49.2833 | 124.5833 | 633 | 1924 | 1986 | 63 | 32 | DY | 66.8 |
| 45-1064 | CAMP GRISDALE | WA | 47.3667 | 123.6000 | 820 | 1956 | 1986 | 31 | 151 | HR | 166.4 |
| 35-1329 | CANBY 2 NE | OR | 45.2833 | 122.6667 | 89 | 1948 | 1979 | 32 | 31 | DY | 42.8 |
| TH-1168 | CAPITOL FOREST | WA | 46.9215 | 123.0900 | 450 | 1995 | 2000 | 6 | 142 | HR | 80.0 |
| 1031402 | CARMANAH POINT | BC | 48.6167 | 124.7500 | 124 | 1968 | 1995 | 28 | 5 | DY | 120.0 |
| 45-1146 | CARNATION 4 NW | WA | 47.6833 | 121.9833 | 50 | 1941 | 2000 | 60 | 31 | HR | 49.0 |
| 45-1160 | CARSON FISH HATCHERY | WA | 45.8667 | 121.9667 | 1134 | 1977 | 2000 | 24 | 14 | DY | 102.0 |
| 45-1160 | CARSON FISH HATCHERY | WA | 45.8667 | 121.9667 | 1134 | 1977 | 2000 | 24 | 14 | HR | 102.0 |
| 35-1407 | CASCADE LOCKS | OR | 45.6833 | 121.8833 | 102 | 1948 | 1954 | 7 | 15 | DY | 89.1 |
| 45-1191 | CASTLE ROCK 2 NW | WA | 46.2667 | 122.9167 | 39 | 1954 | 1978 | 25 | 31 | HR | 47.7 |
| 45-1205 | CATHLAMET 6 NE | WA | 46.2667 | 123.3000 | 180 | 1959 | 2000 | 42 | 142 | DY | 77.3 |
| 45-1207 | CATHLAMET 9 NE | WA | 46.3167 | 123.2667 | 479 | 1948 | 1959 | 12 | 142 | DY | 80.9 |
| 45-1233 | CEDAR LAKE | WA | 47.4167 | 121.7333 | 1560 | 1931 | 2000 | 70 | 15 | DY | 106.9 |
| 45-1233 | CEDAR LAKE | WA | 47.4167 | 121.7333 | 1560 | 1953 | 2000 | 48 | 15 | HR | 106.9 |
| 45-1276 | CENTRALIA | WA | 46.7167 | 122.9500 | 185 | 1902 | 2000 | 99 | 31 | DY | 46.2 |
| 45-1277 | CENTRALIA 1 W | WA | 46.7000 | 122.9667 | 185 | 1941 | 2000 | 60 | 31 | HR | 46.1 |
| 1021480 | CHATHAM POINT | BC | 50.3333 | 125.4333 | 75 | 1958 | 1995 | 38 | 142 | DY | 86.3 |
| 1011500 | CHEMAINUS | BC | 48.9333 | 123.7333 | 246 | 1919 | 1995 | 77 | 32 | DY | 44.5 |
| 35-1552 | CHERRY GROVE 2 S | OR | 45.4167 | 123.2500 | 781 | 1948 | 1983 | 36 | 32 | DY | 54.3 |
| 1101530 | CHILLIWACK | BC | 49.1667 | 121.9333 | 19 | 1879 | 1995 | 117 | 14 | DY | 70.7 |

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1101N65 | CHILLIWACK R HATCHER | BC | 49.0833 | 121.7000 | 698 | 1961 | 1995 | 35 | 15 | DY | 62.6 |
| 45-1414 | CHIMACUM 4 S | WA | 47.9500 | 122.7833 | 140 | 1944 | 2000 | 57 | 32 | DY | 29.2 |
| 45-1426 | CHIWAWA RIVER | WA | 48.0333 | 120.8333 | 2713 | 1935 | 1958 | 24 | 14 | DY | 35.9 |
| 45-1457 | CINEBAR 2 E | WA | 46.6000 | 122.4833 | 1040 | 1941 | 2000 | 60 | 15 | HR | 57.9 |
| 21D13S | CLACKAMAS LAKE | OR | 45.0833 | 121.7500 | 3400 | 1981 | 2000 | 20 | 14 | DY | 56.5 |
| 45-1465 | CLALLAM BAY 1 NNE | WA | 48.2667 | 124.2500 | 30 | 1928 | 1976 | 49 | 142 | DY | 83.4 |
| 35-1643 | CLATSKANIE | OR | 46.1000 | 123.2000 | 22 | 1948 | 2000 | 53 | 32 | DY | 52.3 |
| 35-1643 | CLATSKANIE | OR | 46.1000 | 123.2000 | 22 | 1954 | 2000 | 47 | 32 | HR | 52.3 |
| 45-1504 | CLE ELUM | WA | 47.1833 | 120.9500 | 1920 | 1901 | 2000 | 100 | 14 | DY | 26.8 |
| 21D12S | CLEAR LAKE | OR | 45.2000 | 121.7167 | 3500 | 1981 | 2000 | 20 | 14 | DY | 55.1 |
| 45-1484 | CLEARBROOK | WA | 48.9667 | 122.3333 | 64 | 1903 | 2000 | 98 | 31 | DY | 51.2 |
| 45-1496 | CLEARWATER | WA | 47.5833 | 124.3000 | 80 | 1931 | 2000 | 70 | 5 | DY | 117.6 |
| 45-1496 | CLEARWATER | WA | 47.5833 | 124.3000 | 80 | 1943 | 2000 | 58 | 5 | HR | 117.6 |
| 35-1682 | CLOVERDALE | OR | 45.2000 | 123.8833 | 12 | 1948 | 2000 | 53 | 5 | DY | 98.5 |
| 35-1735 | COLTON | OR | 45.1667 | 122.4167 | 680 | 1948 | 2000 | 53 | 31 | HR | 58.9 |
| 1021830 | COMOX A | BC | 49.7167 | 124.9000 | 79 | 1944 | 1996 | 53 | 142 | DY | 48.6 |
| 45-1679 | CONCRETE PPL FISH ST | WA | 48.5500 | 121.7667 | 195 | 1925 | 2000 | 76 | 15 | DY | 63.7 |
| 1101890 | COQUITLAM LAKE | BC | 49.3667 | 122.8000 | 528 | 1924 | 1982 | 59 | 15 | DY | 111.5 |
| 21B13S | CORRAL PASS | WA | 47.0167 | 121.4667 | 6000 | 1982 | 1999 | 18 | 14 | DY | 70.1 |
| 45-1759 | COUGAR 4 SW | WA | 46.0167 | 122.3500 | 520 | 1941 | 2000 | 60 | 15 | HR | 67.1 |
| 45-1760 | COUGAR 6 E | WA | 46.0500 | 122.2000 | 659 | 1930 | 2000 | 71 | 15 | DY | 121.1 |
| 21B42S | COUGAR MOUNTAIN | WA | 47.2500 | 121.6333 | 3200 | 1982 | 1999 | 18 | 15 | DY | 89.6 |
| 45-1783 | COUPEVILLE 1 S | WA | 48.2000 | 122.7000 | 50 | 1916 | 2000 | 85 | 31 | DY | 22.4 |
| 1012010 | COWICHAN BAY CHERRY | BC | 48.7167 | 123.5500 | 3 | 1913 | 1995 | 83 | 32 | DY | 41.5 |
| 1012040 | COWICHAN LAKE FOREST | BC | 48.8333 | 124.1333 | 580 | 1931 | 1995 | 65 | 142 | DY | 84.3 |
| 1102220 | CULTUS LAKE | BC | 49.0833 | 121.9833 | 150 | 1931 | 1994 | 64 | 14 | DY | 65.2 |
| 45-1934 | CUSHMAN DAM | WA | 47.4167 | 123.2167 | 760 | 1931 | 1973 | 43 | 142 | DY | 97.0 |
| 45-1934 | CUSHMAN DAM | WA | 47.4167 | 123.2167 | 760 | 1941 | 2000 | 60 | 142 | HR | 97.0 |
| 45-1939 | CUSHMAN PWR HOUSE 2 | WA | 47.3667 | 123.1500 | 21 | 1973 | 2000 | 28 | 32 | DY | 67.3 |
| 45-1992 | DARRINGTON RANGER ST | WA | 48.2500 | 121.6000 | 550 | 1931 | 2000 | 70 | 15 | DY | 73.6 |
| 45-1992 | DARRINGTON RANGER ST | WA | 48.2500 | 121.6000 | 550 | 1941 | 2000 | 60 | 15 | HR | 73.6 |
| 45-2157 | DIABLO DAM | WA | 48.7167 | 121.1500 | 891 | 1931 | 2000 | 70 | 14 | DY | 69.1 |
| 45-2157 | DIABLO DAM | WA | 48.7167 | 121.1500 | 891 | 1944 | 2000 | 57 | 14 | HR | 69.1 |
| 35-2325 | DILLEY 1 S | OR | 45.4833 | 123.1167 | 165 | 1948 | 2000 | 53 | 32 | DY | 45.5 |
| 35-2348 | DIXIE MOUNTAIN | OR | 45.6833 | 122.9167 | 1430 | 1976 | 2000 | 25 | 32 | HR | 66.9 |
| 45-2220 | DOTY 3 E | WA | 46.6333 | 123.2000 | 260 | 1958 | 2000 | 43 | 32 | DY | 55.2 |
| 45-2253 | DRYAD | WA | 46.6333 | 123.2500 | 310 | 1937 | 1978 | 42 | 32 | DY | 56.3 |
| 45-2309 | DUVALL 3NE | WA | 47.7666 | 121.9333 | 813 | 1932 | 1954 | 23 | 31 | DY | 57.9 |
| 35-2493 | EAGLE CREEK 9 SE | OR | 45.2667 | 122.2000 | 926 | 1973 | 2000 | 28 | 15 | DY | 68.8 |
| KI-14U | EAST FK ISSAQUAH CRK | WA | 47.5327 | 121.9873 | 520 | 1988 | 2000 | 13 | 15 | DY | 79.3 |
| 45-2384 | EASTON | WA | 47.2333 | 121.1833 | 2170 | 1941 | 2000 | 60 | 14 | HR | 49.5 |
| TH-1938 | EATON CREEK | WA | 46.9742 | 122.7300 | 264 | 1992 | 2000 | 9 | 31 | HR | 45.0 |
| 21A32S | ELBOW LAKE | WA | 48.6833 | 121.9000 | 3200 | 1996 | 1999 | 4 | 15 | DY | 97.7 |
| 45-2493 | ELECTRON HEADWORKS | WA | 46.9000 | 122.0333 | 1730 | 1948 | 1980 | 33 | 15 | DY | 69.6 |
| 45-2493 | ELECTRON HEADWORKS | WA | 46.9000 | 122.0333 | 1730 | 1943 | 1980 | 38 | 15 | HR | 69.6 |
| 45-2500 | ELK MOUNTAIN | WA | 46.1333 | 122.4667 | 4480 | 1983 | 1990 | 8 | 15 | HR | 118.4 |
| 45-2531 | ELMA | WA | 47.0000 | 123.4000 | 70 | 1928 | 2000 | 73 | 32 | DY | 67.2 |
| 45-2548 | ELWHA R S | WA | 48.0333 | 123.5833 | 360 | 1943 | 2000 | 58 | 142 | DY | 56.3 |
| 1012700 | ESQUIMALT | BC | 48.4333 | 123.4167 | 45 | 1872 | 1950 | 79 | 32 | DY | 35.0 |
| 35-2693 | ESTACADA 2 SE | OR | 45.2667 | 122.3167 | 450 | 1948 | 2000 | 53 | 31 | DY | 62.6 |
| 35-2697 | ESTACADA 24 SE | OR | 45.0667 | 121.9667 | 2200 | 1948 | 2000 | 53 | 15 | HR | 72.2 |
| KI-18U | EVANS CREEK | WA | 47.6873 | 122.0305 | 150 | 1989 | 2000 | 12 | 31 | DY | 49.8 |
| 45-2675 | EVERETT | WA | 47.9833 | 122.1833 | 60 | 1930 | 2000 | 71 | 31 | DY | 37.4 |
| 45-2675 | EVERETT | WA | 47.9833 | 122.1833 | 60 | 1941 | 2000 | 60 | 31 | HR | 37.4 |
| 21B04S | FISH LAKE | WA | 47.5167 | 121.0667 | 3371 | 1982 | 1999 | 18 | 14 | DY | 74.5 |
| 35-2997 | FOREST GROVE | OR | 45.5167 | 123.1000 | 180 | 1928 | 2000 | 73 | 32 | DY | 43.6 |
| 45-2914 | FORKS 1 E | WA | 47.9500 | 124.3500 | 350 | 1928 | 2000 | 73 | 151 | DY | 122.0 |
| 45-2984 | FRANCES | WA | 46.5500 | 123.5000 | 231 | 1941 | 2000 | 60 | 142 | HR | 97.8 |
| 45-3160 | GLACIER R S | WA | 48.8833 | 121.9500 | 935 | 1935 | 1983 | 49 | 15 | DY | 65.5 |
| 45-3160 | GLACIER R S | WA | 48.8833 | 121.9500 | 935 | 1971 | 2000 | 30 | 15 | HR | 65.5 |
| 45-3177 | GLENOMA | WA | 46.5167 | 122.1333 | 840 | 1906 | 2000 | 95 | 15 | DY | 68.0 |
| 45-3183 | GLENWOOD | WA | 46.0167 | 121.2833 | 1896 | 1941 | 2000 | 60 | 14 | HR | 34.7 |
| 35-3318 | GLENWOOD 2 WNW | OR | 45.6500 | 123.3000 | 644 | 1948 | 2000 | 53 | 142 | HR | 65.8 |
| 35-3340 | GOBLE 3 SW | OR | 45.9833 | 122.9167 | 530 | 1948 | 2000 | 53 | 32 | HR | 48.3 |
| 1033232 | GOLD RIVER TOWNSITE | BC | 49.7833 | 126.0500 | 383 | 1966 | 1995 | 30 | 142 | DY | 121.8 |
| 1013240 | GOLDSTREAM LAKE | BC | 48.4500 | 123.5500 | 1505 | 1894 | 1953 | 60 | 142 | DY | 43.7 |
| 35-3402 | GOVERNMENT CAMP | OR | 45.3000 | 121.7333 | 3980 | 1951 | 2000 | 50 | 15 | DY | 72.6 |
| 35-3402 | GOVERNMENT CAMP | OR | 45.3000 | 121.7333 | 3980 | 1955 | 2000 | 46 | 15 | HR | 72.6 |
| 35-3421 | GRAND RONDE TREE FAR | OR | 45.0500 | 123.6167 | 395 | 1948 | 2000 | 53 | 5 | HR | 56.1 |
| 45-3284 | GRAPEVIEW 3 SW | WA | 47.3000 | 122.8667 | 51 | 1931 | 1995 | 65 | 32 | DY | 53.1 |
| 45-3320 | GRAYLAND | WA | 46.8000 | 124.0833 | 10 | 1948 | 2000 | 53 | 5 | DY | 77.5 |
| 45-3333 | GRAYS RIVER HATCHERY | WA | 46.3833 | 123.5667 | 100 | 1962 | 2000 | 39 | 5 | DY | 107.4 |
| 45-3333 | GRAYS RIVER HATCHERY | WA | 46.3833 | 123.5667 | 100 | 1954 | 2000 | 47 | 5 | HR | 107.4 |
| 21C10S | GREEN LAKE | WA | 46.5500 | 121.1667 | 6000 | 1983 | 1999 | 17 | 14 | DY | 38.4 |
| 21D01S | GREENPOINT | OR | 45.6167 | 121.7000 | 3200 | 1980 | 2000 | 21 | 14 | DY | 57.6 |
| 45-3357 | GREENWATER | WA | 47.1333 | 121.6333 | 1730 | 1939 | 1981 | 43 | 15 | DY | 61.6 |
| 45-3357 | GREENWATER | WA | 47.1333 | 121.6333 | 1730 | 1940 | 1999 | 60 | 15 | HR | 61.6 |

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 35-3521 | GRESHAM | OR | 45.4833 | 122.4167 | 310 | 1948 | 2000 | 53 | 31 | HR | 53.0 |
| 45-3386 | GROTTO | WA | 47.7333 | 121.4167 | 850 | 1948 | 1970 | 23 | 15 | DY | 110.0 |
| 20B11S | GROUSE CAMP | WA | 47.2667 | 120.4833 | 5380 | 1983 | 1999 | 17 | 14 | DY | 30.1 |
| 1103332 | HANEY UBC RF ADMIN | BC | 49.2667 | 122.5667 | 469 | 1962 | 1996 | 35 | 15 | HR | 88.0 |
| KP-24 | HANSVILLE-HOOD CANAL | WA | 47.9064 | 122.5686 | 230 | 1982 | 2000 | 19 | 32 | DY | 30.1 |
| 20A05S | HARTS PASS | WA | 48.7167 | 120.6500 | 6500 | 1982 | 1999 | 18 | 14 | DY | 54.2 |
| 20A05S | HARTS PASS 2 | WA | 48.7167 | 120.6500 | 6500 | 1991 | 1994 | 4 | 14 | DY | 54.2 |
| 35-3705 | HASKINS DAM | OR | 45.3000 | 123.3500 | 756 | 1948 | 2000 | 53 | 142 | DY | 72.6 |
| 35-3705 | HASKINS DAM | OR | 45.3000 | 123.3500 | 756 | 1948 | 2000 | 53 | 142 | HR | 72.6 |
| 35-3770 | HEADWORKS PTLD WTR B | OR | 45.4500 | 122.1500 | 748 | 1931 | 2000 | 70 | 15 | DY | 75.6 |
| 35-3770 | HEADWORKS PTLD WTR B | OR | 45.4500 | 122.1500 | 748 | 1976 | 2000 | 25 | 15 | HR | 75.6 |
| 35-3908 | HILLSBORO | OR | 45.5000 | 122.9833 | 160 | 1948 | 2000 | 53 | 32 | DY | 38.8 |
| 45-3730 | HOLDEN VILLAGE | WA | 48.2000 | 120.7833 | 3220 | 1938 | 2000 | 63 | 14 | DY | 44.5 |
| KP-25 | HOLLY BEACH | WA | 47.5578 | 122.9775 | 15 | 1991 | 2000 | 10 | 32 | DY | 56.4 |
| 1103510 | HOLLYBURN RIDGE | BC | 49.3833 | 123.1833 | 3051 | 1954 | 1995 | 42 | 15 | DY | 112.1 |
| 35-4003 | HOOD RIVER EXP STN | OR | 45.6833 | 121.5167 | 500 | 1928 | 2000 | 73 | 14 | DY | 29.8 |
| 35-4008 | HOOD RIVER TUCKER BR | OR | 45.6500 | 121.5333 | 383 | 1941 | 2000 | 60 | 14 | HR | 30.6 |
| 1113540 | HOPE A | BC | 49.3667 | 121.4833 | 127 | 1934 | 1995 | 62 | 14 | DY | 66.8 |
| 1113540 | HOPE A | BC | 49.3667 | 121.4833 | 127 | 1947 | 1991 | 45 | 14 | S6 | 66.8 |
| 1113550 | HOPE KAWKAWA LAKE | BC | 49.3833 | 121.4000 | 498 | 1910 | 1977 | 68 | 14 | DY | 62.5 |
| 1113581 | HOPE SLIDE | BC | 49.2833 | 121.2333 | 2211 | 1975 | 1995 | 21 | 14 | DY | 56.1 |
| 45-3807 | HOQUIAM FCWOS AP | WA | 46.9833 | 123.9333 | 12 | 1943 | 2000 | 58 | 5 | DY | 73.6 |
| 45-3826 | HUMPTULIPS SALMON HA | WA | 47.2333 | 123.9833 | 140 | 1987 | 2000 | 14 | 151 | DY | 93.1 |
| 45-3909 | INDEX | WA | 47.8167 | 121.5500 | 531 | 1935 | 1956 | 22 | 15 | DY | 101.5 |
| 1103660 | IOCO REFINERY | BC | 49.3000 | 122.8833 | 173 | 1916 | 1995 | 80 | 31 | DY | 73.1 |
| 1013720 | JAMES ISLAND | BC | 48.6000 | 123.3500 | 177 | 1914 | 1978 | 65 | 32 | DY | 31.9 |
| 35-4276 | JEWELL WILDLIFE MEAD | OR | 45.9333 | 123.5167 | 570 | 1954 | 2000 | 47 | 142 | HR | 94.5 |
| 1013754 | JORDAN RIVER DIVERSI | BC | 48.5000 | 124.0000 | 1289 | 1973 | 1996 | 24 | 151 | HR | 122.5 |
| 22C09S | JUNE LAKE | WA | 46.1333 | 122.1500 | 3340 | 1983 | 1999 | 17 | 15 | DY | 111.0 |
| 45-4085 | KALAMA 5 ENE | WA | 46.0500 | 122.7500 | 902 | 1948 | 1967 | 20 | 15 | DY | 59.1 |
| 45-4084 | KALAMA FALLS HATCHER | WA | 46.0167 | 122.7167 | 312 | 1968 | 2000 | 33 | 15 | DY | 64.0 |
| 45-4169 | KENT | WA | 47.4000 | 122.2333 | 30 | 1912 | 2000 | 89 | 31 | DY | 38.7 |
| 45-4187 | KEYPORT TORPEDO STN | WA | 47.7000 | 122.6167 | 39 | 1915 | 1958 | 44 | 32 | DY | 44.2 |
| 45-4201 | KID VALLEY | WA | 46.3667 | 122.6167 | 689 | 1941 | 1980 | 40 | 15 | DY | 70.2 |
| 1034170 | KILDONAN | BC | 49.0000 | 125.0000 | 9 | 1937 | 1976 | 40 | 151 | DY | 172.7 |
| 45-4360 | LA GRANDE | WA | 46.8333 | 122.3167 | 961 | 1954 | 1983 | 30 | 15 | DY | 44.9 |
| 1104468 | LADNER | BC | 49.0833 | 123.0667 | 29 | 1878 | 1934 | 57 | 31 | DY | 44.1 |
| 1104488 | LAIDLAW | BC | 49.3500 | 121.5833 | 88 | 1977 | 1995 | 19 | 14 | DY | 80.5 |
| 45-4394 | LAKE CLE ELUM | WA | 47.2500 | 121.0667 | 2260 | 1909 | 1977 | 69 | 14 | DY | 38.9 |
| 1014493 | LAKE COWICHAN | BC | 48.8167 | 124.0500 | 590 | 1924 | 1995 | 72 | 142 | DY | 101.8 |
| 45-4406 | LAKE KACHESS | WA | 47.2667 | 121.2000 | 2270 | 1908 | 1977 | 70 | 14 | DY | 57.2 |
| 45-4414 | LAKE KEECHELUS | WA | 47.3167 | 121.3333 | 2480 | 1908 | 1977 | 70 | 14 | DY | 74.3 |
| 45-4438 | LAKE SUTHERLAND | WA | 48.0833 | 123.7000 | 570 | 1929 | 1976 | 48 | 142 | DY | 59.9 |
| 45-4446 | LAKE WENATCHEE | WA | 47.8333 | 120.7833 | 2005 | 1914 | 2000 | 87 | 14 | DY | 38.1 |
| 45-4446 | LAKE WENATCHEE | WA | 47.8333 | 120.7833 | 2005 | 1971 | 2000 | 30 | 14 | HR | 38.1 |
| 45-4454 | LAKE WHATCOM | WA | 48.6833 | 122.3000 | 322 | 1944 | 1954 | 11 | 15 | DY | 57.5 |
| 45-4486 | LANDSBURG | WA | 47.3833 | 121.9833 | 535 | 1931 | 2000 | 70 | 31 | DY | 56.0 |
| 45-4486 | LANDSBURG | WA | 47.3833 | 121.9833 | 535 | 1954 | 2000 | 47 | 31 | HR | 56.0 |
| 45-4572 | LEAVENWORTH 3 S | WA | 47.5500 | 120.6667 | 1128 | 1914 | 2000 | 87 | 14 | DY | 28.1 |
| 35-4824 | LEES CAMP | OR | 45.5833 | 123.5167 | 655 | 1948 | 2000 | 53 | 151 | HR | 113.6 |
| 45-4634 | LESTER | WA | 47.2000 | 121.4833 | 1630 | 1948 | 1975 | 28 | 15 | HR | 80.4 |
| 21C26S | LONE PINE | WA | 46.2667 | 121.9667 | 3800 | 1982 | 1999 | 18 | 15 | DY | 92.2 |
| 45-4748 | LONG BEACH EXP STN | WA | 46.3667 | 124.0333 | 30 | 1953 | 2000 | 48 | 5 | DY | 82.6 |
| 45-4764 | LONGMIRE RAINIER NPS | WA | 46.7500 | 121.8167 | 2762 | 1909 | 2000 | 92 | 15 | DY | 84.7 |
| 45-4764 | LONGMIRE RAINIER NPS | WA | 46.7500 | 121.8167 | 2762 | 1979 | 2000 | 22 | 15 | HR | 84.7 |
| 45-4769 | LONGVIEW | WA | 46.1500 | 122.9167 | 12 | 1931 | 2000 | 70 | 31 | DY | 46.1 |
| 45-4769 | LONGVIEW | WA | 46.1500 | 122.9167 | 12 | 1954 | 2000 | 47 | 31 | HR | 46.1 |
| 21C39S | LOST HORSE | WA | 46.3500 | 121.1167 | 5000 | 1991 | 1999 | 9 | 14 | DY | 34.6 |
| 45-4849 | LUCERNE 1 N | WA | 48.2333 | 120.6000 | 1200 | 1942 | 1989 | 48 | 14 | HR | 22.6 |
| 20A23S | LYMAN LAKE | WA | 48.2000 | 120.9167 | 5900 | 1980 | 1999 | 20 | 14 | DY | 84.8 |
| 45-4999 | MARBLEMOUNT RANGER S | WA | 48.5333 | 121.4500 | 348 | 1941 | 2000 | 60 | 15 | HR | 69.8 |
| 45-5028 | MARIETTA 3 NNW | WA | 48.8333 | 122.6000 | 20 | 1914 | 1958 | 45 | 31 | DY | 41.2 |
| 45-5080 | MATLOCK 3 W | WA | 47.2333 | 123.4833 | 340 | 1945 | 1985 | 41 | 32 | DY | 101.3 |
| 45-5086 | MATLOCK 8 S | WA | 47.1500 | 123.4000 | 110 | 1986 | 2000 | 15 | 32 | DY | 94.3 |
| 45-5110 | MAYFIELD POWER PLANT | WA | 46.5000 | 122.5833 | 280 | 1980 | 2000 | 21 | 31 | DY | 56.7 |
| 45-5128 | MAZAMA 6 SE | WA | 48.5333 | 120.3333 | 1962 | 1948 | 1977 | 30 | 14 | DY | 23.3 |
| 45-5149 | MC CHORD AFB | WA | 47.1500 | 122.4833 | 290 | 1941 | 1979 | 39 | 31 | HR | 39.8 |
| 45-5224 | MC MILLIN RESERVOIR | WA | 47.1333 | 122.2667 | 579 | 1941 | 2000 | 60 | 31 | DY | 41.5 |
| 45-5224 | MC MILLIN RESERVOIR | WA | 47.1333 | 122.2667 | 579 | 1941 | 2000 | 60 | 31 | HR | 41.5 |
| 35-5384 | MC MINNVILLE | OR | 45.2167 | 123.1500 | 155 | 1928 | 2000 | 73 | 32 | DY | 41.6 |
| 21B59S | MEADOWS PASS | WA | 47.2667 | 121.4667 | 3500 | 1994 | 1999 | 6 | 14 | DY | 105.0 |
| 45-5305 | MERWIN DAM | WA | 45.9500 | 122.5500 | 224 | 1934 | 2000 | 67 | 31 | DY | 67.4 |
| 45-5305 | MERWIN DAM | WA | 45.9500 | 122.5500 | 224 | 1983 | 1988 | 6 | 31 | HR | 67.4 |
| 1015105 | METCHOSIN | BC | 48.3833 | 123.5667 | 400 | 1915 | 1995 | 81 | 32 | DY | 39.9 |
| 45-5425 | MINERAL 1 SW | WA | 46.7167 | 122.1833 | 1470 | 1935 | 1980 | 46 | 15 | DY | 84.3 |
| 20A40S | MINERS RIDGE | WA | 48.1667 | 120.9833 | 6200 | 1989 | 1999 | 11 | 14 | DY | 95.0 |
| 20A39S | MIRROR LAKE | WA | 48.1500 | 120.6500 | 5600 | 1983 | 1988 | 6 | 14 | DY | 46.0 |

