Regional Precipitation-Frequency Analysis And Spatial Mapping Of Precipitation For 24- Hour And 2-Hour Durations In Eastern Washington

WA-RD 640.1

Research Report
January 2006

Washington State Department of Transportation

Washington State Transportation Commission
Research Office:
U.S. DOT - Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENTS CATALOG NO
WA-RD 640.1		

4. TITLE AND SUBTILLE	5. REPORT DATE
Regional Precipitation-Frequency Analysis and Spatial Mapping of Precipitation for 24-hour and 2-hour Durations in Eastern Washington	January 2006
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) MG Schaefer Ph. D. P.E. MGS Engineering BL Barker P.E. MGS Engineering GH Taylor CCM Oregon Climate Service JR Wallis Ph.D Yale University	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS MGS Engineering 7326 Boston Harbor Road NE Olympia, WA 98506	10. WORK UNIT NO. 11. CONTRACT OR GRANT NO.
12. CPONSORING AGENCY NAME AND ADDRESS Research Office-WSDOT Transportation Building, MS 7370 Olympia, Washington 98504-7370 Rhonda Brooks, Project Manager, (360) 705-7945	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

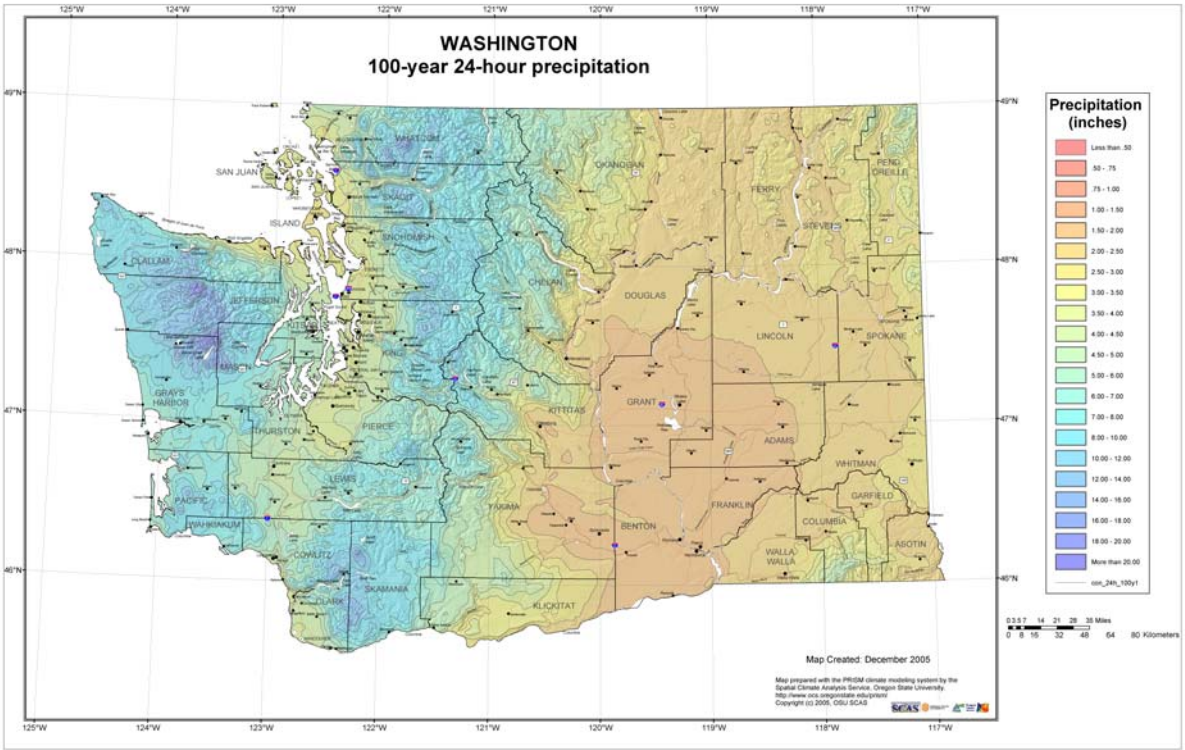
16. ABSTRACT

This report documents the findings of regional precipitation-frequency analyses of 24-hour and 2-hour precipitation annual maxima for eastern Washington. It also describes the procedures used for spatial mapping of the precipitation-frequency estimates for selected recurrence intervals. This is a companion study to the precipitation-frequency study for western Washington[28] that was completed in March 2002.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Climatic Region, Duration, Gage Site, Mean Annual Precipitation, Precipitation, Stations, Ungaged Site, Mapping, 24-hour, 2-hour	No restriction. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None	76	

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



100-Year 24-Hour Precipitation

Washington State
Department of Transportation

January 2006

MGS Engineering Consultants, Inc.

Oregon Climate Service
JR Wallis

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

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

January 2006

MGS Engineering Consultants, Inc.

Oregon Climate Service
JR Wallis

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

EXECUTIVE SUMMARY

Regional frequency analyses were conducted for precipitation annual maxima in eastern Washington for durations of 24-hours and 2-hours. A total of 294 precipitation gages in Washington, southern British Columbia, western Idaho and northern Oregon were included in the study representing 13,749 and 3,335 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 four climatic regions and two transition zones. The four climatic regions were geographic areas that had similar topographic and climatological characteristics and were subjected to similar meteorological conditions during storm events. This included one Cascade Mountain region, two interior lowland regions and one mountainous region on the eastern boundary of the study area. One transition zone was used near the crest of the Cascade Mountains for merging the spatial mapping of precipitation from the prior study for western Washington with this study for eastern Washington. A second transition zone was used for spatial mapping of precipitation at the eastern foothills of the Cascade Mountains. Steep gradients in storm statistical measures were found along with a sharp change in the seasonality of storms in the eastern Cascade foothills area.