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 35-5629 | MIST 1 SE | OR | 45.9833 | 123.2500 | 500 | 1948 | 1958 | 11 | 32 | HR | 54.8 |
| 45-5488 | MOCLIPS | WA | 47.2167 | 124.2000 | 120 | 1942 | 1957 | 16 | 5 | HR | 91.9 |
| 35-5677 | MOLALLA | OR | 45.1500 | 122.5667 | 400 | 1948 | 1977 | 30 | 31 | DY | 48.1 |
| 45-5525 | MONROE | WA | 47.8333 | 121.9833 | 120 | 1929 | 2000 | 72 | 31 | DY | 49.6 |
| 45-5549 | MONTESANO 1 S | WA | 46.9667 | 123.6167 | 25 | 1948 | 1953 | 6 | 32 | DY | 77.1 |
| 45-5549 | MONTESANO 1 S | WA | 46.9667 | 123.6167 | 25 | 1954 | 2000 | 47 | 32 | HR | 77.1 |
| 21C17S | MORSE LAKE | WA | 46.9000 | 121.4833 | 5400 | 1979 | 1999 | 21 | 14 | DY | 76.5 |
| 45-5659 | MOUNT ADAMS RANGER S | WA | 46.0000 | 121.5333 | 1960 | 1925 | 2000 | 76 | 14 | DY | 42.4 |
| 45-5659 | MOUNT ADAMS RANGER S | WA | 46.0000 | 121.5333 | 1960 | 1971 | 2000 | 30 | 14 | HR | 42.4 |
| 45-5663 | MOUNT BAKER LODGE | WA | 48.8667 | 121.6667 | 4150 | 1948 | 1983 | 36 | 15 | HR | 81.1 |
| 23B06S | MOUNT CRAG | WA | 47.7500 | 123.0000 | 4050 | 1990 | 1999 | 10 | 142 | DY | 71.9 |
| 21B21S | MOUNT GARDNER | WA | 47.3500 | 121.5667 | 3000 | 1994 | 1999 | 6 | 15 | DY | 102.0 |
| 45-5678 | MOUNT VERNON 3 WNW | WA | 48.4500 | 122.3667 | 14 | 1956 | 2000 | 45 | 31 | DY | 33.8 |
| 21D08S | MT HOOD TEST SITE | OR | 45.3333 | 121.7167 | 5400 | 1981 | 2000 | 20 | 15 | DY | 116.7 |
| 45-5704 | MUD MOUNTAIN DAM | WA | 47.1500 | 121.9333 | 1308 | 1939 | 2000 | 62 | 15 | DY | 61.3 |
| 45-5704 | MUD MOUNTAIN DAM | WA | 47.1500 | 121.9333 | 1308 | 1940 | 2000 | 61 | 15 | HR | 61.3 |
| 21D35S | MUD RIDGE | OR | 45.2500 | 121.7333 | 3800 | 1979 | 2000 | 22 | 14 | DY | 62.0 |
| 1105658 | N VANC GROUSE MTN RE | BC | 49.3833 | 123.0833 | 3700 | 1971 | 1995 | 25 | 15 | DY | 110.6 |
| 1105655 | N VANCOUVER CAPILANO | BC | 49.3500 | 123.1167 | 305 | 1955 | 1990 | 36 | 15 | DY | 88.3 |
| 35-6151 | N WILLAMETTE EXP STN | OR | 45.2667 | 122.7500 | 150 | 1963 | 2000 | 38 | 31 | DY | 40.1 |
| 1025C70 | NANAIMO DEPARTURE BA | BC | 49.2167 | 123.9500 | 26 | 1913 | 1992 | 80 | 32 | DY | 39.5 |
| 45-5774 | NASELLE 2 ENE | WA | 46.3667 | 123.7500 | 50 | 1930 | 2000 | 71 | 5 | DY | 115.0 |
| 45-5801 | NEAH BAY 1 E | WA | 48.3667 | 124.6167 | 10 | 1930 | 1987 | 58 | 5 | DY | 120.3 |
| 35-5969 | NEHALEM | OR | 45.7167 | 123.9000 | 75 | 1948 | 2000 | 53 | 5 | HR | 78.7 |
| 35-5971 | NEHALEM 9 NE | OR | 45.8000 | 123.7667 | 140 | 1969 | 2000 | 32 | 5 | DY | 109.4 |
| 1105550 | NEW WESTMINSTER | BC | 49.2167 | 122.9333 | 390 | 1874 | 1980 | 107 | 31 | DY | 63.8 |
| 45-5840 | NEWHALEM | WA | 48.6833 | 121.2500 | 525 | 1926 | 2000 | 75 | 14 | DY | 89.4 |
| 1035610 | NITINAT LAKE | BC | 48.7500 | 124.7500 | 26 | 1924 | 1952 | 29 | 151 | DY | 125.7 |
| 45-5876 | NOOKSACK SALMON HATC | WA | 48.9000 | 122.1500 | 410 | 1964 | 2000 | 37 | 15 | HR | 67.0 |
| 22D02S | NORTH FORK | OR | 45.5500 | 122.0167 | 3120 | 1980 | 2000 | 21 | 15 | DY | 132.3 |
| 45-5932 | NORTH HEAD WB | WA | 46.3000 | 124.0833 | 210 | 1940 | 1953 | 14 | 5 | HR | 81.5 |
| KI-51U | NORWAY | WA | 47.7350 | 122.2083 | 180 | 1988 | 2000 | 13 | 31 | DY | 38.2 |
| 45-6011 | OAKVILLE | WA | 46.8333 | 123.2333 | 80 | 1948 | 1998 | 51 | 32 | DY | 56.9 |
| KP-34 | OLALLA | WA | 47.4328 | 122.5731 | 345 | 1983 | 2000 | 18 | 32 | DY | 47.4 |
| 21B55S | OLALLIE MEADOWS | WA | 47.3667 | 121.4333 | 3700 | 1982 | 1999 | 18 | 15 | DY | 110.2 |
| 45-6096 | OLGA 2 SE | WA | 48.6167 | 122.8000 | 80 | 1891 | 2000 | 110 | 31 | DY | 29.8 |
| 45-6114 | OLYMPIA AIRPORT | WA | 46.9667 | 122.9000 | 206 | 1948 | 2000 | 53 | 32 | DY | 50.7 |
| 45-6114 | OLYMPIA AIRPORT | WA | 46.9667 | 122.9000 | 206 | 1948 | 2000 | 53 | 32 | HR | 50.7 |
| 45-6109 | OLYMPIA PRIEST PT PA | WA | 47.0667 | 122.8833 | 30 | 1948 | 1956 | 9 | 32 | DY | 51.5 |
| 35-6334 | OREGON CITY | OR | 45.3500 | 122.6000 | 167 | 1948 | 2000 | 53 | 31 | DY | 47.4 |
| 35-6366 | OTIS 2 NE | OR | 45.0167 | 123.9167 | 150 | 1948 | 2000 | 53 | 5 | DY | 93.5 |
| 1035940 | PACHENA POINT | BC | 48.7167 | 125.1000 | 121 | 1924 | 1995 | 72 | 5 | DY | 127.1 |
| 45-6262 | PACKWOOD | WA | 46.6167 | 121.6667 | 1060 | 1926 | 2000 | 75 | 15 | DY | 63.3 |
| 45-6295 | PALMER 3 ESE | WA | 47.3000 | 121.8500 | 920 | 1931 | 2000 | 70 | 15 | DY | 87.9 |
| 45-6295 | PALMER 3 ESE | WA | 47.3000 | 121.8500 | 920 | 1941 | 2000 | 60 | 15 | HR | 87.9 |
| 21C35S | PARADISE | WA | 46.8333 | 121.7167 | 5120 | 1981 | 1999 | 19 | 15 | DY | 184.7 |
| 20A12S | PARK CREEK RIDGE | WA | 48.4500 | 120.9167 | 4600 | 1979 | 1999 | 21 | 14 | DY | 61.8 |
| 35-6466 | PARKDALE 1 NNE | OR | 45.5333 | 121.5833 | 1520 | 1928 | 2000 | 73 | 14 | DY | 34.6 |
| 21D14S | PEAVINE RIDGE | OR | 45.0500 | 121.9333 | 3500 | 1982 | 2000 | 19 | 15 | DY | 67.1 |
| 1016120 | PENDER ISLAND | BC | 48.7667 | 123.3000 | 85 | 1924 | 1995 | 72 | 32 | DY | 32.3 |
| 21C33S | PIGTAIL PEAK | WA | 46.6167 | 121.4167 | 5900 | 1982 | 1999 | 18 | 14 | DY | 77.1 |
| 1106180 | PITT POLDER | BC | 49.3000 | 122.6333 | 3 | 1964 | 1996 | 33 | 31 | HR | 85.3 |
| 45-6534 | PLAIN | WA | 47.7833 | 120.6333 | 1940 | 1939 | 2000 | 62 | 14 | DY | 30.0 |
| 22C01S | PLAINS OF ABRAHAM | WA | 46.2167 | 122.1500 | 4400 | 1984 | 1987 | 4 | 15 | DY | 120.9 |
| 45-6584 | POINT GRENVILLE | WA | 47.3000 | 124.2833 | 100 | 1947 | 1980 | 34 | 5 | DY | 89.4 |
| 45-6584 | POINT GRENVILLE | WA | 47.3000 | 124.2833 | 100 | 1957 | 1977 | 21 | 5 | HR | 89.4 |
| 20B24S | POPE RIDGE | WA | 47.9833 | 120.5667 | 3540 | 1982 | 1999 | 18 | 14 | DY | 36.9 |
| 1036205 | PORT ALBERNI | BC | 49.2333 | 124.8000 | 193 | 1917 | 1981 | 65 | 142 | DY | 81.7 |
| 1036240 | PORT ALICE | BC | 50.3833 | 127.4500 | 68 | 1924 | 1995 | 72 | 151 | DY | 148.5 |
| 45-6624 | PORT ANGELES | WA | 48.1000 | 123.4167 | 90 | 1948 | 2000 | 53 | 32 | DY | 33.5 |
| 45-6624 | PORT ANGELES | WA | 48.1000 | 123.4167 | 90 | 1941 | 2000 | 60 | 32 | HR | 33.5 |
| 1016335 | PORT RENFREW | BC | 48.5833 | 124.3333 | 39 | 1970 | 1995 | 26 | 151 | DY | 143.9 |
| 45-6678 | PORT TOWNSEND | WA | 48.1000 | 122.7500 | 100 | 1930 | 2000 | 71 | 32 | DY | 23.2 |
| 45-6678 | PORT TOWNSEND | WA | 48.1000 | 122.7500 | 100 | 1941 | 1970 | 30 | 32 | HR | 23.2 |
| 35-6751 | PORTLAND INTL AIRPOR | OR | 45.5833 | 122.6000 | 19 | 1942 | 2000 | 59 | 32 | DY | 38.1 |
| 35-6751 | PORTLAND INTL AIRPOR | OR | 45.5833 | 122.6000 | 19 | 1941 | 2000 | 60 | 32 | HR | 38.1 |
| 35-6749 | PORTLAND KGW-TV | OR | 45.5167 | 122.6833 | 160 | 1928 | 2000 | 73 | 32 | DY | 45.2 |
| 35-6749 | PORTLAND KGW-TV | OR | 45.5167 | 122.6833 | 160 | 1948 | 2000 | 53 | 32 | HR | 45.2 |
| 21C14S | POTATO HILL | WA | 46.3000 | 121.5000 | 4500 | 1982 | 1999 | 18 | 14 | DY | 71.9 |
| KP-15 | POULSBO | WA | 47.7355 | 122.6583 | 18 | 1988 | 2000 | 13 | 32 | DY | 43.4 |
| 45-6803 | PUYALLUP 2 W EXP STN | WA | 47.2000 | 122.3333 | 50 | 1914 | 1995 | 82 | 31 | DY | 40.6 |
| 1036570 | QUATSINO | BC | 50.5333 | 127.6500 | 26 | 1895 | 1995 | 101 | 142 | DY | 99.6 |
| 45-6846 | QUILCENE 2 SW | WA | 47.8167 | 122.9167 | 123 | 1936 | 2000 | 65 | 32 | DY | 48.6 |
| 45-6851 | QUILCENE 5 SW DAM | WA | 47.7833 | 122.9833 | 1028 | 1941 | 2000 | 60 | 142 | HR | 68.2 |
| 45-6858 | QUILLAYUTE WSCMO AP | WA | 47.9333 | 124.5500 | 179 | 1966 | 2000 | 35 | 5 | DY | 104.8 |
| 45-6858 | QUILLAYUTE WSCMO AP | WA | 47.9333 | 124.5500 | 179 | 1966 | 2000 | 35 | 5 | HR | 104.8 |
| 45-6864 | QUINAULT RANGER STN | WA | 47.4667 | 123.8500 | 220 | 1906 | 1977 | 72 | 151 | DY | 110.9 |

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 45-6864 | QUINAULT RANGER STN | WA | 47.4667 | 123.8500 | 220 | 1977 | 2000 | 24 | 151 | HR | 110.9 |
| 45-6887 | RAINBOW FALLS PK 2 E | WA | 46.6333 | 123.1833 | 280 | 1948 | 1963 | 16 | 32 | DY | 55.2 |
| 45-6892 | RAINIER CARBON RIVER | WA | 47.0000 | 121.9167 | 1735 | 1948 | 2000 | 53 | 15 | HR | 78.3 |
| 45-6896 | RAINIER OHANAPECOSH | WA | 46.7333 | 121.5667 | 1950 | 1948 | 2000 | 53 | 15 | DY | 75.5 |
| 45-6896 | RAINIER OHANAPECOSH | WA | 46.7333 | 121.5667 | 1950 | 1941 | 2000 | 60 | 15 | HR | 75.5 |
| 45-6898 | RAINIER PARADISE RNG | WA | 46.7833 | 121.7333 | 5427 | 1924 | 2000 | 77 | 15 | DY | 112.5 |
| 20A09S | RAINY PASS | WA | 48.5500 | 120.7167 | 4780 | 1982 | 1999 | 18 | 14 | DY | 61.7 |
| 45-6909 | RANDLE 1 E | WA | 46.5333 | 121.9333 | 900 | 1930 | 2000 | 71 | 15 | DY | 56.9 |
| 45-6909 | RANDLE 1 E | WA | 46.5333 | 121.9333 | 900 | 1954 | 2000 | 47 | 15 | HR | 56.9 |
| 45-6914 | RAYMOND 2 S | WA | 46.6500 | 123.7167 | 30 | 1980 | 2000 | 21 | 5 | DY | 92.2 |
| 21D04S | RED HILL | OR | 45.4667 | 121.7000 | 4400 | 1979 | 2000 | 22 | 14 | DY | 92.2 |
| 35-7127 | REX 1 S | OR | 45.3000 | 122.9000 | 515 | 1948 | 2000 | 53 | 32 | DY | 44.8 |
| 35-7127 | REX 1 S | OR | 45.3000 | 122.9000 | 515 | 1948 | 2000 | 53 | 32 | HR | 44.8 |
| 21B17S | REX RIVER | WA | 47.3333 | 121.6000 | 4000 | 1996 | 1999 | 4 | 15 | DY | 100.8 |
| 45-7010 | RICHARDSON 3 SE | WA | 48.4333 | 122.8333 | 30 | 1949 | 1958 | 10 | 32 | DY | 27.2 |
| 45-7038 | RIMROCK TIETON DAM | WA | 46.6500 | 121.1333 | 2733 | 1917 | 1977 | 61 | 14 | DY | 24.4 |
| 1016780 | RIVER JORDAN | BC | 48.4167 | 124.0500 | 9 | 1908 | 1972 | 65 | 5 | DY | 119.7 |
| 1106865 | ROSEDALE | BC | 49.1833 | 121.8000 | 36 | 1967 | 1988 | 22 | 14 | DY | 65.1 |
| 45-7185 | ROSS DAM | WA | 48.7333 | 121.0500 | 1236 | 1960 | 2000 | 41 | 14 | DY | 60.4 |
| 1016940 | SAANICHTON CDA | BC | 48.6167 | 123.4167 | 200 | 1914 | 1995 | 82 | 32 | DY | 34.7 |
| 23D01S | SADDLE MOUNTAIN | OR | 45.5333 | 123.3667 | 3250 | 1980 | 2000 | 21 | 142 | DY | 88.4 |
| KP-12 | SAKAI INTERMEDIATE SCH | WA | 47.6445 | 122.5288 | 60 | 1991 | 2000 | 10 | 32 | DY | 43.2 |
| 19A02S | SALMON MEADOWS | WA | 48.6667 | 119.8333 | 4500 | 1982 | 1999 | 18 | 99 | DY | 24.1 |
| 1016990 | SALTSPRING ISLAND | BC | 48.8500 | 123.5000 | 239 | 1893 | 1977 | 85 | 32 | DY | 39.0 |
| 45-7294 | SAM HENRY MOUNTAIN | WA | 46.5167 | 123.0167 | 1460 | 1983 | 1989 | 7 | 32 | HR | 58.8 |
| 45-7319 | SAPPHO 8 E | WA | 48.0667 | 124.1167 | 760 | 1948 | 1997 | 50 | 151 | DY | 91.2 |
| 45-7319 | SAPPHO 8 E | WA | 48.0667 | 124.1167 | 760 | 1940 | 1998 | 59 | 151 | HR | 91.2 |
| 21B51S | SASSE RIDGE | WA | 47.3667 | 121.0500 | 4200 | 1984 | 1999 | 16 | 14 | DY | 60.6 |
| 45-7342 | SATUS PASS 2 SSW | WA | 45.9500 | 120.6667 | 2610 | 1956 | 2000 | 45 | 99 | DY | 22.5 |
| 35-7572 | SAUVIES ISLAND | OR | 45.6500 | 122.8333 | 40 | 1948 | 2000 | 53 | 32 | HR | 45.2 |
| 45-7379 | SCENIC | WA | 47.7000 | 121.1500 | 2221 | 1929 | 1970 | 42 | 14 | DY | 95.2 |
| 35-7586 | SCOGGINS DAM 2 | OR | 45.4833 | 123.2000 | 360 | 1973 | 1985 | 13 | 32 | DY | 48.2 |
| 35-7586 | SCOGGINS DAM 2 | OR | 45.4833 | 123.2000 | 360 | 1973 | 1985 | 13 | 32 | HR | 48.2 |
| 35-7641 | SEASIDE | OR | 45.9833 | 123.9167 | 10 | 1930 | 2000 | 71 | 5 | DY | 74.8 |
| 45-7459 | SEATTLE JACKSON PARK | WA | 47.7333 | 122.3333 | 370 | 1941 | 1986 | 46 | 31 | DY | 36.5 |
| 45-7470 | SEATTLE SAND PT WSFO | WA | 47.6833 | 122.2500 | 60 | 1948 | 2000 | 53 | 31 | DY | 37.5 |
| 45-7473 | SEATTLE TACOMA AIRPO | WA | 47.4500 | 122.3000 | 400 | 1948 | 2000 | 53 | 31 | DY | 37.9 |
| 45-7473 | SEATTLE TACOMA AIRPO | WA | 47.4500 | 122.3000 | 400 | 1941 | 2000 | 60 | 31 | HR | 37.9 |
| 45-7478 | SEATTLE UNIV OF WASH | WA | 47.6500 | 122.2833 | 95 | 1909 | 1983 | 75 | 31 | DY | 37.2 |
| 45-7458 | SEATTLE URBAN SITE | WA | 47.6500 | 122.3000 | 19 | 1948 | 1998 | 51 | 31 | DY | 37.0 |
| 45-7458 | SEATTLE URBAN SITE | WA | 47.6500 | 122.3000 | 19 | 1940 | 1998 | 59 | 31 | HR | 37.0 |
| 45-7483 | SEATTLE WB AP | WA | 47.5333 | 122.3000 | 10 | 1948 | 1965 | 18 | 31 | DY | 37.1 |
| 45-7483 | SEATTLE WB AP | WA | 47.5333 | 122.3000 | 10 | 1948 | 1967 | 20 | 31 | HR | 37.1 |
| 45-7507 | SEDRO WOOLLEY | WA | 48.5000 | 122.2333 | 60 | 1898 | 2000 | 103 | 31 | DY | 44.2 |
| 23D02S | SEINE CREEK | OR | 45.5167 | 123.2833 | 2000 | 1981 | 2000 | 20 | 142 | DY | 60.0 |
| 45-7544 | SEQUIM 2 E | WA | 48.0833 | 123.0500 | 50 | 1916 | 2000 | 85 | 32 | DY | 17.3 |
| 1107200 | SEYMOUR FALLS | BC | 49.4333 | 122.9667 | 800 | 1927 | 1995 | 69 | 15 | DY | 138.0 |
| 1017230 | SHAWNIGAN LAKE | BC | 48.6500 | 123.6167 | 449 | 1911 | 1995 | 85 | 32 | DY | 45.9 |
| 22C10S | SHEEP CANYON | WA | 46.1833 | 122.2500 | 4030 | 1981 | 1999 | 19 | 15 | DY | 113.2 |
| 45-7584 | SHELTON | WA | 47.2000 | 123.1000 | 22 | 1931 | 1999 | 69 | 32 | DY | 63.6 |
| 45-7604 | SHUKSAN | WA | 48.9167 | 121.7000 | 2031 | 1955 | 1974 | 20 | 15 | HR | 86.5 |
| 35-7823 | SILVERTON | OR | 45.0000 | 122.7667 | 408 | 1962 | 2000 | 39 | 31 | DY | 45.0 |
| 35-7823 | SILVERTON | OR | 45.0000 | 122.7667 | 408 | 1962 | 2000 | 39 | 31 | HR | 45.0 |
| 45-7657 | SILVERTON | WA | 48.0667 | 121.5667 | 1475 | 1941 | 1988 | 48 | 15 | HR | 104.4 |
| 45-7690 | SKAGIT POWER PLANT | WA | 48.6833 | 121.2500 | 531 | 1931 | 1959 | 29 | 14 | DY | 89.4 |
| 1117410 | SKAGIT RIVER | BC | 49.0833 | 121.1667 | 1689 | 1936 | 1955 | 20 | 14 | DY | 59.5 |
| 45-7696 | SKAMANIA FISH HATCHE | WA | 45.6167 | 122.2167 | 440 | 1965 | 2000 | 36 | 15 | DY | 81.9 |
| 21B60S | SKOOKUM CREEK | WA | 47.6833 | 121.6000 | 3920 | 1996 | 1999 | 4 | 15 | DY | 94.7 |
| 45-7709 | SKYKOMISH 1 ENE | WA | 47.7000 | 121.3667 | 1030 | 1941 | 2000 | 60 | 15 | HR | 98.3 |
| SN-7124 | SMOKEY POINT FIRE STN | WA | 48.1136 | 122.1847 | 100 | 1991 | 2000 | 10 | 31 | DY | 40.9 |
| 45-7773 | SNOQUALMIE FALLS | WA | 47.5333 | 121.8333 | 440 | 1931 | 2000 | 70 | 31 | DY | 69.0 |
| 45-7773 | SNOQUALMIE FALLS | WA | 47.5333 | 121.8333 | 440 | 1954 | 2000 | 47 | 31 | HR | 69.0 |
| 45-7781 | SNOQUALMIE PASS | WA | 47.4167 | 121.4000 | 3020 | 1931 | 1972 | 42 | 15 | DY | 100.0 |
| 45-7781 | SNOQUALMIE PASS | WA | 47.4167 | 121.4000 | 3020 | 1941 | 2000 | 60 | 15 | HR | 100.0 |
| 45-7871 | SO OLYMPIC TREE FARM | WA | 47.2333 | 123.5833 | 580 | 1945 | 1956 | 12 | 151 | DY | 115.5 |
| 1017560 | SOOKE LAKE | BC | 48.5167 | 123.7000 | 567 | 1903 | 1966 | 64 | 142 | DY | 59.5 |
| 1017563 | SOOKE LAKE NORTH | BC | 48.5667 | 123.6500 | 757 | 1966 | 1995 | 30 | 142 | DY | 57.4 |
| 21C20S | SPENCER MEADOW | WA | 46.1833 | 121.9333 | 3400 | 1982 | 1999 | 18 | 15 | DY | 89.6 |
| 22C12S | SPIRIT LAKE | WA | 46.2667 | 122.1667 | 3120 | 1986 | 1999 | 14 | 15 | DY | 88.1 |
| 45-7919 | SPIRIT LAKE R S | WA | 46.2667 | 122.1500 | 3240 | 1941 | 1958 | 18 | 15 | HR | 87.7 |
| 45-7987 | SPRUCE | WA | 47.8000 | 124.0667 | 370 | 1927 | 1981 | 55 | 151 | DY | 132.6 |
| 35-7466 | ST HELENS RFD | OR | 45.8500 | 122.8000 | 100 | 1976 | 2000 | 25 | 32 | DY | 43.1 |
| 45-8009 | STAMPEDE PASS | WA | 47.2833 | 121.3333 | 3958 | 1944 | 2000 | 57 | 14 | DY | 89.0 |
| 21B10S | STAMPEDE PASS | WA | 47.2833 | 121.3333 | 3860 | 1983 | 1999 | 17 | 14 | DY | 89.0 |
| 45-8009 | STAMPEDE PASS | WA | 47.2833 | 121.3333 | 3958 | 1943 | 2000 | 58 | 14 | HR | 89.0 |
| 45-8034 | STARTUP 1 E | WA | 47.8667 | 121.7167 | 170 | 1939 | 2000 | 62 | 31 | DY | 67.0 |
| 1107680 | STAVE FALLS | BC | 49.2333 | 122.3667 | 360 | 1909 | 1995 | 87 | 15 | DY | 89.3 |

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 45-8059 | STEHEKIN 4 NW | WA | 48.3500 | 120.7167 | 1270 | 1917 | 2000 | 84 | 14 | DY | 34.6 |
| 45-8059 | STEHEKIN 4 NW | WA | 48.3500 | 120.7167 | 1270 | 1976 | 2000 | 25 | 14 | HR | 34.6 |
| 45-8089 | STEVENS PASS | WA | 47.7333 | 121.0833 | 4070 | 1939 | 1994 | 56 | 14 | DY | 84.8 |
| 21B01S | STEVENS PASS | WA | 47.7333 | 121.0833 | 4070 | 1981 | 1999 | 19 | 14 | DY | 84.8 |
| 45-8089 | STEVENS PASS | WA | 47.7333 | 121.0833 | 4070 | 1971 | 2000 | 30 | 14 | HR | 84.8 |
| 1107710 | STEVESTON | BC | 49.1333 | 123.1833 | 3 | 1896 | 1995 | 100 | 31 | DY | 45.0 |
| 45-8115 | STOCKDILL RANCH | WA | 48.3667 | 120.3333 | 2200 | 1922 | 1964 | 43 | 14 | DY | 29.8 |
| 22C08S | STRAWBERRY LANDING | WA | 46.3333 | 122.0500 | 4800 | 1983 | 1989 | 7 | 15 | DY | 107.4 |
| 21C13S | SURPRISE LAKES | WA | 46.1000 | 121.7500 | 4250 | 1981 | 1999 | 19 | 14 | DY | 90.5 |
| 45-8278 | TACOMA 1 | WA | 47.2333 | 122.4000 | 25 | 1935 | 2000 | 66 | 31 | DY | 38.5 |
| 1037890 | TAHSIS | BC | 49.9167 | 126.6500 | 16 | 1952 | 1988 | 37 | 151 | DY | 149.3 |
| 45-8332 | TATOOSH ISLAND WB | WA | 48.3833 | 124.7333 | 100 | 1931 | 1966 | 36 | 5 | DY | 94.4 |
| 45-8332 | TATOOSH ISLAND WB | WA | 48.3833 | 124.7333 | 100 | 1940 | 1966 | 27 | 5 | HR | 94.4 |
| 35-8466 | THREE LYNX | OR | 45.1167 | 122.0667 | 1120 | 1931 | 2000 | 70 | 15 | DY | 72.0 |
| 35-8466 | THREE LYNX | OR | 45.1167 | 122.0667 | 1120 | 1971 | 2000 | 30 | 15 | HR | 72.0 |
| 20A07S | THUNDER BASIN | WA | 48.5167 | 120.9833 | 4200 | 1988 | 1999 | 12 | 14 | DY | 99.2 |
| 45-8442 | TIETON INTAKE | WA | 46.6667 | 121.0000 | 2280 | 1920 | 1972 | 53 | 99 | DY | 20.0 |
| 35-8494 | TILLAMOOK 1 W | OR | 45.4500 | 123.8667 | 10 | 1948 | 2000 | 53 | 5 | DY | 88.3 |
| 35-8504 | TILLAMOOK 12 ESE | OR | 45.4000 | 123.5833 | 420 | 1949 | 2000 | 52 | 151 | HR | 112.5 |
| 35-8505 | TILLAMOOK 13 ENE | OR | 45.5500 | 123.6000 | 390 | 1970 | 1978 | 9 | 151 | DY | 117.6 |
| 35-8522 | TIMBER | OR | 45.7167 | 123.3000 | 940 | 1948 | 1976 | 29 | 142 | DY | 65.8 |
| 21B20S | TINKHAM CREEK | WA | 47.3167 | 121.4667 | 3070 | 1994 | 1999 | 6 | 15 | DY | 114.3 |
| 45-8500 | TOLEDO | WA | 46.4667 | 122.8333 | 325 | 1950 | 2000 | 51 | 32 | DY | 44.1 |
| 45-8508 | TOLT SOUTH FORK RESE | WA | 47.7000 | 121.7833 | 1800 | 1963 | 2000 | 38 | 15 | DY | 77.5 |
| 20B25S | TROUGH | WA | 47.2333 | 120.3167 | 5300 | 1979 | 1999 | 21 | 14 | DY | 28.1 |
| 35-8634 | TROUTDALE SUBSTATION | OR | 45.5500 | 122.4000 | 29 | 1948 | 2000 | 53 | 31 | DY | 45.6 |
| 45-8688 | UNDERWOOD 4 W | WA | 45.7333 | 121.6000 | 1260 | 1941 | 1962 | 22 | 14 | HR | 43.0 |
| 45-8715 | UPPER BAKER DAM | WA | 48.6500 | 121.6833 | 690 | 1960 | 2000 | 41 | 15 | DY | 77.6 |
| 45-8715 | UPPER BAKER DAM | WA | 48.6500 | 121.6833 | 690 | 1965 | 2000 | 36 | 15 | HR | 77.6 |
| KI-25U | UPPER ISSAQUAH CREEK | WA | 47.4123 | 121.9263 | 750 | 1988 | 2000 | 13 | 31 | DY | 66.7 |
| 20B07S | UPPER WHEELER | WA | 47.2833 | 120.3667 | 4400 | 1982 | 1999 | 18 | 99 | DY | 28.3 |
| 45-8773 | VANCOUVER 4 NNE | WA | 45.6667 | 122.6500 | 210 | 1898 | 2000 | 103 | 31 | DY | 41.5 |
| 1108446 | VANCOUVER HARBOUR CS | BC | 49.3000 | 123.1167 | 3 | 1925 | 1995 | 71 | 31 | DY | 64.2 |
| 45-8778 | VANCOUVER INTERSTATE | WA | 45.6167 | 122.6667 | 2 | 1949 | 1959 | 11 | 31 | DY | 39.5 |
| 1108447 | VANCOUVER INT'L A | BC | 49.1833 | 123.1667 | 6 | 1937 | 1995 | 59 | 31 | DY | 50.2 |
| 1108447 | VANCOUVER INT'L A | BC | 49.1833 | 123.1667 | 6 | 1947 | 1995 | 49 | 31 | S6 | 50.2 |
| 45-8802 | VASHON ISLAND | WA | 47.4500 | 122.5000 | 230 | 1915 | 1955 | 41 | 32 | DY | 43.5 |
| 45-8838 | VERLOT | WA | 48.1000 | 121.7833 | 975 | 1971 | 2000 | 30 | 15 | HR | 110.3 |
| 35-8884 | VERNONIA 2 | OR | 45.8500 | 123.1833 | 625 | 1948 | 2000 | 53 | 32 | DY | 52.7 |
| 35-8884 | VERNONIA 2 | OR | 45.8500 | 123.1833 | 625 | 1954 | 2000 | 47 | 32 | HR | 52.7 |
| 1018610 | VICTORIA GONZALES HT | BC | 48.4167 | 123.3167 | 229 | 1898 | 1995 | 98 | 32 | DY | 30.0 |
| 1018620 | VICTORIA INT'L A | BC | 48.6500 | 123.4333 | 62 | 1940 | 1996 | 57 | 32 | DY | 35.0 |
| 1018620 | VICTORIA INT'L A | BC | 48.6500 | 123.4333 | 62 | 1947 | 1995 | 49 | 32 | S6 | 35.0 |
| 35-9051 | WARREN | OR | 45.8167 | 122.8500 | 79 | 1950 | 1976 | 27 | 32 | DY | 44.2 |
| 45-8999 | WASHOUGAL 8 NE | WA | 45.6000 | 122.1833 | 761 | 1950 | 1965 | 16 | 15 | DY | 72.0 |
| 45-9021 | WAUNA 3 W | WA | 47.3667 | 122.7000 | 17 | 1939 | 2000 | 62 | 32 | DY | 50.8 |
| 21A31S | WELLS CREEK | WA | 48.8500 | 121.7833 | 4200 | 1996 | 1999 | 4 | 15 | DY | 99.1 |
| 35-9208 | WEST LINN | OR | 45.3333 | 122.6500 | 70 | 1948 | 1969 | 22 | 31 | DY | 47.6 |
| 45-9112 | WESTPORT 2 S | WA | 46.8667 | 124.1000 | 20 | 1940 | 2000 | 61 | 5 | HR | 76.2 |
| 21C28S | WHITE PASS E.S. | WA | 46.6333 | 121.3833 | 4500 | 1981 | 1999 | 19 | 14 | DY | 77.5 |
| 45-9171 | WHITE RIVER R S | WA | 46.9000 | 121.5500 | 3500 | 1949 | 1976 | 28 | 15 | DY | 71.7 |
| 45-9171 | WHITE RIVER R S | WA | 46.9000 | 121.5500 | 3500 | 1944 | 1981 | 38 | 15 | HR | 71.7 |
| 1108910 | WHITE ROCK CAMPBELL | BC | 49.0167 | 122.7833 | 49 | 1929 | 1995 | 67 | 31 | DY | 48.8 |
| 35-9372 | WILLAMINA | OR | 45.0667 | 123.4833 | 230 | 1948 | 2000 | 53 | 32 | DY | 48.5 |
| 45-9291 | WILLAPA HARBOR | WA | 46.6833 | 123.7500 | 10 | 1910 | 1980 | 71 | 5 | DY | 88.1 |
| 45-9295 | WILLARD FISH LAB | WA | 45.7667 | 121.6333 | 770 | 1962 | 1976 | 15 | 14 | HR | 59.0 |
| 45-9342 | WIND RIVER | WA | 45.8000 | 121.9333 | 1150 | 1911 | 1977 | 67 | 15 | DY | 101.5 |
| 45-9358 | WINTERS MOUNTAIN | WA | 46.4500 | 122.3167 | 3650 | 1983 | 1989 | 7 | 15 | HR | 78.1 |
| 45-9376 | WINTHROP 1 WSW | WA | 48.4667 | 120.1833 | 1755 | 1906 | 2000 | 95 | 99 | DY | 13.7 |
| 45-9485 | YELM | WA | 46.9500 | 122.6000 | 351 | 1941 | 1979 | 39 | 31 | HR | 42.7 |

Table A2 – Station Catalog of Gages Used in Analyses of Precipitation Annual Maxima at 2-Hour Duration

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1100030 | ABBOTSFORD A | BC | 49.0333 | 122.3667 | 190 | 1976 | 1996 | 21 | 31 | HR | 57.8 |
| 45-0013 | ABERDEEN 20 NNE | WA | 47.2667 | 123.7000 | 435 | 1940 | 2000 | 61 | 151 | HR | 131.0 |
| 1100120 | AGASSIZ CDA | BC | 49.2500 | 121.7667 | 49 | 1960 | 1990 | 31 | 14 | HR | 67.6 |
| 1030426 | AMPHITRITE POINT | BC | 48.9167 | 125.5500 | 88 | 1980 | 1996 | 17 | 5 | HR | 130.3 |
| 35-0328 | ASTORIA AP PORT OF | OR | 46.1500 | 123.8667 | 9 | 1953 | 2000 | 48 | 5 | HR | 77.3 |
| 45-0324 | AUBURN | WA | 47.3167 | 122.2333 | 79 | 1954 | 1977 | 24 | 31 | HR | 38.5 |
| 45-0400 | BALDY MOUNTAIN | WA | 46.1000 | 122.7000 | 2190 | 1983 | 1989 | 7 | 15 | HR | 90.2 |
| 35-0571 | BEAR SPRINGS RS | OR | 45.1167 | 121.5333 | 3360 | 1961 | 2000 | 40 | 14 | HR | 28.5 |
| 45-0574 | BELLINGHAM CAA AP | WA | 48.8000 | 122.5333 | 147 | 1941 | 1952 | 12 | 31 | HR | 39.4 |
| 45-0729 | BLAINE | WA | 49.0000 | 122.7500 | 60 | 1941 | 2000 | 60 | 31 | HR | 45.6 |
| 35-0897 | BONNEVILLE DAM | OR | 45.6333 | 121.9500 | 62 | 1940 | 2000 | 61 | 15 | HR | 78.1 |
| 35-1033 | BRIGHTWOOD 1 WNW | OR | 45.3833 | 122.0333 | 978 | 1971 | 2000 | 30 | 15 | HR | 79.1 |
| 1101140 | BUNTZEN LAKE | BC | 49.3833 | 122.8667 | 32 | 1969 | 1983 | 15 | 15 | HR | 131.7 |
| 45-0986 | BURLINGTON | WA | 48.4667 | 122.3167 | 30 | 1941 | 2000 | 60 | 31 | HR | 36.5 |
| 110JA54 | BURNABY MTN BCHPA | BC | 49.2833 | 122.9167 | 1525 | 1974 | 1992 | 19 | 15 | HR | 71.0 |
| 35-1222 | BUXTON | OR | 45.6833 | 123.1833 | 355 | 1948 | 2000 | 53 | 32 | HR | 55.2 |
| 35-1227 | BUXTON MOUNTAINDALE | OR | 45.6833 | 123.0667 | 360 | 1948 | 1975 | 28 | 32 | HR | 53.5 |
| 45-1064 | CAMP GRISDALE | WA | 47.3667 | 123.6000 | 820 | 1956 | 1986 | 31 | 151 | HR | 166.4 |
| TH-1168 | CAPITOL FOREST | WA | 46.9215 | 123.0900 | 450 | 1995 | 2000 | 6 | 142 | HR | 80.0 |
| 45-1146 | CARNATION 4 NW | WA | 47.6833 | 121.9833 | 50 | 1941 | 2000 | 60 | 31 | HR | 49.0 |
| 1031413 | CARNATION CREEK CDF | BC | 48.9000 | 125.0000 | 200 | 1975 | 1986 | 12 | 5 | HR | 130.7 |
| 45-1160 | CARSON FISH HATCHERY | WA | 45.8667 | 121.9667 | 1134 | 1977 | 2000 | 24 | 14 | HR | 102.0 |
| 45-1191 | CASTLE ROCK 2 NW | WA | 46.2667 | 122.9167 | 39 | 1954 | 1978 | 25 | 31 | HR | 47.7 |
| 45-1233 | CEDAR LAKE | WA | 47.4167 | 121.7333 | 1560 | 1953 | 2000 | 48 | 15 | HR | 106.9 |
| 45-1277 | CENTRALIA 1 W | WA | 46.7000 | 122.9667 | 185 | 1941 | 2000 | 60 | 31 | HR | 46.1 |
| 45-1457 | CINEBAR 2 E | WA | 46.6000 | 122.4833 | 1040 | 1941 | 2000 | 60 | 15 | HR | 57.9 |
| 35-1643 | CLATSKANIE | OR | 46.1000 | 123.2000 | 22 | 1954 | 2000 | 47 | 32 | HR | 52.3 |
| 45-1496 | CLEARWATER | WA | 47.5833 | 124.3000 | 80 | 1943 | 2000 | 58 | 5 | HR | 117.6 |
| 35-1735 | COLTON | OR | 45.1667 | 122.4167 | 680 | 1948 | 2000 | 53 | 31 | HR | 58.9 |
| 1021830 | COMOX A | BC | 49.7167 | 124.9000 | 78 | 1962 | 1996 | 35 | 142 | HR | 48.6 |
| 1101890 | COQUITLAM LAKE | BC | 49.3667 | 122.8000 | 528 | 1970 | 1982 | 13 | 15 | HR | 111.5 |
| 45-1759 | COUGAR 4 SW | WA | 46.0167 | 122.3500 | 520 | 1941 | 2000 | 60 | 15 | HR | 67.1 |
| 1021990 | COURTENAY PUNTLEDGE | BC | 49.6833 | 125.0333 | 78 | 1964 | 1995 | 32 | 32 | HR | 53.7 |
| 45-1934 | CUSHMAN DAM | WA | 47.4167 | 123.2167 | 760 | 1941 | 2000 | 60 | 142 | HR | 97.0 |
| 45-1992 | DARRINGTON RANGER ST | WA | 48.2500 | 121.6000 | 550 | 1941 | 2000 | 60 | 15 | HR | 73.6 |
| 45-2157 | DIABLO DAM | WA | 48.7167 | 121.1500 | 891 | 1944 | 2000 | 57 | 14 | HR | 69.1 |
| 35-2348 | DIXIE MOUNTAIN | OR | 45.6833 | 122.9167 | 1430 | 1976 | 2000 | 25 | 32 | HR | 66.9 |
| KI-14U | EAST FORK ISSAQUAH CK | WA | 47.5327 | 121.9873 | 520 | 1988 | 2000 | 13 | 15 | DY | 79.3 |
| 45-2384 | EASTON | WA | 47.2333 | 121.1833 | 2170 | 1941 | 2000 | 60 | 14 | HR | 49.5 |
| TH-1938 | EATON CREEK | WA | 46.9742 | 122.7300 | 264 | 1992 | 2000 | 9 | 31 | HR | 45.0 |
| 45-2493 | ELECTRON HEADWORKS | WA | 46.9000 | 122.0333 | 1730 | 1943 | 1980 | 38 | 15 | HR | 69.6 |
| 45-2500 | ELK MOUNTAIN | WA | 46.1333 | 122.4667 | 4480 | 1983 | 1990 | 8 | 15 | HR | 118.4 |
| 35-2697 | ESTACADA 24 SE | OR | 45.0667 | 121.9667 | 2200 | 1948 | 2000 | 53 | 15 | HR | 72.2 |
| 45-2675 | EVERETT | WA | 47.9833 | 122.1833 | 60 | 1941 | 2000 | 60 | 31 | HR | 37.4 |
| 45-2984 | FRANCES | WA | 46.5500 | 123.5000 | 231 | 1941 | 2000 | 60 | 142 | HR | 97.8 |
| 45-3160 | GLACIER R S | WA | 48.8833 | 121.9500 | 935 | 1971 | 2000 | 30 | 15 | HR | 65.5 |
| 45-3183 | GLENWOOD | WA | 46.0167 | 121.2833 | 1896 | 1941 | 2000 | 60 | 14 | HR | 34.7 |
| 35-3318 | GLENWOOD 2 WNW | OR | 45.6500 | 123.3000 | 644 | 1948 | 2000 | 53 | 142 | HR | 65.8 |
| 35-3340 | GOBLE 3 SW | OR | 45.9833 | 122.9167 | 530 | 1948 | 2000 | 53 | 32 | HR | 48.3 |
| 35-3402 | GOVERNMENT CAMP | OR | 45.3000 | 121.7333 | 3980 | 1955 | 2000 | 46 | 15 | HR | 72.6 |
| 35-3421 | GRAND RONDE TREE FAR | OR | 45.0500 | 123.6167 | 395 | 1948 | 2000 | 53 | 5 | HR | 56.1 |
| 45-3333 | GRAYS RIVER HATCHERY | WA | 46.3833 | 123.5667 | 100 | 1954 | 2000 | 47 | 5 | HR | 107.4 |
| 45-3357 | GREENWATER | WA | 47.1333 | 121.6333 | 1730 | 1940 | 1999 | 60 | 15 | HR | 61.6 |
| 35-3521 | GRESHAM | OR | 45.4833 | 122.4167 | 310 | 1948 | 2000 | 53 | 31 | HR | 53.0 |
| 1103328 | HANEY MICROWAVE | BC | 49.2000 | 122.5167 | 1049 | 1963 | 1984 | 22 | 15 | HR | 74.9 |
| 1103332 | HANEY UBC RF ADMIN | BC | 49.2667 | 122.5667 | 469 | 1962 | 1996 | 35 | 15 | HR | 88.0 |
| 35-3705 | HASKINS DAM | OR | 45.3000 | 123.3500 | 756 | 1948 | 2000 | 53 | 142 | HR | 72.6 |
| 35-3770 | HEADWORKS PTLD WTR B | OR | 45.4500 | 122.1500 | 748 | 1976 | 2000 | 25 | 15 | HR | 75.6 |
| 35-4008 | HOOD RIVER TUCKER BR | OR | 45.6500 | 121.5333 | 383 | 1941 | 2000 | 60 | 14 | HR | 30.6 |
| 1113540 | HOPE A | BC | 49.3667 | 121.4833 | 127 | 1963 | 1995 | 33 | 14 | HR | 66.8 |
| 35-4276 | JEWELL WILDLIFE MEAD | OR | 45.9333 | 123.5167 | 570 | 1954 | 2000 | 47 | 142 | HR | 94.5 |
| 1013754 | JORDAN RIVER DIVERSI | BC | 48.5000 | 124.0000 | 1289 | 1973 | 1996 | 24 | 151 | HR | 122.5 |
| 45-4446 | LAKE WENATCHEE | WA | 47.8333 | 120.7833 | 2005 | 1971 | 2000 | 30 | 14 | HR | 38.1 |
| 45-4486 | LANDSBURG | WA | 47.3833 | 121.9833 | 535 | 1954 | 2000 | 47 | 31 | HR | 56.0 |
| 1104555 | LANGLEY LOCHIEL | BC | 49.0500 | 122.5833 | 331 | 1971 | 1986 | 16 | 31 | HR | 59.6 |
| 35-4824 | LEES CAMP | OR | 45.5833 | 123.5167 | 655 | 1948 | 2000 | 53 | 151 | HR | 113.6 |
| 45-4634 | LESTER | WA | 47.2000 | 121.4833 | 1630 | 1948 | 1975 | 28 | 15 | HR | 80.4 |
| 45-4764 | LONGMIRE RAINIER NPS | WA | 46.7500 | 121.8167 | 2762 | 1979 | 2000 | 22 | 15 | HR | 84.7 |
| 45-4769 | LONGVIEW | WA | 46.1500 | 122.9167 | 12 | 1954 | 2000 | 47 | 31 | HR | 46.1 |
| 45-4849 | LUCERNE 1 N | WA | 48.2333 | 120.6000 | 1200 | 1942 | 1989 | 48 | 14 | HR | 22.6 |
| 45-4999 | MARBLEMOUNT RANGER S | WA | 48.5333 | 121.4500 | 348 | 1941 | 2000 | 60 | 15 | HR | 69.8 |
| 45-5149 | MC CHORD AFB | WA | 47.1500 | 122.4833 | 290 | 1941 | 1979 | 39 | 31 | HR | 39.8 |