Separate regional analyses were conducted for each of the four 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 22 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 eastern 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 eastern Washington.

TABLE OF CONTENTS

SUBJECT	*PAGE*
OVERVIEW	1
STUDY AREA	2
CLIMATIC AND METEOROLOGIC CHARACTERISTICS OF STUDY AREA	2
Annual Precipitation	2
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	6
Stationarity and Serial Independence	6
REGIONAL ANALYSIS METHODOLOGY	7
Description of Climatic/Geographic Regions	7
Climatic Regions for Western Washington Study Area	10
Climatic Regions for Eastern Washington Study Area	10
Regional Growth Curve	11
FORMING HOMOGENEOUS SUB-REGIONS	12
Heterogeneity Measures of Proposed Homogeneous Sub-Regions	12
Acceptance of Proposed Homogeneous Sub-Regions	13
Systematic Variation of L-Cv and L-Skewness with Mean Annual Precipitation	13
ANALYSES OF 24-HOUR DURATION ANNUAL MAXIMA	14
Regional Solutions for L-Moment Ratios, L-Cv and L-Skewness	15
Cascade Foothills Transition Zone	15
Heterogeneity Measures, 24-Hour Duration	17
Identification of Regional Probability Distribution, 24-Hour Duration	17

TABLE OF CONTENTS

ANALYSES OF 2-HOUR DURATION ANNUAL MAXIMA 18

Regional Solutions for L-Moment Ratios, L-Cv and L-Skewness 19

Heterogeneity Measures, 2-Hour Duration 20

Identification of Regional Probability Distribution, 2-Hour Duration 21

PRECIPITATION MAGNITUDE-FREQUENCY ESTIMATES FOR GAGED SITES 21

SPATIAL MAPPING OF PRECIPITATION-FREQUENCY INFORMATION 24

Mean Annual Precipitation 24

SPATIAL MAPPING OF AT-SITE MEANS 25

Quantitative Assessment of Success Achieved in Spatial Mapping of At-Site Means 27

SPATIAL MAPPING OF REGIONAL L-MOMENT STATISTICAL PARAMETERS 29

PRODUCTION OF ISOPLUVIAL MAPS 32

Precipitation Magnitude-Frequency Estimates for Moderate to Large Size Watersheds 33

Uncertainty Bounds for 100-Year Values 33

ELECTRONIC FILES 34
LISTING AT-SITE AND REGIONAL PARAMETERS FOR ALL GAGED SITES

SEASONALITY OF EXTREME STORMS 35

CATALOG OF EXTREME STORMS 38

REFERENCES 38

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

APPENDIX B B-1
ISOPLUVIAL MAPS FOR SELECTED RECURRENCE INTERVALS

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

APPENDIX D D-1
L-MOMENT STATISTICS

APPENDIX E E-1
SELECTED DEFINITIONS

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

January 2006

OVERVIEW

This report documents the findings of regional precipitation-frequency analyses of 24-hour and 2-hour precipitation annual maxima for eastern Washington. It also describes the procedures used for spatial mapping of the precipitation-frequency estimates for selected recurrence intervals. This is a companion study to the precipitation-frequency study for western Washington[28] that was completed in March 2002.

This study for eastern Washington 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 37-years of record collected since 1966 as well as additional data sources not available in 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 1966 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[4] 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 the high topographic and climatic variability that exist in eastern Washington. Both of these methodologies have been utilized in conducting the precipitation-frequency analyses and in developing the isopluvial maps for selected recurrence intervals.

As this study for eastern Washington was nearing completion, Oregon Climate Service[20] released a high resolution update of the PRISM map of mean annual precipitation for Washington. This new map of mean annual precipitation was produced for the period from 1971-2000 and incorporated 10 additional years of SNOTEL data in mountain areas, an improved moisture trajectory inflow model, an improved digital terrain model, and higher resolution precipitation mapping. These improvements resulted in significant changes to previously mapped values of mean annual precipitation in some mountain and foothill areas. The PRISM map of mean annual precipitation is the base map from which other spatial mapping is derived for the precipitation-frequency study. These changes necessitated that the spatial mapping that was previously completed for western Washington be updated to reflect changes to the base map of mean annual precipitation.

Color-shaded isopluvial maps depicted in this report reflect the findings of the study for eastern Washington and the updated mapping for western Washington utilizing the new 1971-2000 base map of mean annual precipitation.

STUDY AREA

While eastern Washington is the area of interest, the study area was expanded to provide additional data in border areas. The eastern Washington study area included portions of southern British Columbia, northeastern Oregon, and western Idaho (Figure 1). Specifically, the eastern Washington 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 at latitude 116°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 locations in the Cascade Mountains, Blue Mountains and Selkirk Mountains.