| STATION ID | STATION NAME | STATE | LAT | LONG | ELEV (ft) | YEAR START | YEAR END | YEARS OPEN | RGN | GAGE TYPE | PRISM MAP[3,20] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 45-5224 | MC MILLIN RESERVOIR | WA | 47.1333 | 122.2667 | 579 | 1941 | 2000 | 60 | 31 | HR | 41.5 |
| 1045100 | MERRY ISLAND | BC | 49.4667 | 123.9167 | 26 | 1977 | 1996 | 20 | 31 | HR | 44.9 |
| 45-5305 | MERWIN DAM | WA | 45.9500 | 122.5500 | 224 | 1983 | 1988 | 6 | 31 | HR | 67.4 |
| 1105192 | MISSION WEST ABBEY | BC | 49.1500 | 122.2667 | 725 | 1962 | 1996 | 35 | 31 | HR | 73.1 |
| 35-5629 | MIST 1 SE | OR | 45.9833 | 123.2500 | 500 | 1948 | 1958 | 11 | 32 | HR | 54.8 |
| 45-5488 | MOCLIPS | WA | 47.2167 | 124.2000 | 120 | 1942 | 1957 | 16 | 5 | HR | 91.9 |
| 45-5549 | MONTESANO 1 S | WA | 46.9667 | 123.6167 | 25 | 1954 | 2000 | 47 | 32 | HR | 77.1 |
| 45-5659 | MOUNT ADAMS RANGER S | WA | 46.0000 | 121.5333 | 1960 | 1971 | 2000 | 30 | 14 | HR | 42.4 |
| 45-5663 | MOUNT BAKER LODGE | WA | 48.8667 | 121.6667 | 4150 | 1948 | 1983 | 36 | 15 | HR | 81.1 |
| 45-5704 | MUD MOUNTAIN DAM | WA | 47.1500 | 121.9333 | 1308 | 1940 | 2000 | 61 | 15 | HR | 61.3 |
| 1025370 | NANAIMO A | BC | 49.0500 | 123.8667 | 91 | 1985 | 1996 | 12 | 32 | HR | 44.4 |
| 10253G0 | NANAIMO CITY YARD | BC | 49.1833 | 123.9833 | 374 | 1979 | 1996 | 18 | 32 | HR | 42.1 |
| 35-5969 | NEHALEM | OR | 45.7167 | 123.9000 | 75 | 1948 | 2000 | 53 | 5 | HR | 78.7 |
| 45-5876 | NOOKSACK SALMON HATC | WA | 48.9000 | 122.1500 | 410 | 1964 | 2000 | 37 | 15 | HR | 67.0 |
| 1015628 | NORTH COWICHAN | BC | 48.8333 | 123.7167 | 150 | 1973 | 1995 | 23 | 32 | HR | 45.9 |
| 45-5932 | NORTH HEAD WB | WA | 46.3000 | 124.0833 | 210 | 1940 | 1953 | 14 | 5 | HR | 81.5 |
| 45-6114 | OLYMPIA AIRPORT | WA | 46.9667 | 122.9000 | 206 | 1948 | 2000 | 53 | 32 | HR | 50.7 |
| 45-6295 | PALMER 3 ESE | WA | 47.3000 | 121.8500 | 920 | 1941 | 2000 | 60 | 15 | HR | 87.9 |
| 110FAG9 | PITT MEADOWS STP | BC | 49.2167 | 122.6833 | 16 | 1974 | 1993 | 20 | 31 | HR | 70.2 |
| 1106180 | PITT POLDER | BC | 49.3000 | 122.6333 | 3 | 1964 | 1996 | 33 | 31 | HR | 85.3 |
| 45-6584 | POINT GRENVILLE | WA | 47.3000 | 124.2833 | 100 | 1957 | 1977 | 21 | 5 | HR | 89.4 |
| 1036206 | PORT ALBERNI A | BC | 49.2500 | 124.8333 | 6 | 1969 | 1995 | 27 | 142 | HR | 81.7 |
| 45-6624 | PORT ANGELES | WA | 48.1000 | 123.4167 | 90 | 1941 | 2000 | 60 | 32 | HR | 33.5 |
| 1106256 | PORT COQUITLAM CITY | BC | 49.2667 | 122.7833 | 22 | 1971 | 1990 | 20 | 31 | HR | 78.3 |
| 1046330 | PORT MELLON | BC | 49.5167 | 123.4833 | 26 | 1964 | 1975 | 12 | 15 | HR | 114.3 |
| 1106CL2 | PORT MOODY GLENAYRE | BC | 49.2833 | 122.8833 | 426 | 1970 | 1996 | 27 | 31 | HR | 71.0 |
| 45-6678 | PORT TOWNSEND | WA | 48.1000 | 122.7500 | 100 | 1941 | 1970 | 30 | 32 | HR | 23.2 |
| 35-6751 | PORTLAND INTL AIRPOR | OR | 45.5833 | 122.6000 | 19 | 1941 | 2000 | 60 | 32 | HR | 38.1 |
| 35-6749 | PORTLAND KGW-TV | OR | 45.5167 | 122.6833 | 160 | 1948 | 2000 | 53 | 32 | HR | 45.2 |
| 45-6851 | QUILCENE 5 SW DAM | WA | 47.7833 | 122.9833 | 1028 | 1941 | 2000 | 60 | 142 | HR | 68.2 |
| 45-6858 | QUILLAYUTE WSCMO AP | WA | 47.9333 | 124.5500 | 179 | 1966 | 2000 | 35 | 5 | HR | 104.8 |
| 45-6864 | QUINAULT RANGER STN | WA | 47.4667 | 123.8500 | 220 | 1977 | 2000 | 24 | 151 | HR | 110.9 |
| 45-6892 | RAINIER CARBON RIVER | WA | 47.0000 | 121.9167 | 1735 | 1948 | 2000 | 53 | 15 | HR | 78.3 |
| 45-6896 | RAINIER OHANAPECOSH | WA | 46.7333 | 121.5667 | 1950 | 1941 | 2000 | 60 | 15 | HR | 75.5 |
| 45-6909 | RANDLE 1 E | WA | 46.5333 | 121.9333 | 900 | 1954 | 2000 | 47 | 15 | HR | 56.9 |
| 35-7127 | REX 1 S | OR | 45.3000 | 122.9000 | 515 | 1948 | 2000 | 53 | 32 | HR | 44.8 |
| 1016942 | SAANICH DENSMORE | BC | 48.5000 | 123.4000 | 193 | 1963 | 1974 | 12 | 32 | HR | 34.8 |
| 45-7294 | SAM HENRY MOUNTAIN | WA | 46.5167 | 123.0167 | 1460 | 1983 | 1989 | 7 | 32 | HR | 58.8 |
| 45-7319 | SAPPHO 8 E | WA | 48.0667 | 124.1167 | 760 | 1940 | 1998 | 59 | 151 | HR | 91.2 |
| 35-7572 | SAUVIES ISLAND | OR | 45.6500 | 122.8333 | 40 | 1948 | 2000 | 53 | 32 | HR | 45.2 |
| 35-7586 | SCOGGINS DAM 2 | OR | 45.4833 | 123.2000 | 360 | 1973 | 1985 | 13 | 32 | HR | 48.2 |
| 45-7473 | SEATTLE TACOMA AIRPO | WA | 47.4500 | 122.3000 | 400 | 1941 | 2000 | 60 | 31 | HR | 37.9 |
| 45-7458 | SEATTLE URBAN SITE | WA | 47.6500 | 122.3000 | 19 | 1940 | 1998 | 59 | 31 | HR | 37.0 |
| 45-7483 | SEATTLE WB AP | WA | 47.5333 | 122.3000 | 10 | 1948 | 1967 | 20 | 31 | HR | 37.1 |
| 45-7604 | SHUKSAN | WA | 48.9167 | 121.7000 | 2031 | 1955 | 1974 | 20 | 15 | HR | 86.5 |
| 35-7823 | SILVERTON | OR | 45.0000 | 122.7667 | 408 | 1962 | 2000 | 39 | 31 | HR | 45.0 |
| 45-7657 | SILVERTON | WA | 48.0667 | 121.5667 | 1475 | 1941 | 1988 | 48 | 15 | HR | 104.4 |
| 45-7709 | SKYKOMISH 1 ENE | WA | 47.7000 | 121.3667 | 1030 | 1941 | 2000 | 60 | 15 | HR | 98.3 |
| 45-7773 | SNOQUALMIE FALLS | WA | 47.5333 | 121.8333 | 440 | 1954 | 2000 | 47 | 31 | HR | 69.0 |
| 45-7781 | SNOQUALMIE PASS | WA | 47.4167 | 121.4000 | 3020 | 1941 | 2000 | 60 | 15 | HR | 100.0 |
| 45-7919 | SPIRIT LAKE R S | WA | 46.2667 | 122.1500 | 3240 | 1941 | 1958 | 18 | 15 | HR | 87.7 |
| 45-8009 | STAMPEDE PASS | WA | 47.2833 | 121.3333 | 3958 | 1943 | 2000 | 58 | 14 | HR | 89.0 |
| 45-8059 | STEHEKIN 4 NW | WA | 48.3500 | 120.7167 | 1270 | 1976 | 2000 | 25 | 14 | HR | 34.6 |
| 45-8089 | STEVENS PASS | WA | 47.7333 | 121.0833 | 4070 | 1971 | 2000 | 30 | 14 | HR | 84.8 |
| 1107873 | SURREY KWANTLEN PARK | BC | 49.2000 | 122.8667 | 305 | 1962 | 1996 | 35 | 31 | HR | 62.8 |
| 45-8332 | TATOOSH ISLAND WB | WA | 48.3833 | 124.7333 | 100 | 1940 | 1966 | 27 | 5 | HR | 94.4 |
| 35-8466 | THREE LYNX | OR | 45.1167 | 122.0667 | 1120 | 1971 | 2000 | 30 | 15 | HR | 72.0 |
| 35-8504 | TILLAMOOK 12 ESE | OR | 45.4000 | 123.5833 | 420 | 1949 | 2000 | 52 | 151 | HR | 112.5 |
| 1038205 | TOFINO A | BC | 49.0833 | 125.7667 | 78 | 1970 | 1996 | 27 | 5 | HR | 128.4 |
| 45-8688 | UNDERWOOD 4 W | WA | 45.7333 | 121.6000 | 1260 | 1941 | 1962 | 22 | 14 | HR | 43.0 |
| 45-8715 | UPPER BAKER DAM | WA | 48.6500 | 121.6833 | 690 | 1965 | 2000 | 36 | 15 | HR | 77.6 |
| 1108446 | VANCOUVER HARBOUR CS | BC | 49.3000 | 123.1167 | 3 | 1976 | 1995 | 20 | 31 | HR | 64.2 |
| 1108447 | VANCOUVER INT'L A | BC | 49.1833 | 123.1667 | 6 | 1960 | 1996 | 37 | 31 | HR | 50.2 |
| 1108487 | VANCOUVER UBC | BC | 49.2500 | 123.2500 | 285 | 1960 | 1990 | 31 | 31 | HR | 52.1 |
| 45-8838 | VERLOT | WA | 48.1000 | 121.7833 | 975 | 1971 | 2000 | 30 | 15 | HR | 110.3 |
| 35-8884 | VERNONIA 2 | OR | 45.8500 | 123.1833 | 625 | 1954 | 2000 | 47 | 32 | HR | 52.7 |
| 1018610 | VICTORIA GONZALES HT | BC | 48.4167 | 123.3167 | 229 | 1960 | 1988 | 29 | 32 | HR | 30.0 |
| 1018620 | VICTORIA INT'L A | BC | 48.6500 | 123.4333 | 62 | 1964 | 1982 | 19 | 32 | HR | 35.0 |
| 45-9112 | WESTPORT 2 S | WA | 46.8667 | 124.1000 | 20 | 1940 | 2000 | 61 | 5 | HR | 76.2 |
| 45-9171 | WHITE RIVER R S | WA | 46.9000 | 121.5500 | 3500 | 1944 | 1981 | 38 | 15 | HR | 71.7 |
| 1108914 | WHITE ROCK STP | BC | 49.0167 | 122.7667 | 49 | 1964 | 1996 | 33 | 31 | HR | 48.8 |
| 45-9295 | WILLARD FISH LAB | WA | 45.7667 | 121.6333 | 770 | 1962 | 1976 | 15 | 14 | HR | 59.0 |
| 45-9358 | WINTERS MOUNTAIN | WA | 46.4500 | 122.3167 | 3650 | 1983 | 1989 | 7 | 15 | HR | 78.1 |
| 45-9485 | YELM | WA | 46.9500 | 122.6000 | 351 | 1941 | 1979 | 39 | 31 | HR | 42.7 |

## OVERVIEW

This appendix contains isopluvial maps of the 2-year, 10-year, 25-year, 50-year, and 100-year precipitation for the 24-hour and 2-hour durations. An isopluvial map for the 6-month recurrence interval (twice-year) is also depicted for the 24-hour duration. Estimates of precipitation for 6-month and 2-year recurrence intervals were made using standard conversions developed by Langbein[15,27] for conversion from annual maxima to partial duration series equivalents. Gridded datasets used to create these maps are contained on the Compact Disc (CD) described in Appendix A. Electronic files of the graphic images (jpeg files) contained in this appendix are also included on the CD.

## 6-month 24-hour Precipitation, Western Washington

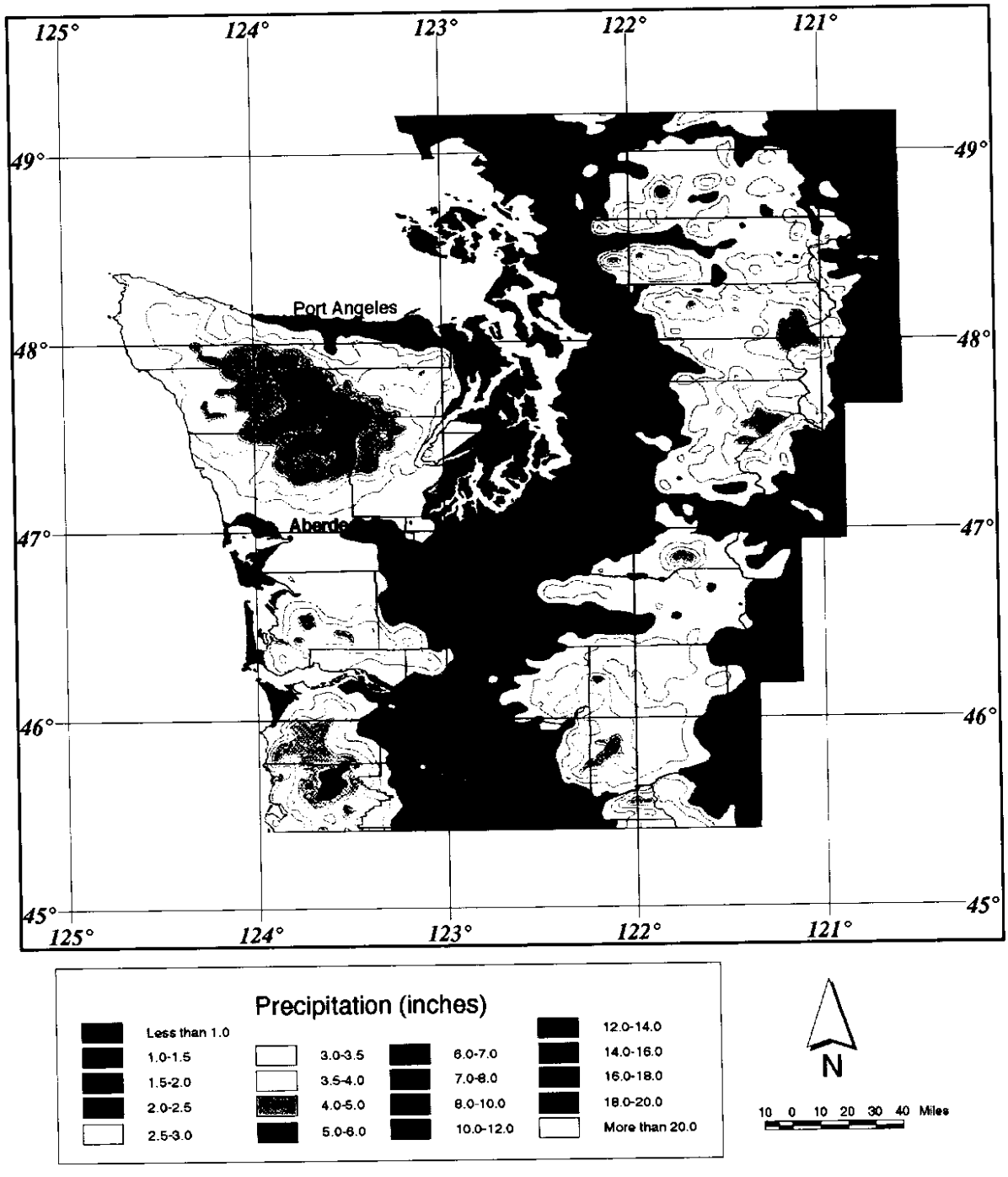



Figure B1 – Isopluvial Map of 24-Hour Precipitation for 6-Month Recurrence Interval for Western Washington

## 2-year 24-hour Precipitation, Western Washington

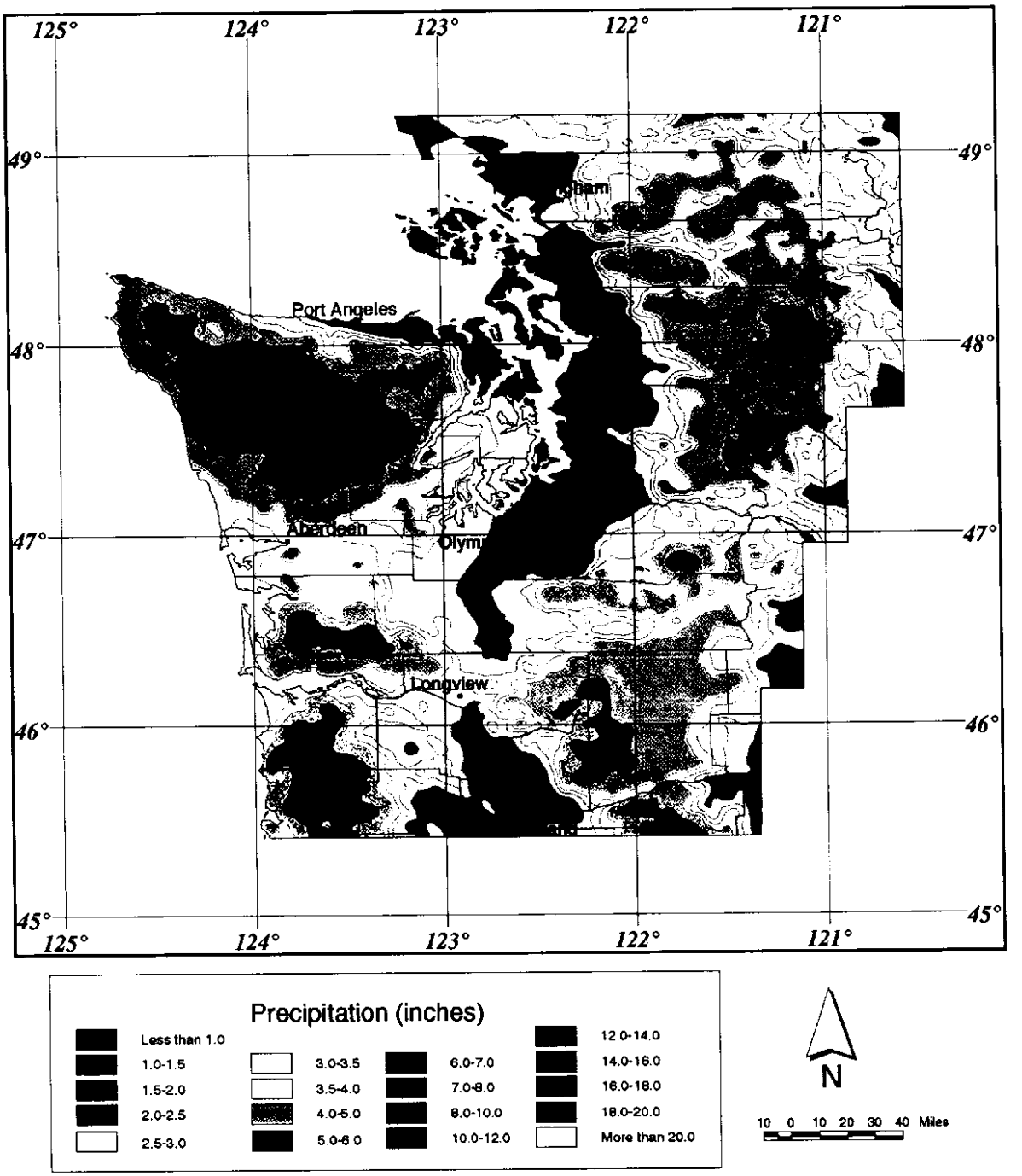



Figure B2 – Isopluvial Map of 24-Hour Precipitation for 2-Year Recurrence Interval for Western Washington

## 10-year 24-hour Precipitation, Western Washington

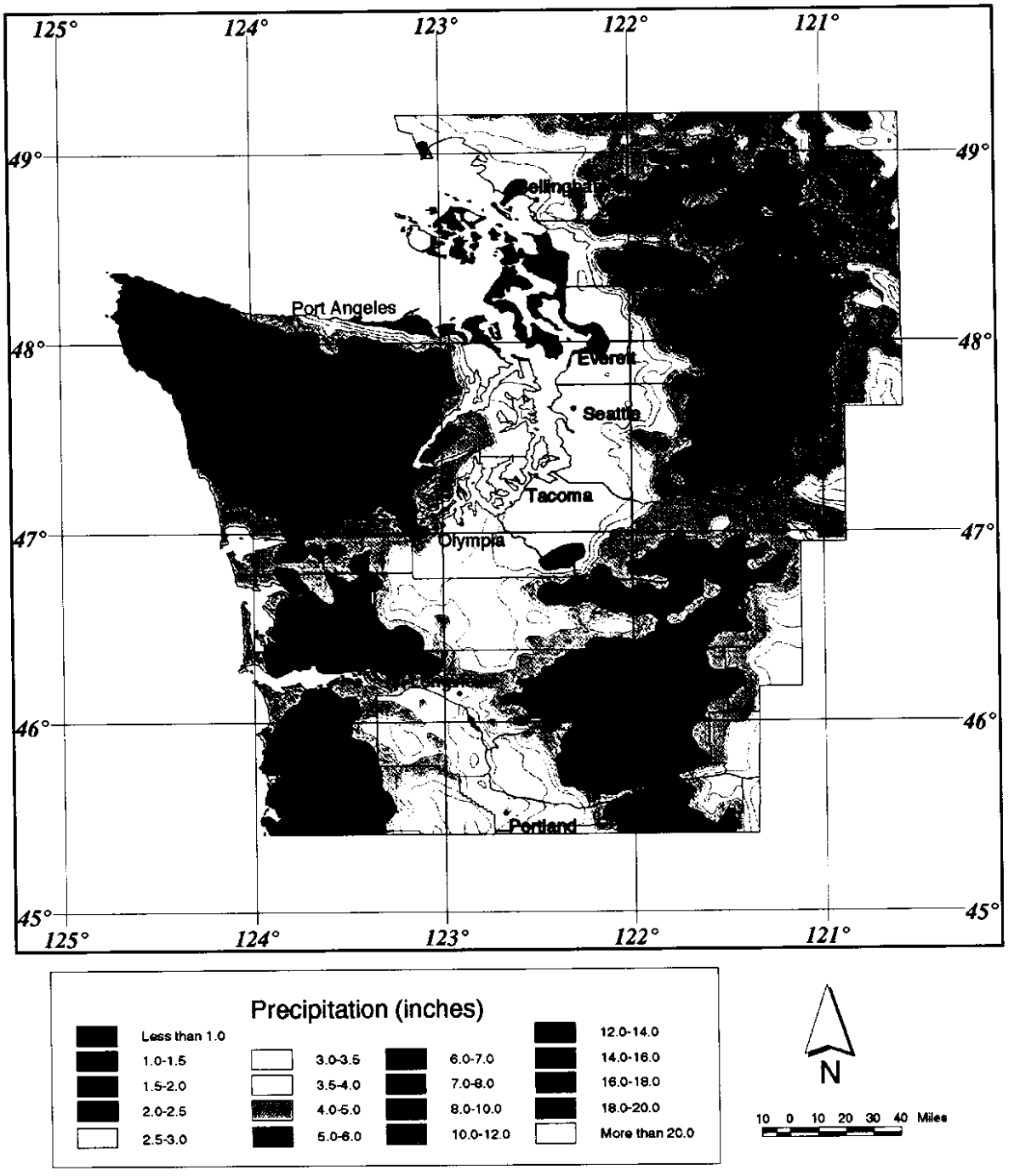



Figure B3 – Isopluvial Map of 24-Hour Precipitation for 10-Year Recurrence Interval for Western Washington

## 25-year 24-hour Precipitation, Western Washington

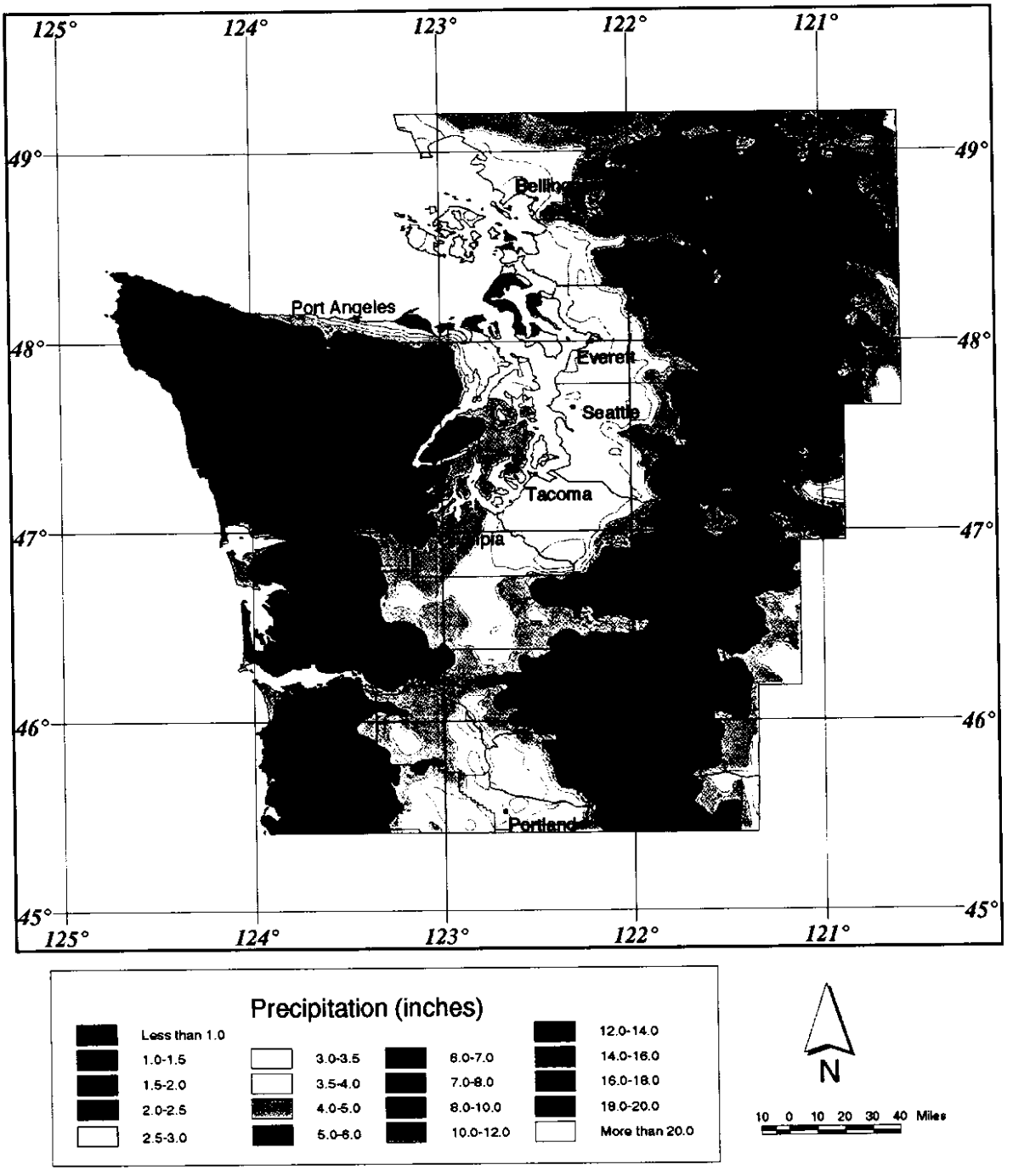



Figure B4 – Isopluvial Map of 24-Hour Precipitation for 25-Year Recurrence Interval for Western Washington

## 50-year 24-hour Precipitation, Western Washington

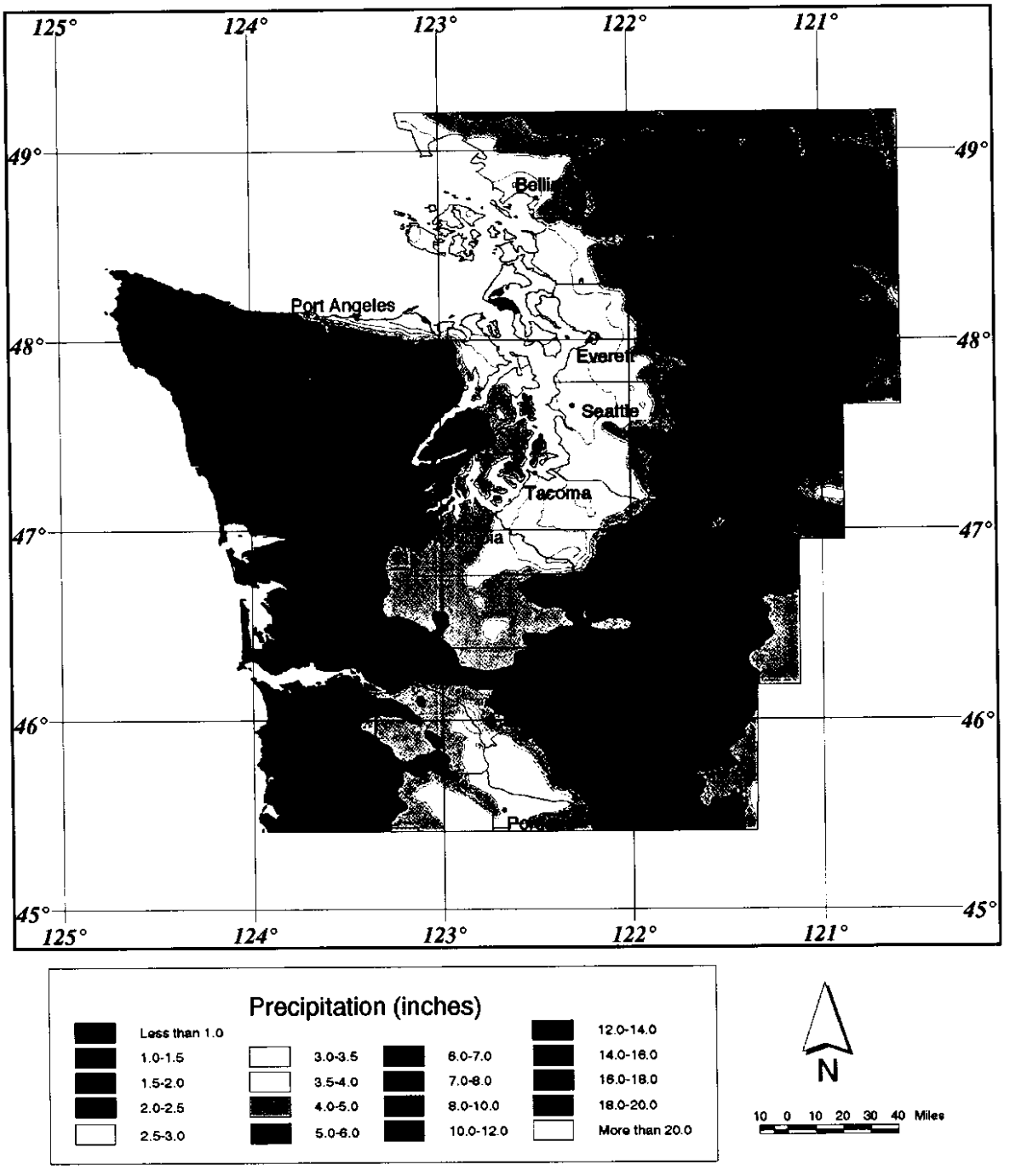



Figure B5 – Isopluvial Map of 24-Hour Precipitation for 50-Year Recurrence Interval for Western Washington

## 100-year 24-hour Precipitation, Western Washington

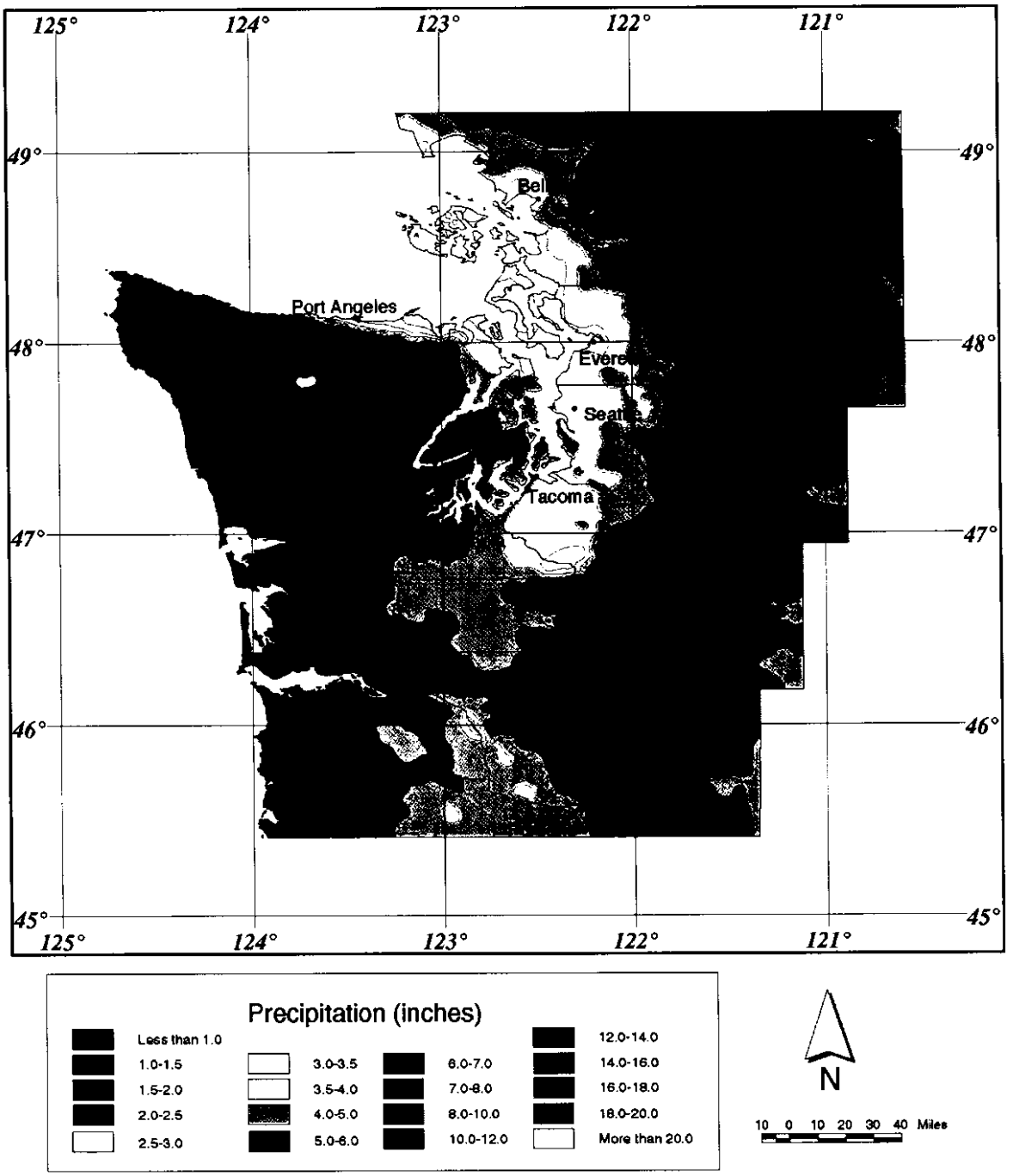



Figure B6 – Isopluvial Map of 24-Hour Precipitation for 100-Year Recurrence Interval for Western Washington

## 2-year 2-hour Precipitation, Western Washington

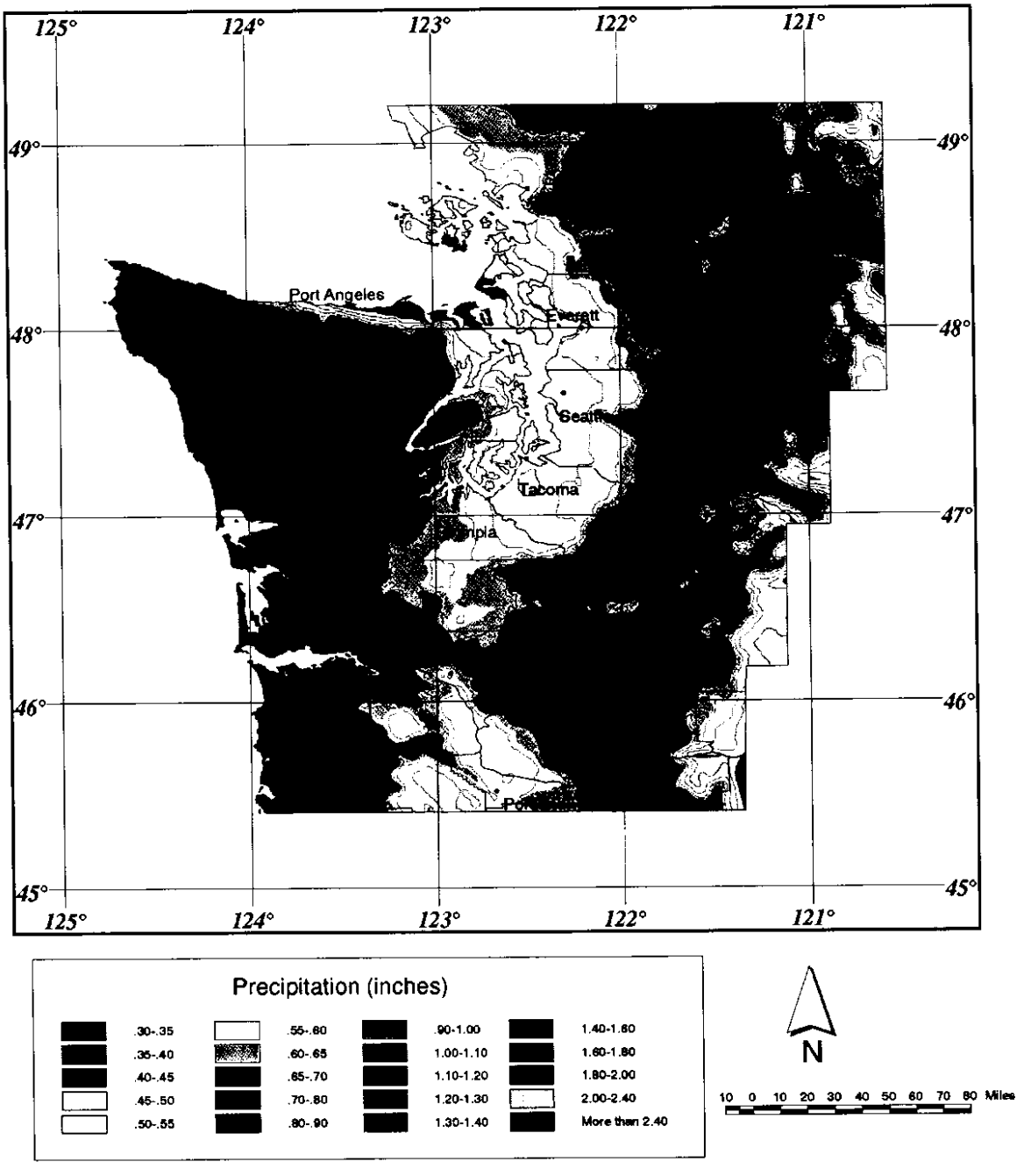



Figure B7 – Isopluvial Map of 2-Hour Precipitation for 2-Year Recurrence Interval for Western Washington

## 10-year 2-hour Precipitation, Western Washington

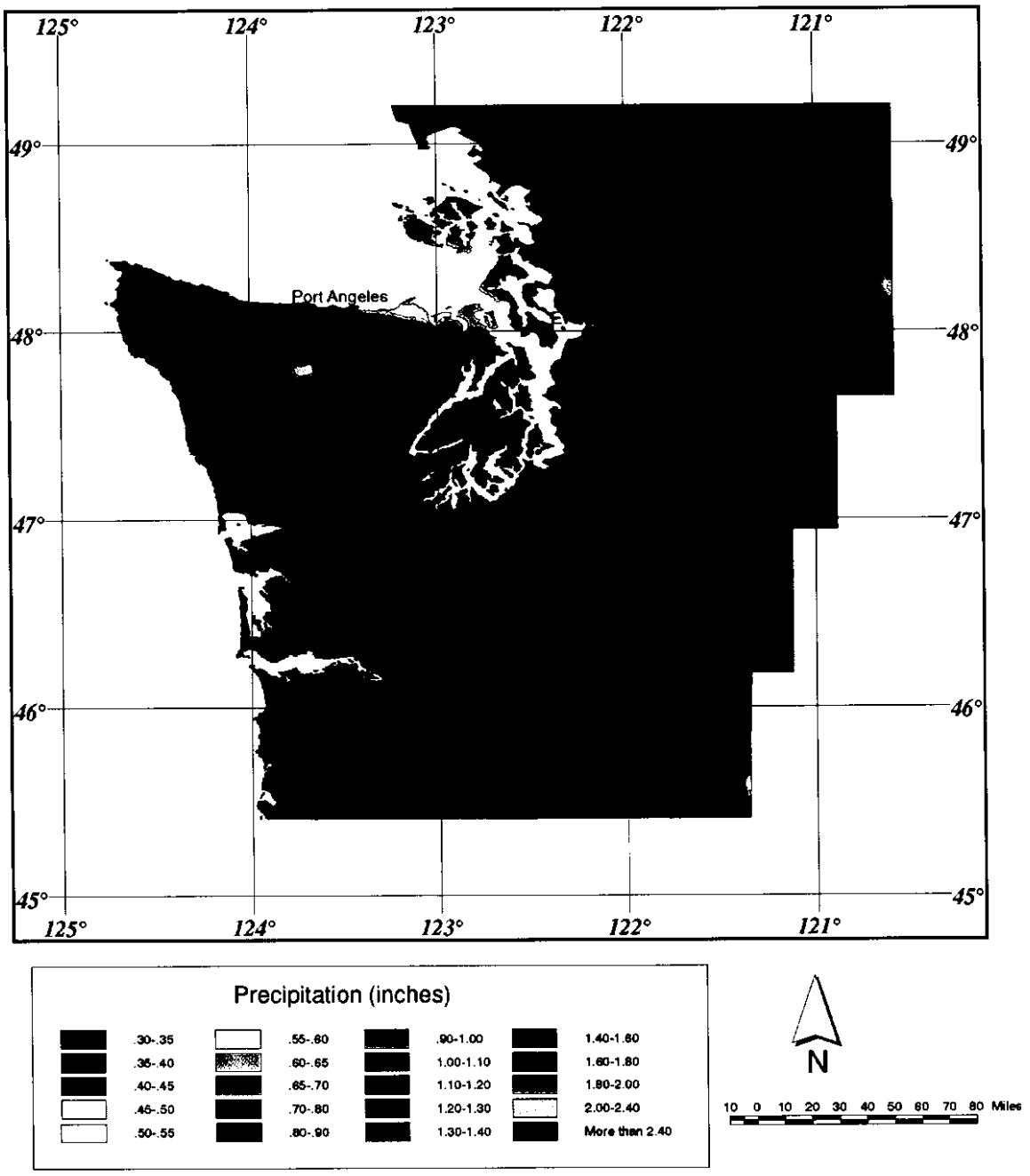



Figure B8 – Isopluvial Map of 2-Hour Precipitation for 10-Year Recurrence Interval for Western Washington