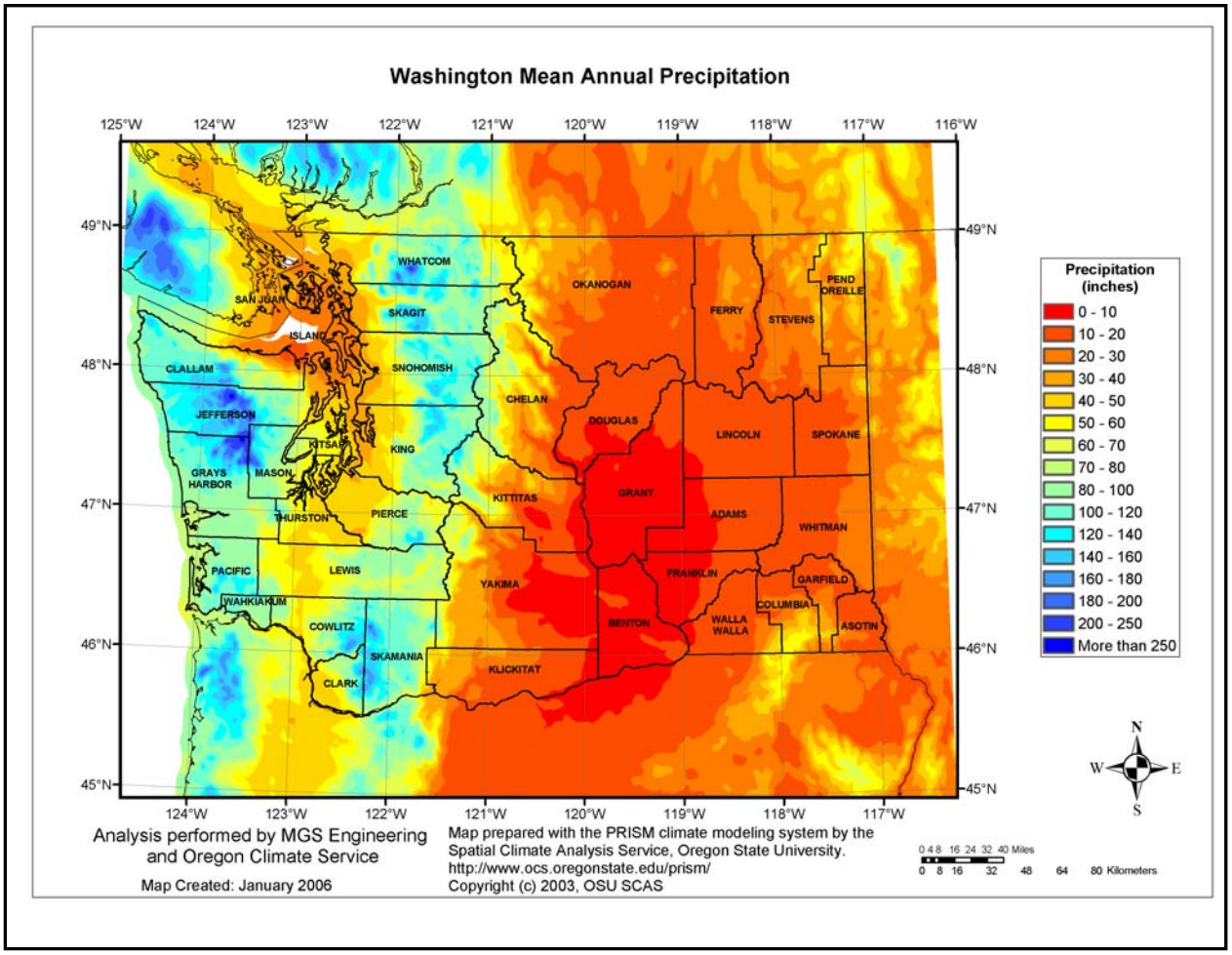


Figure 1 – Mean Annual Precipitation[20,21] for Washington State including Eastern Washington Study Area

CLIMATIC AND METEOROLOGIC CHARACTERISTICS OF STUDY AREA

Annual Precipitation

Mean annual precipitation within the eastern Washington study area varies dramatically from the eastern slopes of the Cascade Mountains to the desert areas in central Washington (Figure 1). Mean Annual Precipitation[20,21] (MAP) ranges from a high of over 200-inches in the Cascade Mountains, to a low near 7-inches on the Columbia Plateau.

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 four generalized geographic areas that are sources of atmospheric moisture to the study area[16,18,19] 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. The Gulf of Mexico is a fourth source of moisture that occasionally penetrates sufficiently north to be a source of precipitation in warm months.

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 Cascade, Selkirk and Blue 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 on both the west and east slopes of the Cascade Mountains. The remainder of eastern Washington experiences precipitation annual maxima at the 24-hour duration in both the fall and winter months as well as the spring and summer months. Additional information on the seasonality of precipitation annual maxima is presented in the discussion of climatic regions.

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 this case, the 2-hour annual maxima are embedded within much longer duration storm events. 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. The moisture source for thunderstorm events may originate over the Pacific Ocean or, in some cases, originate as far south as the Gulf of Mexico[19].

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 southern British Columbia were obtained from the Canadian Atmospheric Environment Services Agency (Environment Canada EC). Data from Snotel gages in mountains areas were obtained from the electronic files of the Natural Resources Conservation Service (NRCS).

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 precipitation measurement sites in the US and BC. This occurred at 68 stations in Washington, Oregon, Idaho and British Columbia. 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. This yielded a total of 294 gages that were used in the study for eastern Washington. The precipitation station networks are shown in Figures 2a,b for the 24-hour and 2-hour durations, respectively. Precipitation stations are also shown in Figures 2a,b for the west slopes of the Cascade Mountains, but were not included in the station counts listed in Tables 1a,b.