## 25-year 2-hour Precipitation, Western Washington

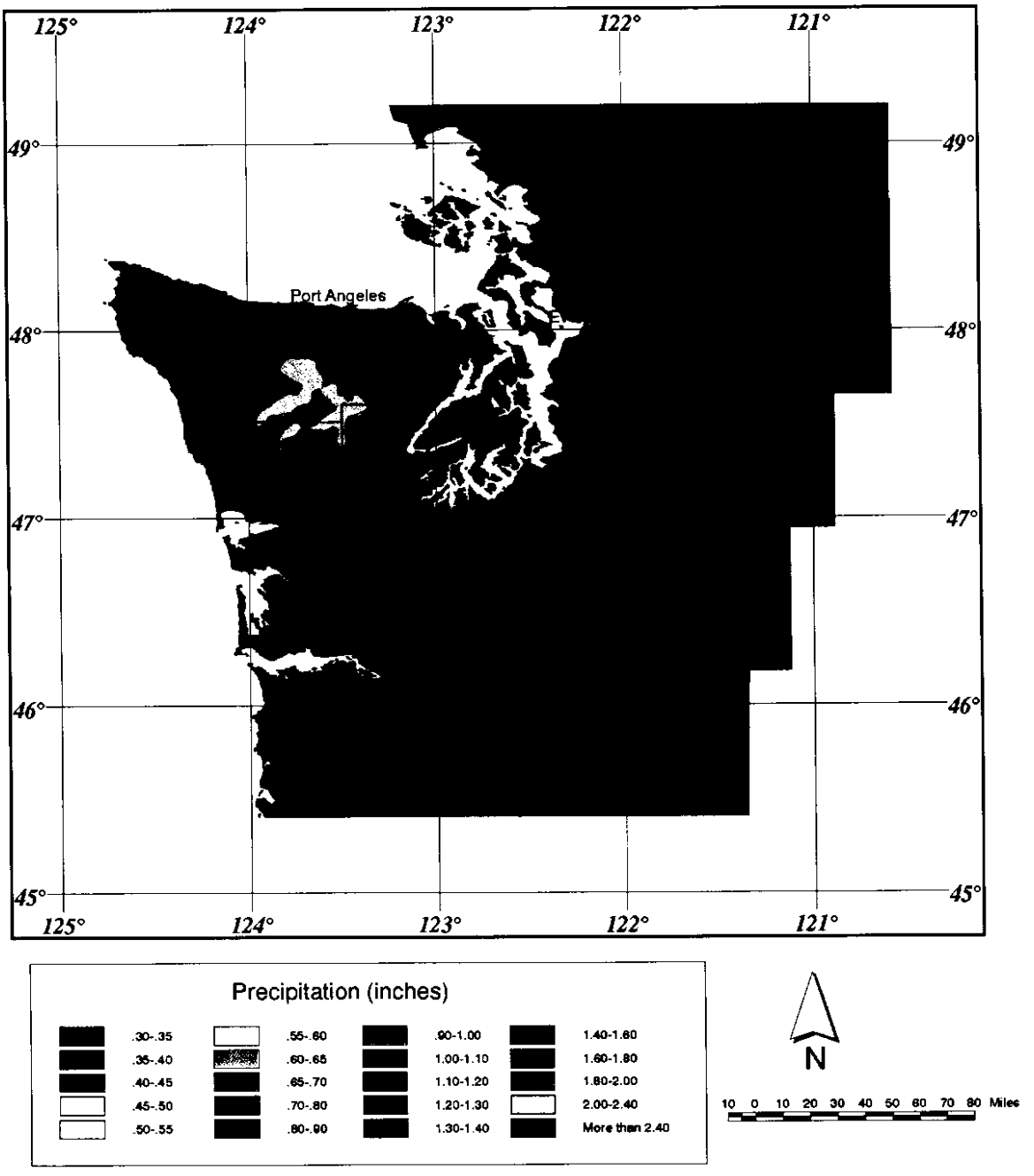



Figure B9 – Isopluvial Map of 2-Hour Precipitation for 25-Year Recurrence Interval for Western Washington

## 50-year 2-hour Precipitation, Western Washington

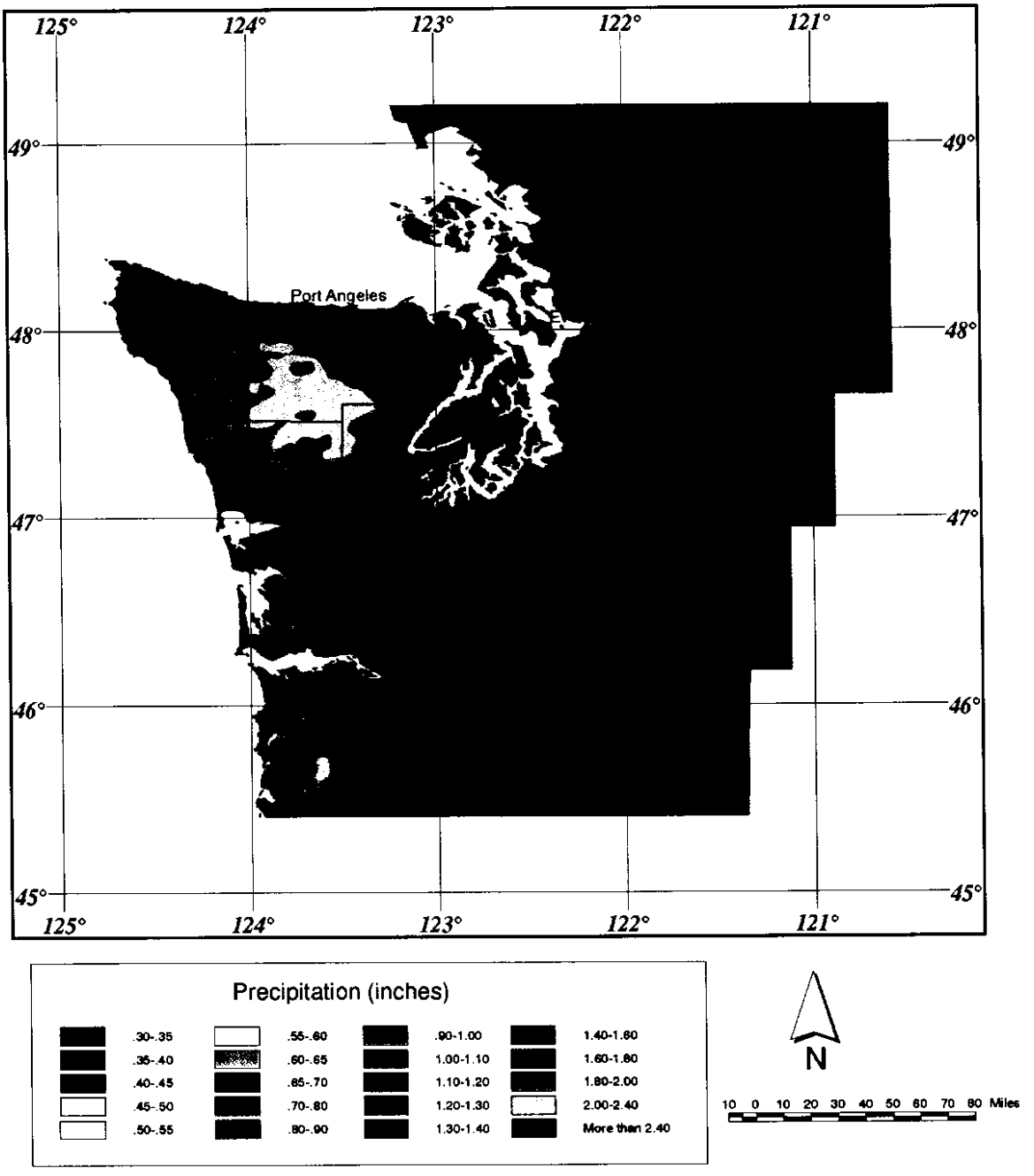



Figure B10 – Isopluvial Map of 2-Hour Precipitation for 50-Year Recurrence Interval for Western Washington

## 100-year 2-hour Precipitation, Western Washington

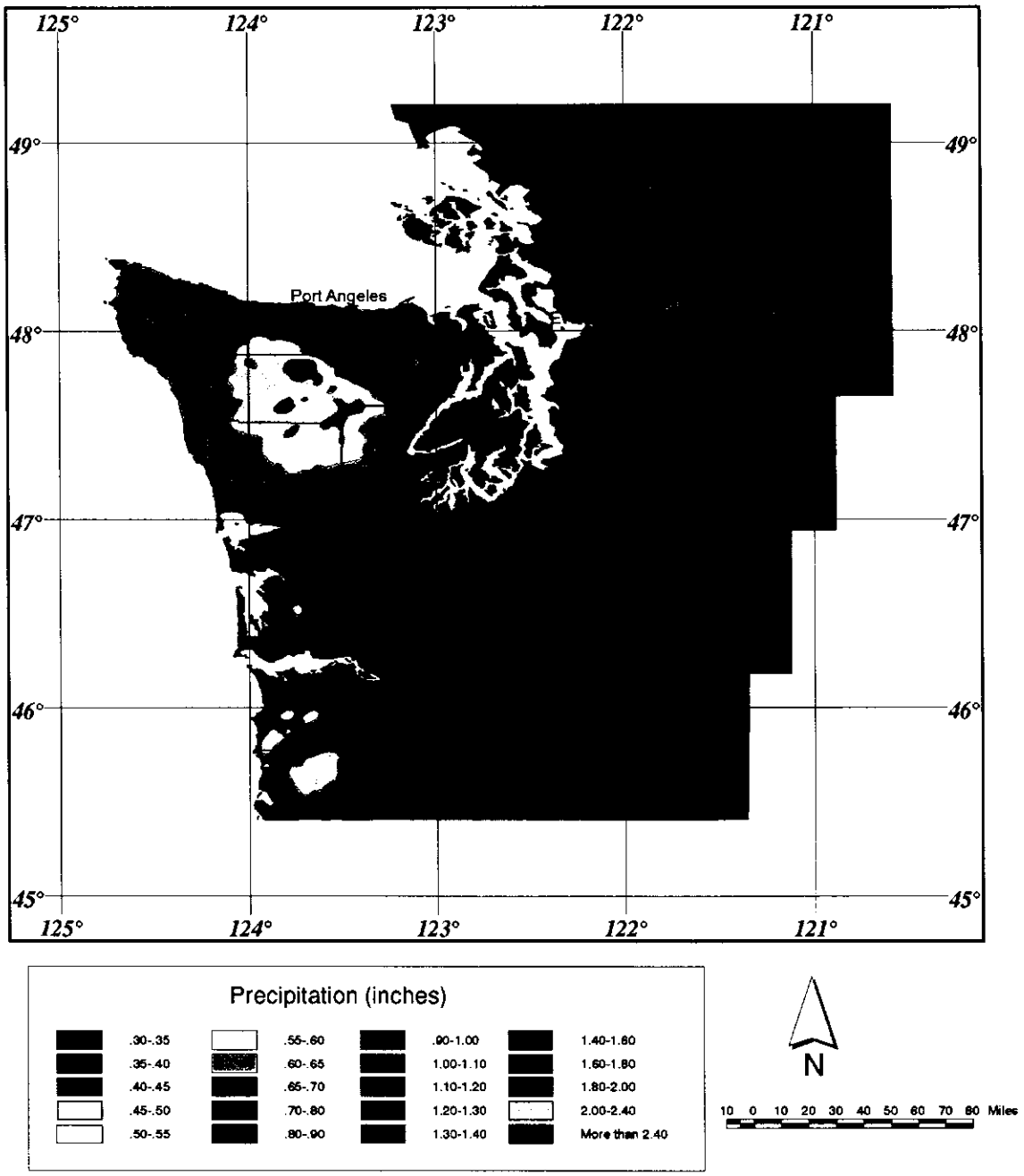



Figure B11 – Isopluvial Map of 2-Hour Precipitation for 100-Year Recurrence Interval for Western Washington

## OVERVIEW

The seasonality of extreme storms was investigated by constructing frequency histograms of the storm dates for rare 24-hour and 2-hour precipitation amounts for each of the seven climatic regions. Extreme storms were taken to be precipitation amounts with annual exceedance probabilities less than 0.05 (rarer than a 20-year event). Precipitation amounts/gages with duplicate storm dates (generally dates within 7 calendar days) were removed before constructing the frequency histograms for each climatic region.

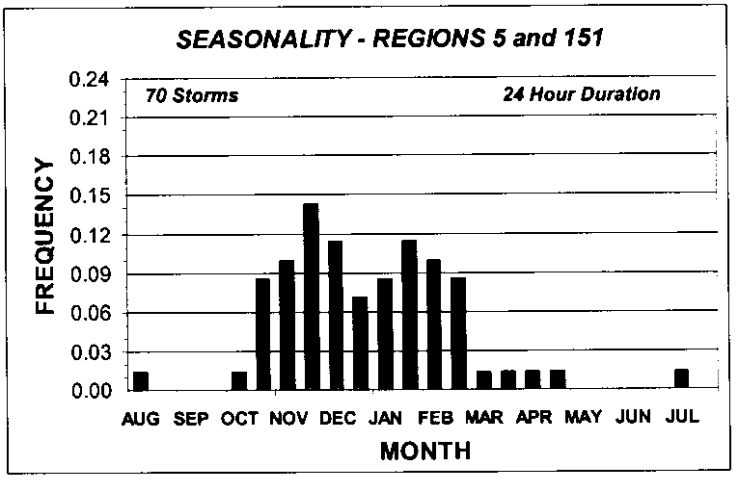



Figure C1 – Seasonality of Extreme Storms at 24-Hour Duration
for Coastal Lowlands and Coastal Mountains West, Climatic Regions 5 and 151

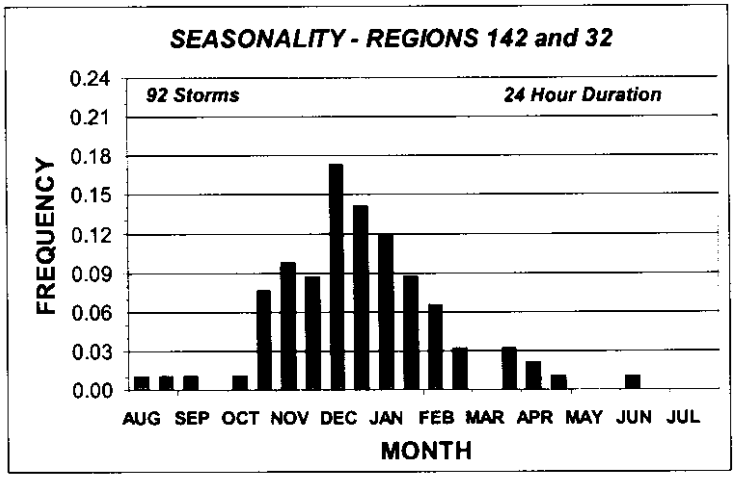



Figure C2 – Seasonality of Extreme Storms at 24-Hour Duration
for Coastal Mountains East and Interior Lowlands West, Climatic Regions 142 and 32

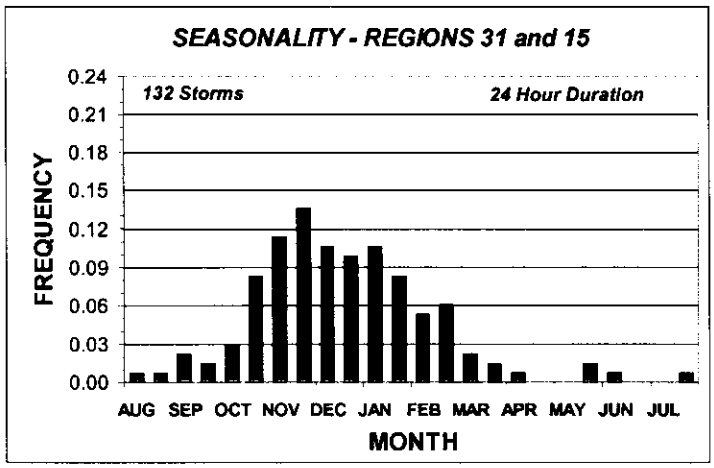



Figure C3 – Seasonality of Extreme Storms at 24-Hour Duration
for Interior Lowlands East and Cascade Mountains West, Climatic Regions 31 and 15

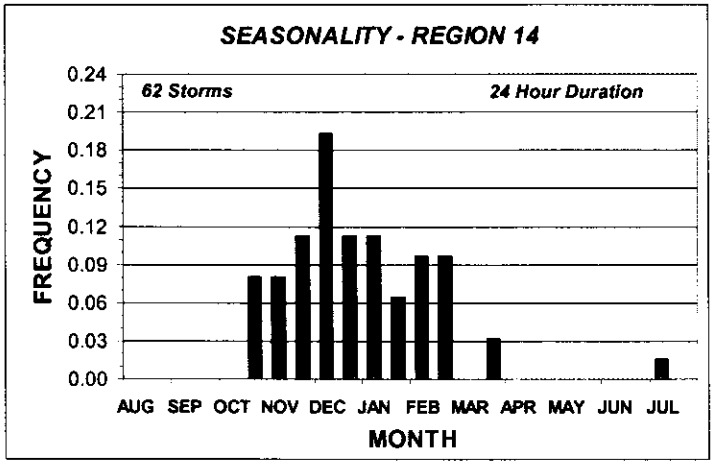



Figure C4 – Seasonality of Extreme Storms at 24-Hour Duration
for Cascade Mountains East, Climatic Region 14

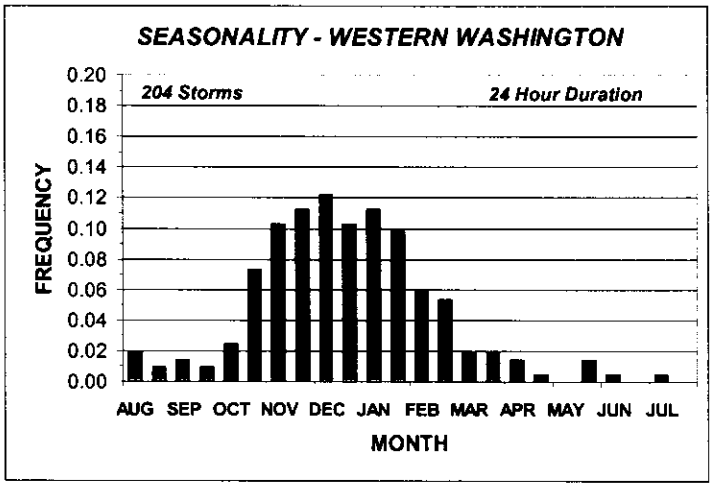



Figure C5 – Seasonality of Extreme Storms at 24-Hour Duration
for All Western Washington Climatic Regions

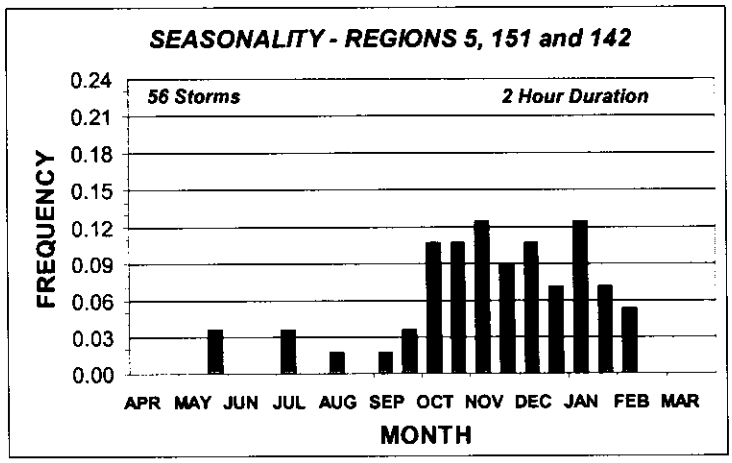



Figure C6 – Seasonality of Extreme Storms at 2-Hour Duration
for Coastal Lowlands and Coastal Mountains, Climatic Regions 5, 151 and 142

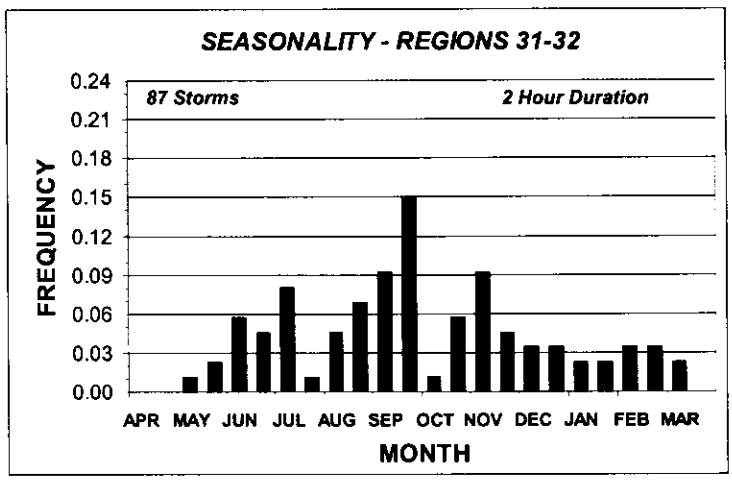



Figure C7 – Seasonality of Extreme Storms at 2-Hour Duration
for Interior Lowlands East and West, Climatic Regions 31 and 32

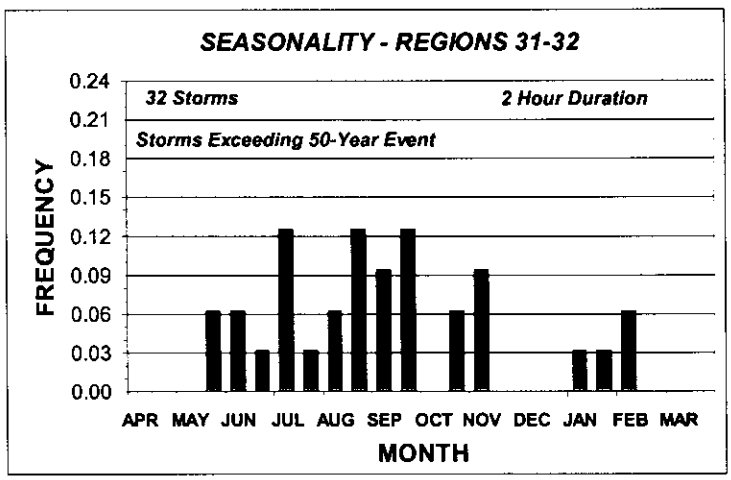



Figure C8 – Seasonality of Extreme Storms that Exceed 50-Year Event at 2-Hour Duration
for Interior Lowlands East and West, Climatic Regions 31 and 32

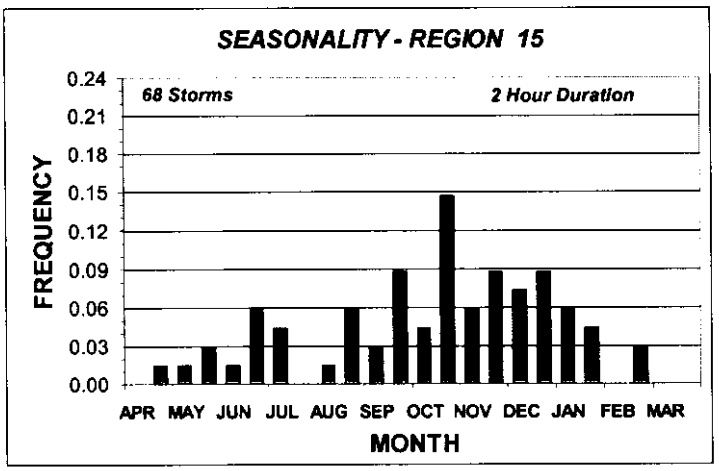



Figure C9 – Seasonality of Extreme Storms at 2-Hour Duration for Cascade Mountains West, Climatic Region 15

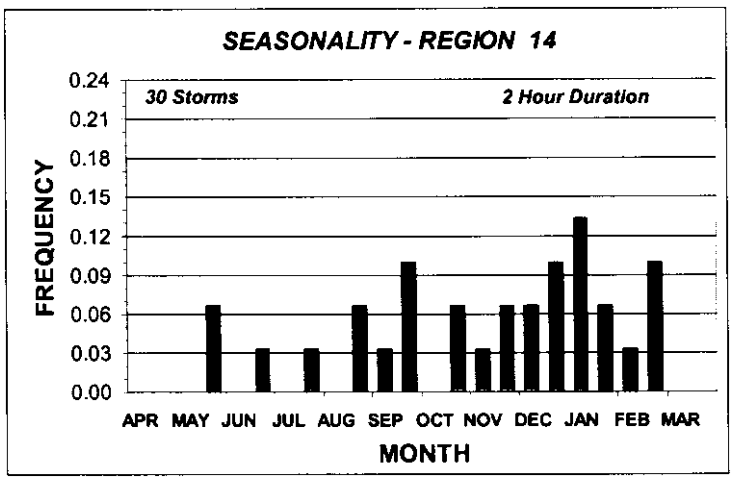



Figure C10 – Seasonality of Extreme Storms at 2-Hour Duration for Cascade Mountains East, Climatic Region 14

# Appendix D

## CATALOGS OF EXTREME STORMS
## FOR 24-HOUR AND 2-HOUR DURATIONS

## OVERVIEW

This appendix contains catalogs of the dates and locations of the occurrence of extreme storms. An extreme storm is deemed to occur when a recorded precipitation amount has exceeded a 20-year recurrence interval for that site. When numerous gages record precipitation amounts that exceed the 20-year threshold for a given storm date, the hourly gage with the rarest precipitation measurement is listed in the catalog. Hourly gages are listed because the primary application of the storm catalog is for identification of temporal storm patterns that would be useful in rainfall-runoff modeling of extreme events. Separate tables have been prepared, where the location, date and precipitation amount are listed for the various climatic regions.