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	35	0	0
Washington	105	31	27
Idaho	20	9	10
Oregon	31	10	16
TOTAL	**191**	**50**	**53**

68 NCDC and BC stations have co-located daily and hourly gages (not included above)

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

STATION LOCATION	HOURLY GAGE
British Columbia	2
Washington	50
Idaho	14
Oregon	17
TOTAL	**83**

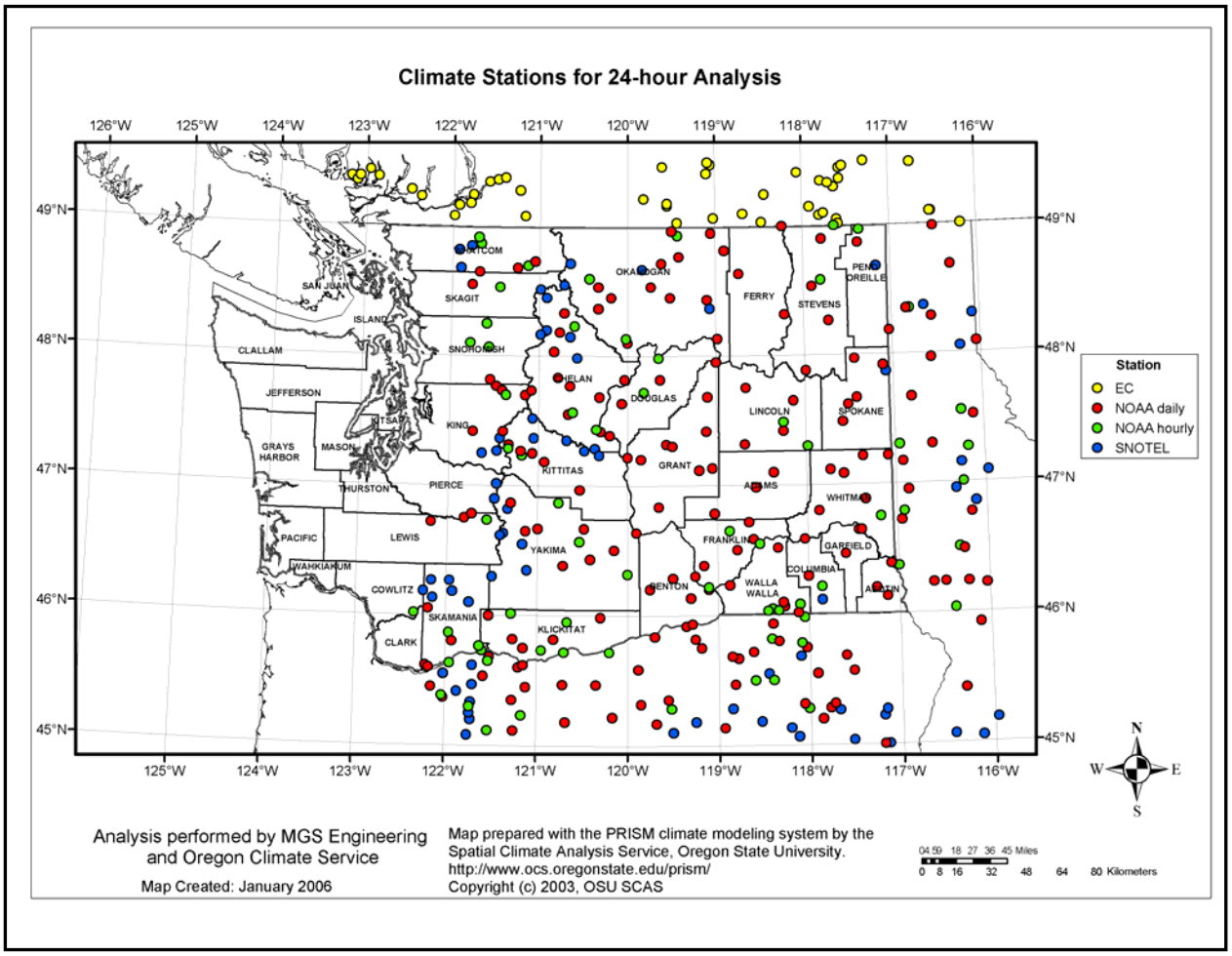


Figure 2a – Precipitation Gaging Network for Analysis of 24-Hour Annual Maxima

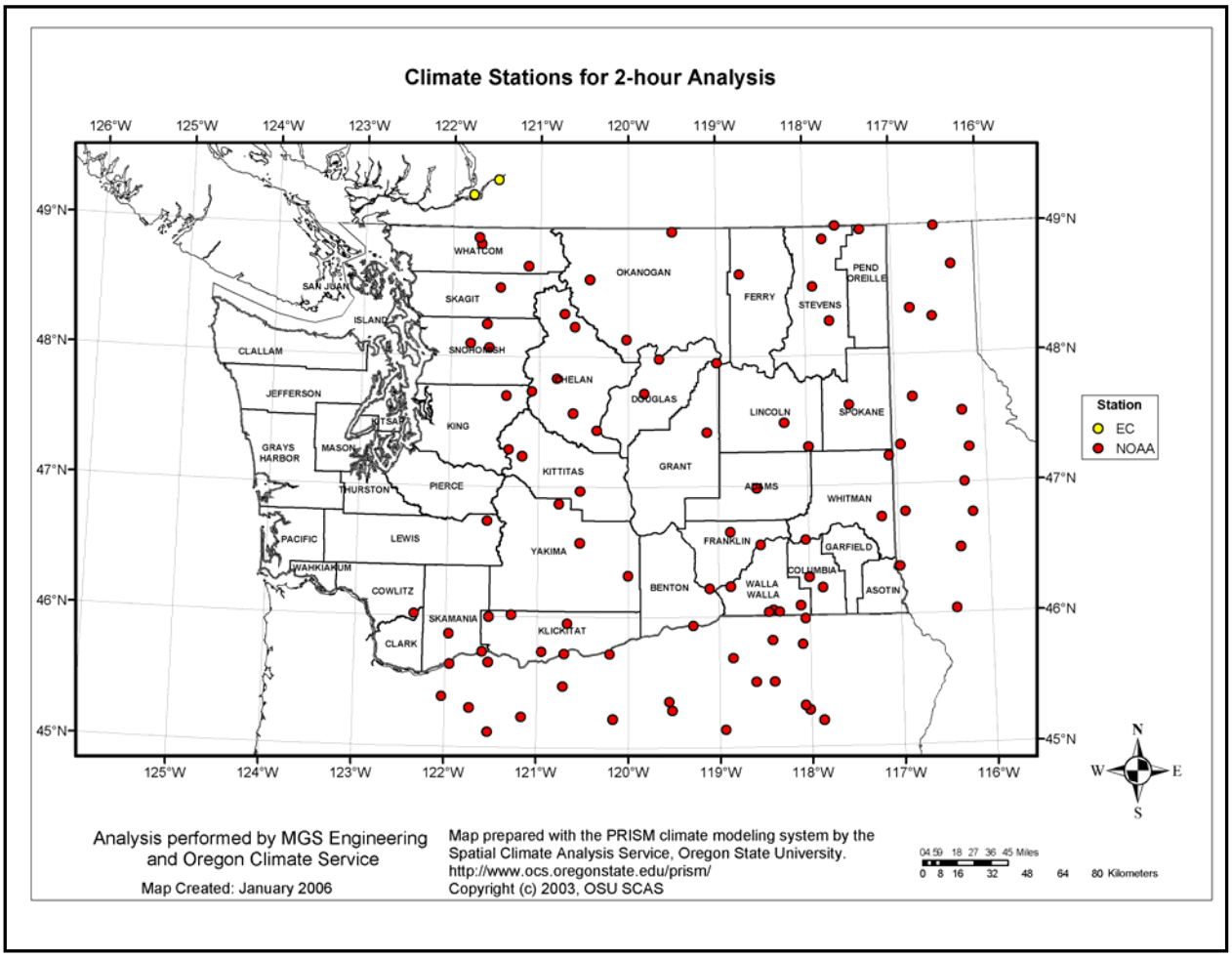


Figure 2b – Precipitation Gaging Network for Analysis of 2-Hour Annual Maxima

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, and 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 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 use, 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 +0.05%, and +0.11% 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 mountain areas (Schaefer[23,24,25,26,27,28]). Each of the region designations utilized in these prior studies were based, to some extent, on the spatial distribution of mean annual precipitation and topographic characteristics, particularly the orientation of mountain ranges.

This information was augmented by analyses of the seasonality of 24-hour precipitation annual maxima. Those analyses revealed winter storms to be the dominate events in the Cascade Mountains and western Washington (Figure 3a). Other areas to the east exhibited seasonality characteristics with a mixture of winter (Nov-Apr), spring-summer (May-Aug) and fall (Sep-Oct) annual maxima (Figures 3a,b,c, respectively).