Table D1 - Catalog of Extreme Storms for Coastal Lowlands Climatic Region 5 for 24-Hour Duration

| EXTREME STORMS AT 24-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-1496 | CLEARWATER | 5 | 52 | 47.6 | 124.3 | 1.66 | 8.41 | 12 | 1 | 1943 |
| 45-8332 | TATOOSH ISLAND WB | 5 | 25 | 48.4 | 124.7 | 1.66 | 5.33 | 10 | 23 | 1944 |
| 35-5969 | NEHALEM | 5 | 52 | 45.7 | 123.9 | 1.57 | 5.86 | 2 | 10 | 1949 |
| 45-5488 | MOCLIPS | 5 | 16 | 47.2 | 124.2 | 1.34 | 4.22 | 1 | 20 | 1950 |
| 45-3333 | GRAYS RIVER HATCHERY | 5 | 43 | 46.4 | 123.6 | 1.44 | 6.64 | 1 | 14 | 1958 |
| 45-6584 | POINT GRENVILLE | 5 | 19 | 47.3 | 124.3 | 1.44 | 5.15 | 11 | 20 | 1959 |
| 45-5549 | MONTESANO 1 S | 5 | 44 | 47.0 | 123.6 | 1.55 | 5.39 | 11 | 19 | 1962 |
| 35-5969 | NEHALEM | 5 | 52 | 45.7 | 123.9 | 1.59 | 5.94 | 1 | 28 | 1965 |
| 45-6858 | QUILLAYUTE WSCMO AP | 5 | 34 | 47.9 | 124.6 | 1.83 | 8.32 | 1 | 19 | 1968 |
| 45-1496 | CLEARWATER | 5 | 52 | 47.6 | 124.3 | 1.76 | 8.90 | 7 | 12 | 1972 |
| 45-6858 | QUILLAYUTE WSCMO AP | 5 | 34 | 47.9 | 124.6 | 1.49 | 6.76 | 12 | 26 | 1972 |
| 45-1496 | CLEARWATER | 5 | 52 | 47.6 | 124.3 | 1.84 | 9.30 | 2 | 13 | 1982 |
| 45-2984 | FRANCES | 5 | 56 | 46.6 | 123.5 | 1.52 | 6.20 | 3 | 3 | 1987 |
| 35-0328 | ASTORIA AP PORT OF | 5 | 48 | 46.2 | 123.9 | 1.70 | 5.14 | 1 | 9 | 1990 |
| 45-9112 | WESTPORT 2 S | 5 | 60 | 46.9 | 124.1 | 1.48 | 4.40 | 2 | 10 | 1990 |
| 45-9112 | WESTPORT 2 S | 5 | 60 | 46.9 | 124.1 | 1.78 | 5.30 | 11 | 24 | 1990 |
| 45-5549 | MONTESANO 1 S | 5 | 44 | 47.0 | 123.6 | 1.55 | 5.40 | 12 | 10 | 1993 |
| 45-3333 | GRAYS RIVER HATCHERY | 5 | 43 | 46.4 | 123.6 | 1.67 | 7.70 | 12 | 27 | 1994 |
| 45-2984 | FRANCES | 5 | 56 | 46.6 | 123.5 | 1.52 | 6.20 | 4 | 23 | 1996 |
| 35-0328 | ASTORIA AP PORT OF | 5 | 48 | 46.2 | 123.9 | 1.84 | 5.57 | 11 | 25 | 1998 |
| 45-2984 | FRANCES | 5 | 56 | 46.6 | 123.5 | 1.42 | 5.80 | 2 | 25 | 1999 |

Table D2 - Catalog of Extreme Storms for Coastal Mountains West Climatic Region 151 for 24-Hour Duration

| EXTREME STORMS AT 24-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-7319 | SAPPHO 8 E | 151 | 57 | 48.1 | 124.1 | 1.87 | 8.15 | 11 | 3 | 1955 |
| 45-7319 | SAPPHO 8 E | 151 | 57 | 48.1 | 124.1 | 1.55 | 6.74 | 12 | 9 | 1956 |
| 45-1064 | CAMP GRISDALE | 151 | 27 | 47.4 | 123.6 | 1.72 | 10.68 | 11 | 19 | 1962 |
| 35-8504 | TILLAMOOK 12 ESE | 151 | 48 | 45.4 | 123.6 | 1.46 | 7.43 | 12 | 2 | 1977 |
| 45-7319 | SAPPHO 8 E | 151 | 57 | 48.1 | 124.1 | 1.47 | 6.40 | 1 | 24 | 1982 |
| 45-0013 | ABERDEEN 20 NNE | 151 | 59 | 47.3 | 123.7 | 1.58 | 9.00 | 2 | 13 | 1982 |
| 45-6864 | QUINAULT RANGER STN | 151 | 19 | 47.5 | 123.9 | 1.89 | 13.50 | 11 | 10 | 1990 |
| 45-7319 | SAPPHO 8 E | 151 | 57 | 48.1 | 124.1 | 1.47 | 6.40 | 11 | 8 | 1995 |

Table D3 - Catalog of Extreme Storms for Coastal Mountains East Climatic Region 142 for 24-Hour Duration

| EXTREME STORMS AT 24-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 35-4276 | JEWELL WILDLIFE MEAD | 142 | 42 | 45.9 | 123.5 | 1.62 | 5.90 | 1 | 11 | 1972 |
| 35-3318 | GLENWOOD 2 WNW | 142 | 50 | 45.7 | 123.3 | 1.66 | 5.35 | 12 | 13 | 1977 |
| 35-3318 | GLENWOOD 2 WNW | 142 | 50 | 45.7 | 123.3 | 1.67 | 5.40 | 10 | 6 | 1981 |
| 45-6851 | QUILCENE 5 SW DAM | 142 | 55 | 47.8 | 123.0 | 1.87 | 7.90 | 10 | 22 | 1982 |
| 45-1934 | CUSHMAN DAM | 142 | 59 | 47.4 | 123.2 | 1.81 | 9.40 | 1 | 18 | 1986 |
| 35-3705 | HASKINS DAM | 142 | 49 | 45.3 | 123.4 | 1.43 | 5.60 | 4 | 5 | 1991 |
| 45-6851 | QUILCENE 5 SW DAM | 142 | 55 | 47.8 | 123.0 | 1.45 | 6.10 | 12 | 10 | 1993 |
| 45-1934 | CUSHMAN DAM | 142 | 59 | 47.4 | 123.2 | 1.58 | 8.20 | 12 | 20 | 1994 |
| 45-1934 | CUSHMAN DAM | 142 | 59 | 47.4 | 123.2 | 1.77 | 9.20 | 3 | 19 | 1997 |
| 45-6851 | QUILCENE 5 SW DAM | 142 | 55 | 47.8 | 123.0 | 1.75 | 7.40 | 1 | 29 | 1999 |

Table D4 - Catalog of Extreme Storms for Interior Lowlands West Climatic Region 32 for 24-Hour Duration

| EXTREME STORMS AT 24-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-6678 | PORT TOWNSEND | 32 | 29 | 48.1 | 122.8 | 2.10 | 2.26 | 6 | 13 | 1946 |
| 45-6624 | PORT ANGELES | 32 | 57 | 48.1 | 123.4 | 1.85 | 3.26 | 2 | 16 | 1949 |
| 45-6114 | OLYMPIA AIRPORT | 32 | 46 | 47.0 | 122.9 | 1.76 | 4.93 | 2 | 9 | 1951 |
| 45-6624 | PORT ANGELES | 32 | 57 | 48.1 | 123.4 | 1.77 | 3.12 | 1 | 15 | 1961 |
| 35-1227 | BUXTON MOUNTAINDALE | 32 | 26 | 45.7 | 123.1 | 1.47 | 3.26 | 1 | 15 | 1974 |
| 35-1222 | BUXTON | 32 | 51 | 45.7 | 123.2 | 1.61 | 4.40 | 12 | 13 | 1977 |
| 35-8884 | VERNONIA 2 | 32 | 45 | 45.9 | 123.2 | 1.72 | 4.00 | 10 | 6 | 1981 |
| 45-6624 | PORT ANGELES | 32 | 57 | 48.1 | 123.4 | 2.16 | 3.80 | 1 | 18 | 1986 |
| 35-1643 | CLATSKANIE | 32 | 43 | 46.1 | 123.2 | 1.57 | 4.30 | 1 | 9 | 1990 |
| 45-6114 | OLYMPIA AIRPORT | 32 | 46 | 47.0 | 122.9 | 2.10 | 5.90 | 11 | 24 | 1990 |
| 35-2348 | DIXIE MOUNTAIN | 32 | 22 | 45.7 | 122.9 | 1.39 | 4.00 | 4 | 5 | 1991 |
| 35-6749 | PORTLAND KGW-TV | 32 | 50 | 45.5 | 122.7 | 2.23 | 4.80 | 10 | 27 | 1994 |
| 35-6751 | PORTLAND INTL AIRPOR | 32 | 59 | 45.6 | 122.6 | 1.38 | 2.82 | 11 | 11 | 1995 |
| 35-1643 | CLATSKANIE | 32 | 43 | 46.1 | 123.2 | 1.72 | 4.70 | 2 | 8 | 1996 |
| 35-6749 | PORTLAND KGW-TV | 32 | 50 | 45.5 | 122.7 | 1.95 | 4.20 | 11 | 19 | 1996 |
| 35-2348 | DIXIE MOUNTAIN | 32 | 22 | 45.7 | 122.9 | 1.39 | 4.00 | 12 | 29 | 1996 |
| 35-1222 | BUXTON | 32 | 51 | 45.7 | 123.2 | 1.72 | 4.70 | 1 | 14 | 1998 |

Table D5 - Catalog of Extreme Storms for Interior Lowlands East Climatic Region 31 for 24-Hour Duration

| EXTREME STORMS AT 24-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-1277 | CENTRALIA 1 W | 31 | 56 | 46.7 | 123.0 | 1.38 | 2.98 | 10 | 31 | 1942 |
| 45-0986 | BURLINGTON | 31 | 58 | 48.5 | 122.3 | 2.63 | 4.91 | 10 | 24 | 1945 |
| 45-0986 | BURLINGTON | 31 | 58 | 48.5 | 122.3 | 1.83 | 3.42 | 2 | 16 | 1949 |
| 45-9485 | YELM | 31 | 38 | 47.0 | 122.6 | 1.45 | 2.79 | 11 | 12 | 1949 |
| 45-5149 | MC CHORD AFB | 31 | 35 | 47.2 | 122.5 | 1.77 | 3.03 | 2 | 9 | 1951 |
| 45-0729 | BLAINE | 31 | 58 | 49.0 | 122.8 | 1.76 | 3.63 | 11 | 3 | 1955 |
| 45-0324 | AUBURN | 31 | 22 | 47.3 | 122.2 | 1.71 | 3.63 | 11 | 21 | 1959 |
| 45-4769 | LONGVIEW | 31 | 42 | 46.2 | 122.9 | 2.36 | 5.41 | 11 | 20 | 1962 |
| 45-2675 | EVERETT | 31 | 58 | 48.0 | 122.2 | 1.57 | 2.56 | 1 | 4 | 1967 |
| 45-0729 | BLAINE | 31 | 58 | 49.0 | 122.8 | 1.67 | 3.46 | 11 | 4 | 1971 |
| 45-7773 | SNOQUALMIE FALLS | 31 | 44 | 47.5 | 121.8 | 1.56 | 4.90 | 3 | 5 | 1972 |
| 45-4769 | LONGVIEW | 31 | 42 | 46.2 | 122.9 | 2.05 | 4.70 | 12 | 2 | 1977 |
| 45-7473 | SEATTLE TACOMA AIRPO | 31 | 60 | 47.5 | 122.3 | 1.78 | 3.74 | 10 | 6 | 1981 |
| 45-0729 | BLAINE | 31 | 58 | 49.0 | 122.8 | 1.60 | 3.30 | 12 | 30 | 1983 |
| 45-7458 | SEATTLE URBAN SITE | 31 | 49 | 47.7 | 122.3 | 2.18 | 4.48 | 1 | 18 | 1986 |
| 45-4769 | LONGVIEW | 31 | 42 | 46.2 | 122.9 | 2.05 | 4.70 | 2 | 23 | 1986 |
| 45-5224 | MC MILLIN RESERVOIR | 31 | 57 | 47.1 | 122.3 | 1.94 | 3.80 | 11 | 24 | 1986 |
| 45-7773 | SNOQUALMIE FALLS | 31 | 44 | 47.5 | 121.8 | 1.56 | 4.90 | 1 | 9 | 1990 |
| 45-0986 | BURLINGTON | 31 | 58 | 48.5 | 122.3 | 1.61 | 3.00 | 11 | 9 | 1990 |
| 45-1277 | CENTRALIA 1 W | 31 | 56 | 46.7 | 123.0 | 2.36 | 5.10 | 11 | 24 | 1990 |
| 45-1277 | CENTRALIA 1 W | 31 | 56 | 46.7 | 123.0 | 1.85 | 4.00 | 2 | 8 | 1996 |
| 45-2675 | EVERETT | 31 | 58 | 48.0 | 122.2 | 1.60 | 2.60 | 12 | 29 | 1996 |
| 45-5224 | MC MILLIN RESERVOIR | 31 | 57 | 47.1 | 122.3 | 1.84 | 3.60 | 11 | 25 | 1998 |

Table D6 - Catalog of Extreme Storms for Cascade Mountains West Climatic Region 15 for 24-Hour Duration

| EXTREME STORMS AT 24-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-7919 | SPIRIT LAKE R S | 15 | 15 | 46.3 | 122.2 | 1.84 | 5.74 | 10 | 23 | 1943 |
| 35-0897 | BONNEVILLE DAM | 15 | 59 | 45.6 | 122.0 | 1.83 | 6.40 | 10 | 18 | 1947 |
| 45-9171 | WHITE RIVER R S | 15 | 32 | 46.9 | 121.6 | 1.41 | 4.04 | 2 | 17 | 1949 |
| 45-7657 | SILVERTON | 15 | 47 | 48.1 | 121.6 | 1.48 | 6.39 | 2 | 9 | 1951 |
| 45-4634 | LESTER | 15 | 23 | 47.2 | 121.5 | 1.63 | 4.69 | 12 | 9 | 1956 |
| 45-7781 | SNOQUALMIE PASS | 15 | 56 | 47.4 | 121.4 | 1.52 | 7.00 | 11 | 22 | 1959 |
| 45-7709 | SKYKOMISH 1 ENE | 15 | 57 | 47.7 | 121.4 | 1.80 | 7.70 | 12 | 15 | 1959 |
| 45-6896 | RAINIER OHANAPECOSH | 15 | 51 | 46.7 | 121.6 | 2.00 | 7.78 | 11 | 20 | 1962 |
| 1106180 | PITT POLDER | 15 | 30 | 49.3 | 122.6 | 1.46 | 5.68 | 1 | 18 | 1968 |
| 45-6295 | PALMER 3 ESE | 15 | 59 | 47.3 | 121.9 | 1.42 | 5.10 | 1 | 9 | 1971 |
| 45-6295 | PALMER 3 ESE | 15 | 59 | 47.3 | 121.9 | 1.37 | 4.90 | 11 | 4 | 1971 |
| 45-7604 | SHUKSAN | 15 | 14 | 48.9 | 121.7 | 1.32 | 4.45 | 12 | 26 | 1972 |
| 45-9171 | WHITE RIVER R S | 15 | 32 | 46.9 | 121.6 | 1.50 | 4.30 | 11 | 9 | 1973 |
| 35-2697 | ESTACADA 24 SE | 15 | 49 | 45.1 | 122.0 | 1.59 | 4.30 | 1 | 15 | 1974 |
| 45-1457 | CINEBAR 2 E | 15 | 46 | 46.6 | 122.5 | 2.20 | 6.80 | 12 | 2 | 1977 |
| 45-3160 | GLACIER R S | 15 | 25 | 48.9 | 122.0 | 1.80 | 5.90 | 12 | 14 | 1979 |
| 45-5663 | MOUNT BAKER LODGE | 15 | 23 | 48.9 | 121.7 | 1.32 | 5.20 | 2 | 26 | 1980 |
| 45-8715 | UPPER BAKER DAM | 15 | 33 | 48.7 | 121.7 | 1.41 | 5.80 | 11 | 21 | 1980 |
| 45-3357 | GREENWATER | 15 | 56 | 47.1 | 121.6 | 1.99 | 5.30 | 1 | 23 | 1982 |
| 45-8838 | VERLOT | 15 | 21 | 48.1 | 121.8 | 1.31 | 6.20 | 2 | 14 | 1982 |
| 45-7657 | SILVERTON | 15 | 47 | 48.1 | 121.6 | 1.78 | 7.70 | 12 | 3 | 1982 |
| 45-5876 | NOOKSACK SALMON HAT | 15 | 32 | 48.9 | 122.2 | 1.75 | 6.30 | 1 | 10 | 1983 |
| 45-3357 | GREENWATER | 15 | 56 | 47.1 | 121.6 | 1.69 | 4.50 | 1 | 24 | 1984 |
| 45-1992 | DARRINGTON RGR STN | 15 | 56 | 48.3 | 121.6 | 1.89 | 6.60 | 1 | 18 | 1986 |
| 45-4999 | MARBLEMOUNT RGR STN | 15 | 56 | 48.5 | 121.5 | 1.82 | 6.20 | 2 | 24 | 1986 |
| 45-5704 | MUD MOUNTAIN DAM | 15 | 61 | 47.2 | 121.9 | 1.81 | 4.20 | 11 | 24 | 1986 |
| 45-1457 | CINEBAR 2 E | 15 | 46 | 46.6 | 122.5 | 1.62 | 5.00 | 1 | 9 | 1990 |
| 45-5876 | NOOKSACK SALMON HAT | 15 | 32 | 48.9 | 122.2 | 1.86 | 6.70 | 2 | 10 | 1990 |
| 45-4999 | MARBLEMOUNT RGR STN | 15 | 56 | 48.5 | 121.5 | 1.82 | 6.20 | 11 | 10 | 1990 |
| 45-1233 | CEDAR LAKE | 15 | 45 | 47.4 | 121.7 | 1.74 | 6.40 | 11 | 24 | 1990 |
| 45-5704 | MUD MOUNTAIN DAM | 15 | 61 | 47.2 | 121.9 | 1.73 | 4.00 | 2 | 20 | 1991 |
| 45-1759 | COUGAR 4 SW | 15 | 59 | 46.0 | 122.4 | 1.45 | 6.40 | 10 | 31 | 1994 |
| 45-4764 | LONGMIRE RAINIER NPS | 15 | 22 | 46.8 | 121.8 | 1.68 | 6.40 | 11 | 28 | 1995 |
| 45-5704 | MUD MOUNTAIN DAM | 15 | 61 | 47.2 | 121.9 | 1.64 | 3.80 | 2 | 8 | 1996 |
| 35-0897 | BONNEVILLE DAM | 15 | 59 | 45.6 | 122.0 | 1.69 | 5.90 | 11 | 19 | 1996 |
| 35-0897 | BONNEVILLE DAM | 15 | 59 | 45.6 | 122.0 | 1.46 | 5.10 | 11 | 25 | 1999 |

Table D7 - Catalog of Extreme Storms for Coastal Lowlands Climatic Region 5 for 2-Hour Duration

| EXTREME STORMS AT 2-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-5932 | NORTH HEAD WB | 5 | 13 | 46.3 | 124.1 | 1.42 | 1.13 | 11 | 13 | 1941 |
| 45-8332 | TATOOSH ISLAND WB | 5 | 25 | 48.4 | 124.7 | 1.75 | 1.53 | 10 | 10 | 1942 |
| 45-9112 | WESTPORT 2 S | 5 | 56 | 46.9 | 124.1 | 1.77 | 1.47 | 10 | 30 | 1950 |
| 45-5488 | MOCLIPS | 5 | 15 | 47.2 | 124.2 | 1.46 | 1.30 | 1 | 2 | 1951 |
| 35-5969 | NEHALEM | 5 | 52 | 45.7 | 123.9 | 1.40 | 1.23 | 1 | 21 | 1954 |
| 45-5549 | MONTESANO 1 S | 5 | 44 | 47.0 | 123.6 | 1.39 | 1.14 | 11 | 2 | 1955 |
| 45-6584 | POINT GRENVILLE | 5 | 19 | 47.3 | 124.3 | 1.42 | 1.33 | 11 | 20 | 1959 |
| 45-5549 | MONTESANO 1 S | 5 | 44 | 47.0 | 123.6 | 1.36 | 1.12 | 12 | 22 | 1961 |
| 35-0328 | ASTORIA AP PORT OF | 5 | 47 | 46.2 | 123.9 | 1.85 | 1.54 | 10 | 8 | 1962 |
| 45-1496 | CLEARWATER | 5 | 54 | 47.6 | 124.3 | 1.30 | 1.34 | 1 | 12 | 1966 |
| 45-6858 | QUILLAYUTE WSCMO AP | 5 | 34 | 47.9 | 124.6 | 1.34 | 1.22 | 10 | 1 | 1967 |
| 45-3333 | GRAYS RIVER HATCHERY | 5 | 42 | 46.4 | 123.6 | 1.27 | 1.30 | 12 | 10 | 1977 |
| 45-3333 | GRAYS RIVER HATCHERY | 5 | 42 | 46.4 | 123.6 | 1.47 | 1.50 | 11 | 6 | 1980 |
| 45-2984 | FRANCES | 5 | 58 | 46.6 | 123.5 | 1.76 | 1.50 | 12 | 15 | 1982 |
| 45-3333 | GRAYS RIVER HATCHERY | 5 | 42 | 46.4 | 123.6 | 1.27 | 1.30 | 2 | 13 | 1982 |
| 45-3333 | GRAYS RIVER HATCHERY | 5 | 42 | 46.4 | 123.6 | 1.27 | 1.30 | 10 | 26 | 1985 |
| 45-2984 | FRANCES | 5 | 58 | 46.6 | 123.5 | 1.53 | 1.30 | 1 | 14 | 1988 |
| 45-1496 | CLEARWATER | 5 | 54 | 47.6 | 124.3 | 1.35 | 1.40 | 10 | 21 | 1990 |
| 45-9112 | WESTPORT 2 S | 5 | 56 | 46.9 | 124.1 | 1.57 | 1.30 | 12 | 4 | 1990 |
| 45-6858 | QUILLAYUTE WSCMO AP | 5 | 34 | 47.9 | 124.6 | 1.41 | 1.29 | 8 | 6 | 1995 |
| 45-2984 | FRANCES | 5 | 58 | 46.6 | 123.5 | 1.65 | 1.40 | 9 | 29 | 1995 |
| 45-1496 | CLEARWATER | 5 | 54 | 47.6 | 124.3 | 1.35 | 1.40 | 10 | 25 | 1995 |
| 45-9112 | WESTPORT 2 S | 5 | 56 | 46.9 | 124.1 | 1.69 | 1.40 | 9 | 16 | 1997 |
| 35-0328 | ASTORIA AP PORT OF | 5 | 47 | 46.2 | 123.9 | 2.21 | 1.84 | 11 | 25 | 1998 |

Table D8 - Catalog of Extreme Storms for Coastal Mountains West Climatic Region 151 for 2-Hour Duration

| EXTREME STORMS AT 2-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-7319 | SAPPHO 8 E | 151 | 58 | 48.1 | 124.1 | 2.40 | 1.92 | 2 | 2 | 1947 |
| 45-7319 | SAPPHO 8 E | 151 | 58 | 48.1 | 124.1 | 1.76 | 1.41 | 12 | 9 | 1956 |
| 45-1064 | CAMP GRISDALE | 151 | 28 | 47.4 | 123.6 | 1.75 | 2.00 | 11 | 20 | 1959 |
| 35-8504 | TILLAMOOK 12 ESE | 151 | 51 | 45.4 | 123.6 | 2.36 | 2.25 | 1 | 11 | 1972 |
| 45-0013 | ABERDEEN 20 NNE | 151 | 57 | 47.3 | 123.7 | 1.40 | 1.50 | 12 | 26 | 1975 |
| 45-7319 | SAPPHO 8 E | 151 | 58 | 48.1 | 124.1 | 1.62 | 1.30 | 11 | 8 | 1976 |
| 45-0013 | ABERDEEN 20 NNE | 151 | 57 | 47.3 | 123.7 | 2.33 | 2.50 | 5 | 28 | 1982 |
| 45-6864 | QUINAULT RANGER STN | 151 | 20 | 47.5 | 123.9 | 1.54 | 2.00 | 11 | 23 | 1986 |
| 45-0013 | ABERDEEN 20 NNE | 151 | 57 | 47.3 | 123.7 | 1.59 | 1.70 | 10 | 31 | 1994 |