Four climatic/geographic regions were identified (Figure 4) for the eastern Washington study area based on information contained in prior studies, the spatial characteristics of mean annual precipitation, and the seasonality of 24-hour annual maxima. In particular, the map of mean annual precipitation (Figure 1) developed by Daly using the PRISM[4] model provided the basic mapping information for delineating the boundaries of the climatic regions.

Locally high gradients in statistical measures of storm characteristics were found where the Cascade Mountain foothills abut the arid and semi-arid lowlands in the Okanogan Valley, and Columbia Basin. In addition, marked changes in statistical measures of the variability of 24-hour annual maxima precipitation data (Figure 7) were observed in the foothill areas. A transition zone was used in this foothill area to provide for a smooth transition in the spatial mapping of precipitation at the boundary between adjacent climatic regions. Another transition zone was used near the Cascade Crest where the windward west face of the Cascade Mountains merges with the leeward eastern face of the Cascade Mountains. Four climatic regions (14, 77, 7 and 13) and two transition zones (154 and 147) for eastern Washington are described in the following sections. Descriptions of the climatic regions in western Washington[28] are listed first to provide continuity with the climatic regions in eastern Washington.

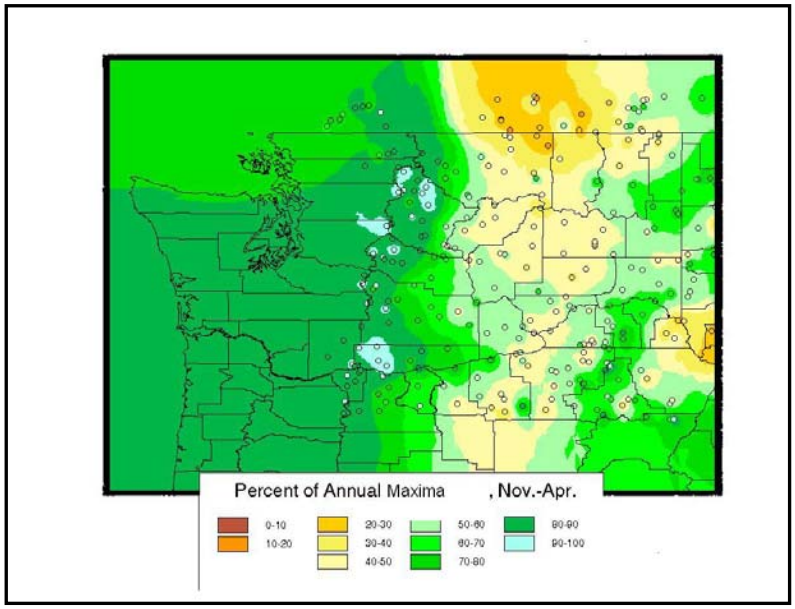


Figure 3a – Frequency of Winter (Nov-Apr) 24-Hour Annual Maxima for Eastern Washington Study Area

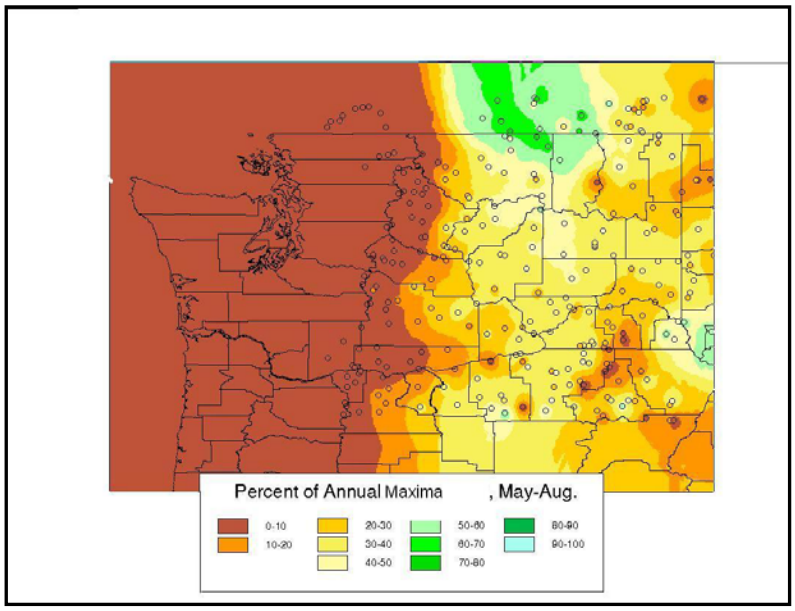


Figure 3b – Frequency of Spring-Summer (May-Aug) 24-Hour Annual Maxima for Eastern Washington Study Area

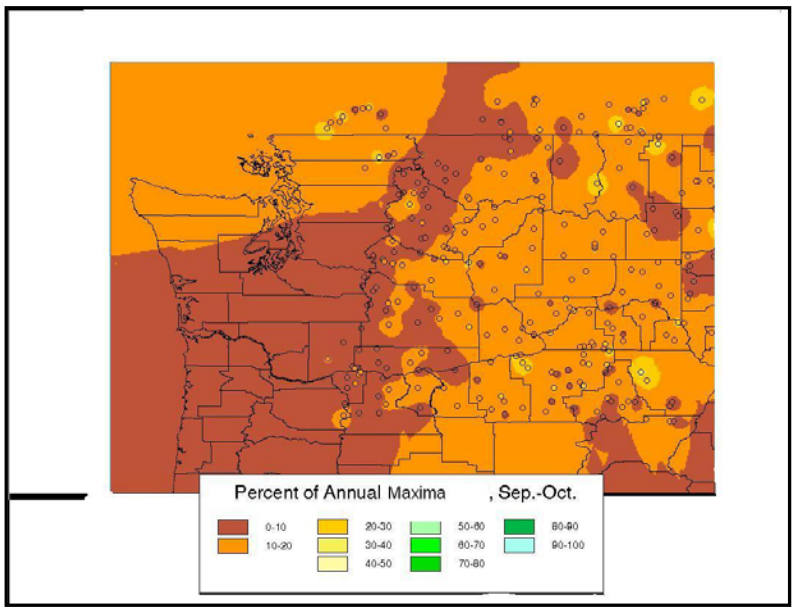


Figure 3c – Frequency of Fall (Sep-Oct) 24-Hour Annual Maxima
for Eastern Washington Study Area