Table D9 - Catalog of Extreme Storms for Coastal Mountains East Climatic Region 142 for 2-Hour Duration

| EXTREME STORMS AT 2-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-6851 | QUILCENE 5 SW DAM | 142 | 58 | 47.8 | 123.0 | 1.63 | 1.35 | 12 | 1 | 1948 |
| 45-6851 | QUILCENE 5 SW DAM | 142 | 58 | 47.8 | 123.0 | 1.34 | 1.11 | 7 | 5 | 1957 |
| 45-1934 | CUSHMAN DAM | 142 | 59 | 47.4 | 123.2 | 1.50 | 1.50 | 12 | 25 | 1980 |
| 45-1934 | CUSHMAN DAM | 142 | 59 | 47.4 | 123.2 | 1.40 | 1.40 | 12 | 3 | 1982 |
| 45-1934 | CUSHMAN DAM | 142 | 59 | 47.4 | 123.2 | 1.70 | 1.70 | 1 | 18 | 1986 |
| 45-6851 | QUILCENE 5 SW DAM | 142 | 58 | 47.8 | 123.0 | 1.44 | 1.20 | 11 | 24 | 1998 |

Table D10 - Catalog of Extreme Storms for Interior Lowlands West Climatic Region 32 for 2-Hour Duration

| EXTREME STORMS AT 2-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-6624 | PORT ANGELES | 32 | 58 | 48.1 | 123.4 | 1.41 | 0.72 | 9 | 27 | 1953 |
| 45-6114 | OLYMPIA AIRPORT | 32 | 47 | 47.0 | 122.9 | 1.53 | 0.97 | 12 | 9 | 1956 |
| 45-6678 | PORT TOWNSEND | 32 | 27 | 48.1 | 122.8 | 1.98 | 0.84 | 9 | 10 | 1967 |
| 45-6624 | PORT ANGELES | 32 | 58 | 48.1 | 123.4 | 1.57 | 0.80 | 11 | 3 | 1978 |
| 45-6624 | PORT ANGELES | 32 | 58 | 48.1 | 123.4 | 1.57 | 0.80 | 12 | 14 | 1984 |
| 45-6114 | OLYMPIA AIRPORT | 32 | 47 | 47.0 | 122.9 | 1.42 | 0.90 | 1 | 9 | 1990 |

Table D11 - Catalog of Extreme Storms for Interior Lowlands East Climatic Region 31 for 2-Hour Duration

| EXTREME STORMS AT 2-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-2675 | EVERETT | 31 | 58 | 48.0 | 122.2 | 1.78 | 1.01 | 9 | 28 | 1944 |
| 45-5224 | MC MILLIN RESERVOIR | 31 | 55 | 47.1 | 122.3 | 1.91 | 1.10 | 7 | 8 | 1946 |
| 45-9485 | YELM | 31 | 39 | 47.0 | 122.6 | 1.39 | 0.72 | 11 | 22 | 1946 |
| 45-1277 | CENTRALIA 1 W | 31 | 58 | 46.7 | 123.0 | 1.93 | 1.15 | 10 | 28 | 1949 |
| 45-7473 | SEATTLE TACOMA AIRPO | 31 | 60 | 47.5 | 122.3 | 1.72 | 0.91 | 3 | 3 | 1950 |
| 45-7473 | SEATTLE TACOMA AIRPO | 31 | 60 | 47.5 | 122.3 | 1.82 | 0.96 | 6 | 29 | 1952 |
| 45-7773 | SNOQUALMIE FALLS | 31 | 45 | 47.5 | 121.8 | 1.35 | 0.95 | 6 | 14 | 1957 |
| 45-5149 | MC CHORD AFB | 31 | 37 | 47.2 | 122.5 | 1.49 | 0.71 | 7 | 14 | 1957 |
| 45-5224 | MC MILLIN RESERVOIR | 31 | 55 | 47.1 | 122.3 | 1.86 | 1.07 | 9 | 17 | 1957 |
| 45-2675 | EVERETT | 31 | 58 | 48.0 | 122.2 | 2.01 | 1.14 | 5 | 31 | 1958 |
| 45-0324 | AUBURN | 31 | 36 | 47.3 | 122.2 | 1.59 | 0.87 | 6 | 8 | 1959 |
| 45-5224 | MC MILLIN RESERVOIR | 31 | 55 | 47.1 | 122.3 | 2.75 | 1.58 | 8 | 26 | 1960 |
| 45-4769 | LONGVIEW | 31 | 43 | 46.2 | 122.9 | 1.74 | 1.07 | 11 | 19 | 1962 |
| 45-7773 | SNOQUALMIE FALLS | 31 | 45 | 47.5 | 121.8 | 1.62 | 1.14 | 9 | 19 | 1964 |
| 45-0986 | BURLINGTON | 31 | 58 | 48.5 | 122.3 | 2.18 | 1.28 | 8 | 12 | 1965 |
| 45-0324 | AUBURN | 31 | 36 | 47.3 | 122.2 | 1.28 | 0.70 | 9 | 17 | 1969 |
| 45-0324 | AUBURN | 31 | 36 | 47.3 | 122.2 | 1.28 | 0.70 | 2 | 28 | 1972 |
| 45-2675 | EVERETT | 31 | 58 | 48.0 | 122.2 | 1.75 | 0.99 | 9 | 22 | 1972 |
| 45-9485 | YELM | 31 | 39 | 47.0 | 122.6 | 1.45 | 0.75 | 12 | 21 | 1972 |
| 45-1191 | CASTLE ROCK 2 NW | 31 | 22 | 46.3 | 122.9 | 1.97 | 1.46 | 9 | 20 | 1973 |
| 45-1277 | CENTRALIA 1 W | 31 | 58 | 46.7 | 123.0 | 1.84 | 1.10 | 7 | 8 | 1974 |
| 45-0986 | BURLINGTON | 31 | 58 | 48.5 | 122.3 | 1.70 | 1.00 | 2 | 12 | 1975 |
| 45-7458 | SEATTLE URBAN SITE | 31 | 50 | 47.7 | 122.3 | 2.97 | 1.61 | 8 | 26 | 1977 |
| 45-1146 | CARNATION 4 NW | 31 | 59 | 47.7 | 122.0 | 2.01 | 1.20 | 9 | 20 | 1977 |
| 45-1277 | CENTRALIA 1 W | 31 | 58 | 46.7 | 123.0 | 1.51 | 0.90 | 9 | 3 | 1979 |
| 45-4486 | LANDSBURG | 31 | 45 | 47.4 | 122.0 | 1.48 | 0.90 | 7 | 11 | 1980 |
| 45-1277 | CENTRALIA 1 W | 31 | 58 | 46.7 | 123.0 | 1.51 | 0.90 | 3 | 3 | 1981 |
| 45-0729 | BLAINE | 31 | 58 | 49.0 | 122.8 | 1.90 | 1.10 | 2 | 15 | 1986 |
| 45-1146 | CARNATION 4 NW | 31 | 59 | 47.7 | 122.0 | 1.68 | 1.00 | 6 | 18 | 1986 |
| 45-0986 | BURLINGTON | 31 | 58 | 48.5 | 122.3 | 1.70 | 1.00 | 5 | 16 | 1988 |
| 45-1146 | CARNATION 4 NW | 31 | 59 | 47.7 | 122.0 | 1.68 | 1.00 | 9 | 19 | 1988 |
| 45-0729 | BLAINE | 31 | 58 | 49.0 | 122.8 | 2.24 | 1.30 | 8 | 15 | 1989 |
| 45-0729 | BLAINE | 31 | 58 | 49.0 | 122.8 | 2.07 | 1.20 | 6 | 11 | 1993 |
| 45-4486 | LANDSBURG | 31 | 45 | 47.4 | 122.0 | 1.48 | 0.90 | 9 | 10 | 1994 |
| 45-4769 | LONGVIEW | 31 | 43 | 46.2 | 122.9 | 1.62 | 1.00 | 11 | 11 | 1995 |
| 45-0986 | BURLINGTON | 31 | 58 | 48.5 | 122.3 | 1.70 | 1.00 | 6 | 21 | 1997 |
| 45-7458 | SEATTLE URBAN SITE | 31 | 50 | 47.7 | 122.3 | 1.53 | 0.83 | 11 | 23 | 1997 |
| 45-7473 | SEATTLE TACOMA AIRPO | 31 | 60 | 47.5 | 122.3 | 1.84 | 0.97 | 11 | 4 | 1998 |

Table D12 - Catalog of Extreme Storms for Cascade Mountains West Climatic Region 15 for 2-Hour Duration

| EXTREME STORMS AT 2-HOUR DURATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STATION ID | STATION NAME | REGION | YEARS RECORD | LAT | LONG | RATIO TO MEAN | PRECIP (in) | MON | DAY | YEAR |
| 45-1992 | DARRINGTON RGR ST | 15 | 54 | 48.3 | 121.6 | 1.47 | 1.01 | 11 | 3 | 1941 |
| 45-7781 | SNOQUALMIE PASS | 15 | 51 | 47.4 | 121.4 | 1.77 | 1.48 | 12 | 4 | 1941 |
| 45-7919 | SPIRIT LAKE R S | 15 | 16 | 46.3 | 122.2 | 1.84 | 1.18 | 10 | 24 | 1943 |
| 45-1759 | COUGAR 4 SW | 15 | 59 | 46.0 | 122.4 | 1.87 | 1.49 | 9 | 21 | 1944 |
| 45-7709 | SKYKOMISH 1 ENE | 15 | 56 | 47.7 | 121.4 | 2.26 | 1.78 | 5 | 25 | 1945 |
| 45-7781 | SNOQUALMIE PASS | 15 | 51 | 47.4 | 121.4 | 1.85 | 1.55 | 10 | 24 | 1945 |
| 45-1457 | CINEBAR 2 E | 15 | 45 | 46.6 | 122.5 | 1.44 | 1.00 | 4 | 17 | 1947 |
| 35-0897 | BONNEVILLE DAM | 15 | 56 | 45.6 | 122.0 | 2.23 | 1.68 | 10 | 19 | 1947 |
| 45-6295 | PALMER 3 ESE | 15 | 59 | 47.3 | 121.9 | 1.42 | 1.20 | 5 | 27 | 1948 |
| 45-2493 | ELECTRON HEADWORKS | 15 | 38 | 46.9 | 122.0 | 1.32 | 0.90 | 12 | 19 | 1948 |
| 45-5663 | MOUNT BAKER LODGE | 15 | 24 | 48.9 | 121.7 | 1.86 | 1.53 | 6 | 16 | 1949 |
| 45-2493 | ELECTRON HEADWORKS | 15 | 38 | 46.9 | 122.0 | 1.76 | 1.20 | 10 | 28 | 1949 |
| 45-9171 | WHITE RIVER R S | 15 | 34 | 46.9 | 121.6 | 1.77 | 1.17 | 2 | 16 | 1949 |
| 45-1457 | CINEBAR 2 E | 15 | 45 | 46.6 | 122.5 | 2.17 | 1.51 | 6 | 9 | 1953 |
| 45-6295 | PALMER 3 ESE | 15 | 59 | 47.3 | 121.9 | 1.36 | 1.15 | 6 | 30 | 1955 |
| 45-7604 | SHUKSAN | 15 | 14 | 48.9 | 121.7 | 1.28 | 0.82 | 11 | 9 | 1955 |
| 45-1759 | COUGAR 4 SW | 15 | 59 | 46.0 | 122.4 | 1.40 | 1.12 | 8 | 2 | 1956 |
| 35-0897 | BONNEVILLE DAM | 15 | 56 | 45.6 | 122.0 | 2.00 | 1.51 | 8 | 25 | 1956 |
| 45-4634 | LESTER | 15 | 23 | 47.2 | 121.5 | 1.70 | 1.05 | 12 | 9 | 1956 |
| 45-7657 | SILVERTON | 15 | 45 | 48.1 | 121.6 | 1.56 | 1.40 | 12 | 9 | 1956 |
| 45-6909 | RANDLE 1 E | 15 | 40 | 46.5 | 121.9 | 2.19 | 1.40 | 8 | 28 | 1957 |
| 45-6892 | RAINIER CARBON RIVER | 15 | 37 | 47.0 | 121.9 | 1.67 | 1.05 | 9 | 17 | 1957 |
| 45-6295 | PALMER 3 ESE | 15 | 59 | 47.3 | 121.9 | 1.62 | 1.37 | 9 | 26 | 1959 |
| 45-6896 | RAINIER OHANAPECOSH | 15 | 53 | 46.7 | 121.6 | 1.69 | 1.23 | 11 | 19 | 1962 |
| 45-8715 | UPPER BAKER DAM | 15 | 33 | 48.7 | 121.7 | 1.42 | 1.10 | 11 | 15 | 1970 |
| 35-0897 | BONNEVILLE DAM | 15 | 56 | 45.6 | 122.0 | 1.86 | 1.40 | 11 | 20 | 1970 |
| 45-4999 | MARBLEMOUNT RGR ST | 15 | 56 | 48.5 | 121.5 | 1.28 | 0.80 | 12 | 25 | 1972 |
| 45-9171 | WHITE RIVER R S | 15 | 34 | 46.9 | 121.6 | 1.81 | 1.20 | 5 | 10 | 1975 |
| 45-5704 | MUD MOUNTAIN DAM | 15 | 56 | 47.2 | 121.9 | 1.60 | 1.04 | 8 | 17 | 1975 |
| 45-1233 | CEDAR LAKE | 15 | 45 | 47.4 | 121.7 | 1.53 | 1.30 | 9 | 20 | 1977 |
| 45-3357 | GREENWATER | 15 | 54 | 47.1 | 121.6 | 1.71 | 1.13 | 12 | 1 | 1977 |
| 45-6909 | RANDLE 1 E | 15 | 40 | 46.5 | 121.9 | 1.88 | 1.20 | 6 | 28 | 1978 |
| 45-5704 | MUD MOUNTAIN DAM | 15 | 56 | 47.2 | 121.9 | 1.71 | 1.11 | 7 | 9 | 1979 |
| 45-7657 | SILVERTON | 15 | 45 | 48.1 | 121.6 | 2.01 | 1.80 | 9 | 30 | 1980 |
| 45-4764 | LONGMIRE RAINIER NPS | 15 | 21 | 46.8 | 121.8 | 1.82 | 1.30 | 1 | 12 | 1980 |
| 45-4999 | MARBLEMOUNT RGR ST | 15 | 56 | 48.5 | 121.5 | 1.43 | 0.90 | 8 | 30 | 1982 |
| 45-6892 | RAINIER CARBON RIVER | 15 | 37 | 47.0 | 121.9 | 1.28 | 0.80 | 9 | 15 | 1982 |
| 45-1992 | DARRINGTON RGR ST | 15 | 54 | 48.3 | 121.6 | 1.60 | 1.10 | 12 | 3 | 1982 |
| 45-3357 | GREENWATER | 15 | 54 | 47.1 | 121.6 | 1.52 | 1.00 | 1 | 23 | 1982 |
| 45-3357 | GREENWATER | 15 | 54 | 47.1 | 121.6 | 1.52 | 1.00 | 1 | 3 | 1984 |
| 45-1992 | DARRINGTON RGR ST | 15 | 54 | 48.3 | 121.6 | 1.45 | 1.00 | 9 | 5 | 1985 |
| 45-5876 | NOOKSACK SALMON HAT | 15 | 35 | 48.9 | 122.2 | 1.74 | 1.40 | 10 | 26 | 1986 |
| 45-6896 | RAINIER OHANAPECOSH | 15 | 53 | 46.7 | 121.6 | 1.65 | 1.20 | 1 | 18 | 1986 |
| 45-4999 | MARBLEMOUNT RGR ST | 15 | 56 | 48.5 | 121.5 | 1.28 | 0.80 | 2 | 23 | 1986 |
| 45-3357 | GREENWATER | 15 | 54 | 47.1 | 121.6 | 1.97 | 1.30 | 7 | 18 | 1987 |
| 45-6896 | RAINIER OHANAPECOSH | 15 | 53 | 46.7 | 121.6 | 1.51 | 1.10 | 12 | 30 | 1988 |
| 45-4999 | MARBLEMOUNT RGR ST | 15 | 56 | 48.5 | 121.5 | 1.28 | 0.80 | 11 | 9 | 1990 |
| 45-6896 | RAINIER OHANAPECOSH | 15 | 53 | 46.7 | 121.6 | 1.51 | 1.10 | 11 | 23 | 1990 |
| 45-3160 | GLACIER R S | 15 | 20 | 48.9 | 122.0 | 1.78 | 1.40 | 12 | 31 | 1990 |
| 45-1457 | CINEBAR 2 E | 15 | 45 | 46.6 | 122.5 | 1.44 | 1.00 | 1 | 9 | 1990 |
| 45-5876 | NOOKSACK SALMON HAT | 15 | 35 | 48.9 | 122.2 | 2.23 | 1.80 | 10 | 20 | 1992 |
| 45-1233 | CEDAR LAKE | 15 | 45 | 47.4 | 121.7 | 1.65 | 1.40 | 6 | 22 | 1993 |
| KI-14U | EAST FORK ISSAQUAH C | 15 | 12 | 47.5 | 122.0 | 1.64 | 1.08 | 7 | 4 | 1994 |
| 45-1759 | COUGAR 4 SW | 15 | 59 | 46.0 | 122.4 | 1.38 | 1.10 | 10 | 31 | 1994 |
| 45-8715 | UPPER BAKER DAM | 15 | 33 | 48.7 | 121.7 | 1.42 | 1.10 | 10 | 9 | 1995 |
| 45-4999 | MARBLEMOUNT RGR ST | 15 | 56 | 48.5 | 121.5 | 1.28 | 0.80 | 11 | 28 | 1995 |
| 45-8838 | VERLOT | 15 | 23 | 48.1 | 121.8 | 1.59 | 1.50 | 12 | 12 | 1995 |
| 45-1992 | DARRINGTON RGR ST | 15 | 54 | 48.3 | 121.6 | 1.45 | 1.00 | 12 | 27 | 1996 |
| 45-6896 | RAINIER OHANAPECOSH | 15 | 53 | 46.7 | 121.6 | 1.51 | 1.10 | 12 | 29 | 1996 |
| 45-4999 | MARBLEMOUNT RGR ST | 15 | 56 | 48.5 | 121.5 | 1.59 | 1.00 | 10 | 30 | 1997 |

# Appendix E

## L-MOMENT STATISTICS

## L-MOMENT STATISTICS

L-moments are a dramatic improvement over conventional statistics for characterizing the variance and skewness of data, for describing the shape of a probability distribution, and for estimating the distribution parameters (Hosking[7,9,13]). They are particularly useful for describing environmental data that are often highly skewed. The at-site L-moment measure of location, and L-moment ratio measures of scale, skewness and kurtosis are:

Location, mean:

$$\text{Mean} = L_1 \tag{E1}$$

Scale, L-Cv ($t_2$):

$$t_2 = L_2/L_1 \tag{E2}$$

L-Skewness ($t_3$):

$$t_3 = L_3/L_2 \tag{E3}$$

L-Kurtosis ($t_4$):

$$t_4 = L_4/L_2 \tag{E4}$$

where:

$$L_1 = \beta_0 \tag{E5}$$
$$L_2 = 2\beta_1 - \beta_0 \tag{E6}$$
$$L_3 = 6\beta_2 - 6\beta_1 + \beta_0 \tag{E7}$$
$$L_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \tag{E8}$$

and where the at-site data are first ranked in ascending order from 1 to n ($x_{1:n}$) and:

$$\beta_0 = n^{-1} \sum_{j=1}^{n} x_j \tag{E9}$$

$$\beta_1 = n^{-1} \sum_{j=2}^{n} x_j \, [(j-1)/(n-1)] \tag{E10}$$

$$\beta_2 = n^{-1} \sum_{j=3}^{n} x_j \, [(j-1)(j-2)]/[(n-1)(n-2)] \tag{E11}$$

$$\beta_3 = n^{-1} \sum_{j=4}^{n} x_j \, [(j-1)(j-2)(j-3)]/[(n-1)(n-2)(n-3)] \tag{E12}$$

Regional L-moments ratios are obtained as weighted averages of the at-site L-moments ratios where the at-site values are weighted by record length. Specifically: $n_i$ is the record length at site $i$ of $N$ sites: $n_R$ is the total record length for the $N$ sites in the region; $t_2^i$, $t_3^i$, $t_4^i$ are L-moment ratios at site $i$; and:

$$n_R = \sum_{i=1}^{N} n_i \tag{E13}$$

Regional Mean ($L_1^R$) is unity using the index-flood procedure:

$$L_1^R = 1 \tag{E14}$$

Regional L-Cv ($t_2^R$):

$$t_2^R = n_R^{-1} \sum_{i=1}^{N} n_i \, t_2^i \tag{E15}$$

Regional L-Skewness ($t_3^R$):

$$t_3^R = n_R^{-1} \sum_{i=1}^{N} n_i \, t_3^i \tag{E16}$$

Regional L-Kurtosis ($t_4^R$):

$$t_4^R = n_R^{-1} \sum_{i=1}^{N} n_i \, t_4^i \tag{E17}$$

The regional L-moment ratios for L-Skewness ($t_3^R$) and L-Kurtosis ($t_4^R$) were corrected for bias based on bias correction equations provided by Hosking and Wallis[8,9]. These equations are valid for the range of regional L-moment ratios observed in the study area, where:

$$\text{bias } t_3^R = 4N(.10 - t_4^R)/n_R \tag{E18}$$

$$\text{bias } t_4^R = 4N(.15 - t_4^R)/n_R \tag{E19}$$

# Appendix F

## SELECTED DEFINITIONS

*At-Site* - the term at-site is used in various ways. It may be used to distinguish analyses/data at a specific site from regional analyses/data. It may be used in reference to a given gage/station or a specific geographic location. Observed at-site precipitation is synonymous with observed point rainfall.

*At-Site Mean* - the mean value of precipitation for a specified duration at a specific location. For a gaged site, it is based on the gaged record for the specified duration. At an ungaged site, it is based on a statistical relationship. Also see mean annual maxima.

*Climatic Region* - a geographic area that has similar physical and climatological characteristics.

*Convective Precipitation* - precipitation that results from lifting of atmospheric moisture due to vertical instability in the air column. The thunderstorm is one type of convective precipitation producing mechanism.

*Convergence Precipitation* - convergence is intended to encompass all precipitation producing mechanisms associated with the circulation of a cyclonic weather system.

*Extreme Storm* - a precipitation amount for a specified duration that has an annual exceedance probability less than 0.05; rarer than a 20-year event.

*Gage Mean* - the mean value computed from the annual maxima data at a precipitation gage for some specified duration. At-site mean values are determined from gage mean values using minor correction factors to adjust from fixed measurement intervals to true intervals. See Weiss[32].

*Gaged Site* - a geographic location where a precipitation gage is used to measure and record precipitation data. See also ungaged site.

*Homogeneous sub-region* - a collection of sites/gages with similar physical and/or climatic characteristics that can be described by a common regional growth curve.

*Mean Annual Maxima (MAM)* - the mean value of precipitation annual maxima for a specified duration at a specific location. It is the terminology commonly used in Canada as an alternate to at-site-mean.

*Mean Annual Precipitation (MAP)* - the average precipitation for a calendar year. (An example of an at-site-mean).

*Orographic Precipitation* - precipitation that occurs due to the lifting of atmospheric moisture over mountain barriers.

*Precipitation Annual Maxima* - the greatest precipitation amount in a 12-month period for a specified duration. The annual period may be a calendar year, or any other 12-month period. The water-year, October 1st to September 30th is the 12-month period used in these analyses.

*Regional* - the term regional is used in a generic manner to distinguish data/analyses for a group of sites/gages as opposed to individual at-site data/analyses. The term regional may be used in reference to homogeneous sub-regions or climatic regions.

*Regional Growth Curve* - a magnitude-frequency curve with a mean value of unity that is applicable to all sites within a homogeneous region.

*Seasonality* - frequency characteristics for the time of year (month) during which certain characteristics of precipitation have been observed to occur.

*Station* - refers to the weather station/collection site for precipitation. A particular station/location may contain any combination of daily, synoptic and automated gages. The term station and site are often used interchangeably.

*Ungaged Site* - a geographic location where no precipitation measurements are available.