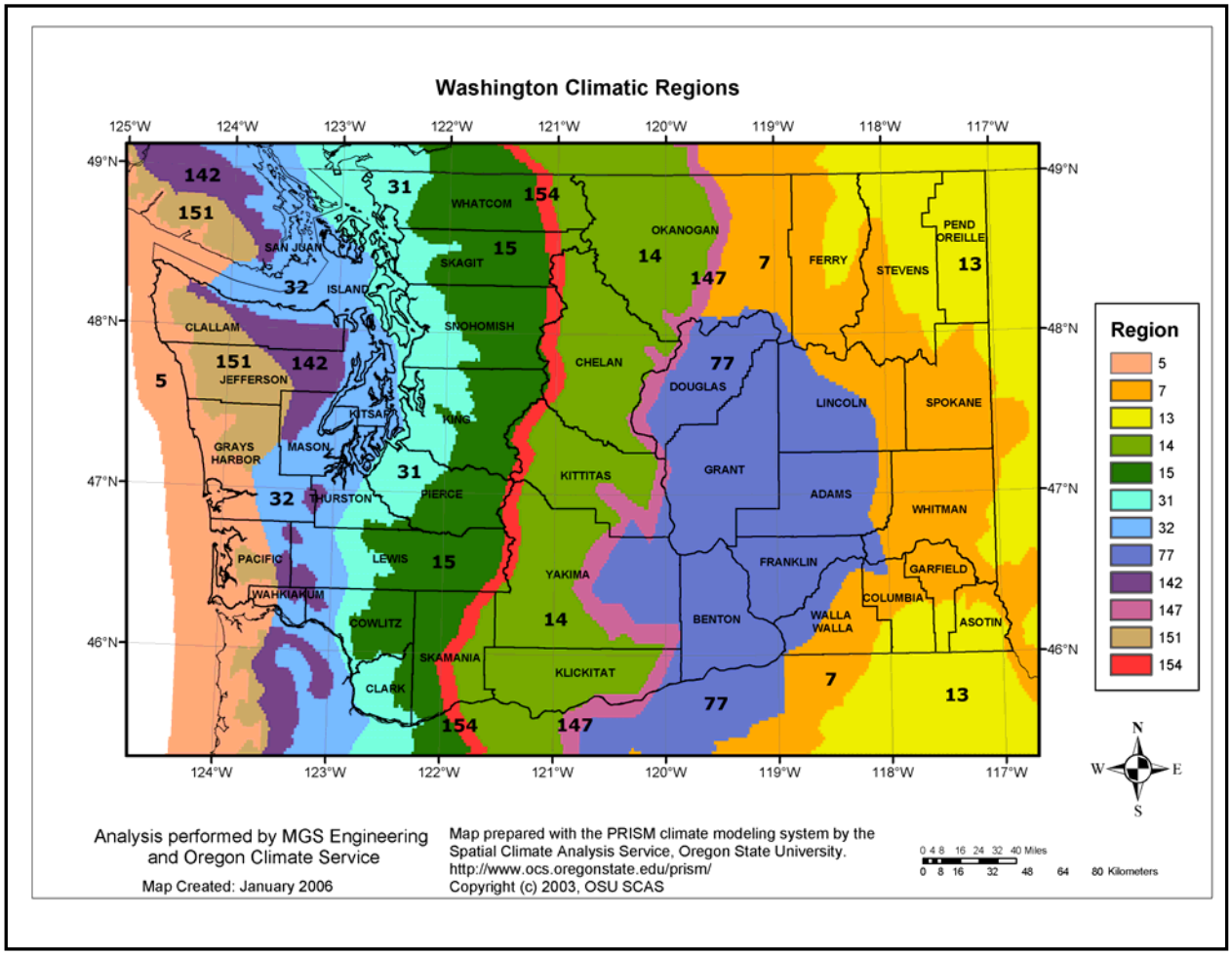


Figure 4 – Delineation of Climatic Regions and Transition Zones
for Washington State and Surrounding Areas

Climatic Regions for Western Washington Study Area
The descriptions of the following six climatic regions have been excerpted from the prior study[28] for the western Washington study area.

***Region 5* - Coastal Lowlands** – 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.

***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.

***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 for Eastern Washington Study Area

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 and is used to provide a smooth transition in spatial mapping of precipitation in the Cascade Crest area.

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 (Figure 3a). 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 14-inch contour of 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 based on recommendations from George Taylor, Oregon Climate Service. Region 147 is used to provide a smooth transition for L-moment ratio statistics and spatial mapping of precipitation between Regions 14 and 77, and Regions 14 and 7.

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 component to precipitation magnitudes. 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 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.

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 within a homogeneous region have a common regional magnitude-frequency curve (regional growth curve, Figure 5) that becomes site-specific after scaling by the at-site mean of the data from the specific site of interest. Thus,

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

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[3] and expanded by Wallis[32,33].

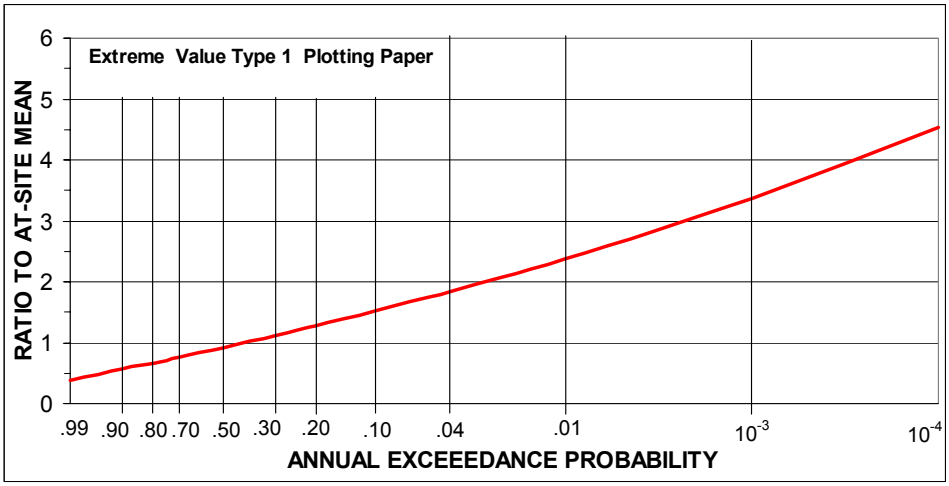


Figure 5 – Example of Regional Growth Curve

FORMING HOMOGENEOUS SUB-REGIONS

Identification and formation of homogeneous regions is an iterative process. 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 and Wallis[9,10], Appendix D) 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 four climatic regions in eastern Washington already had similarities regarding several of the physical and climatological measures listed above. As such, only one 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 small ranges 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[9,12] 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[31] 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 for Washington State[23,28], southern British Columbia[25], and the Sierra Mountains in California[27]. 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 for eastern Washington took the general forms:

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

$$L\text{-}Skew = \alpha\, e^{-\beta(MAP)} + \delta \qquad (2b)$$

where: alpha (α), beta (β), and delta (δ) are parameters specific to a given climatic region or group of climatic regions.

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 10 to 15 gages, 500 to 700 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 22 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 6 depicts the number of stations within various ranges of record length. The prominent spike in the number of stations with record lengths in the range of 21-30 years is primarily due to the installation of Snotel stations, which began operation in the 1970's.

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
14	7	44	14	26	3,650
Zone 147	2	13	5	0	1,045
77	4	38	7	0	2,419
7	5	41	7	0	2,511
13	6	55	17	25	4,124
TOTAL	**22**	**191**	**50**	**51**	**13,749**

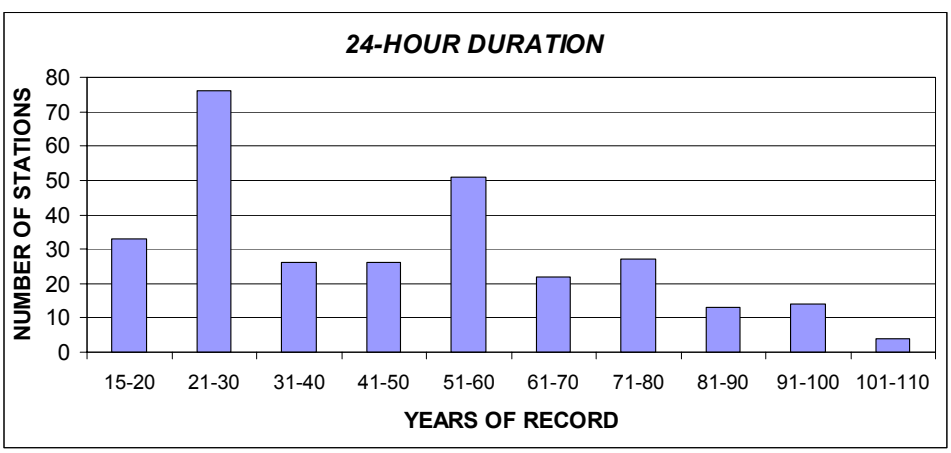


Figure 6 – Histogram of Record Lengths at Stations for 24-Hour Annual Maxima

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 (Table 3). 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 western and eastern 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 Table 3 and graphically depicted in Figure 7.

Cascade Foothills Transition Zone – Review of Figure 7 reveals a marked break in the magnitudes of the variability measure L-Cv for the East Slopes of the Cascade Mountains (Region 14 and Transition Zone 147) relative to that in the arid and semi-arid regions further east (Regions 77, 7 and 13). Review of Figures 3a,b,c also shows a sharp change in storm seasonality accompanies this distinctive change in the magnitude of L-Cv at the Cascade foothills for these regions. Specifically, 24-hour precipitation annual maxima are predominately produced by winter storms on the east slopes of the Cascade Mountains and the 24-hour annual maxima in areas further east are produced by a mixture of winter, spring and summer storms (Figures 21a,b,c). These sharp changes provided the impetus for utilizing a transition zone (Transition Zone 147) in the Cascade foothills area.

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 (Table 4). 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 Table 4 and graphically depicted in Figure 8.

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

$L\text{-}Cv = \alpha * MAP^2 + \beta * MAP + \delta$					
REGIONS	**APPLICABILITY**	**ALPHA**	**BETA**	**DELTA**	**STANDARDIZED RMSE**
14 - 147	MAP < 108-inches	0.0000	-0.0005	0.2090	2.6%
14	MAP ≥ 108-inches	0.0000	0.0000	0.1550	
77 – 7 -13	MAP ≤ 40-inches	0.0000475	-0.0042	0.2281	3.1%
13	MAP > 40-inches	0.0000	0.0000	0.1360	

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

*L-Skewness = α * EXP [-β * MAP] + δ*					
REGIONS	**APPLICABILITY**	**ALPHA**	**BETA**	**DELTA**	**STANDARDIZED RMSE**
14 -147 - 77 -7 -13	All Areas	0.1150	0.0400	0.1580	7.4%

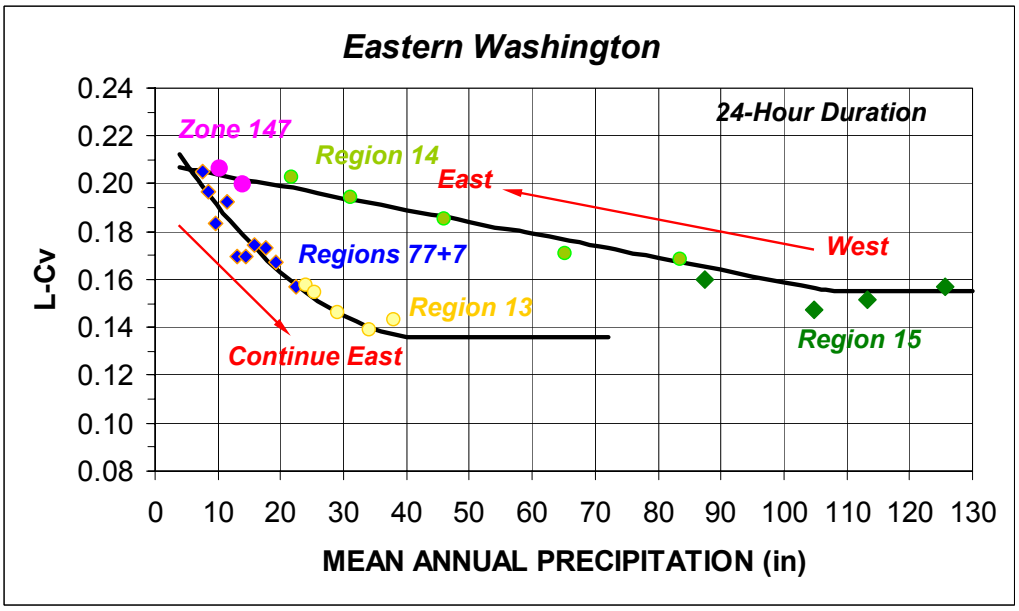


Figure 7 – Predictor Equation Solutions of Observed L-Cv for Climatic Regions in Eastern Washington for 24-Hour Duration

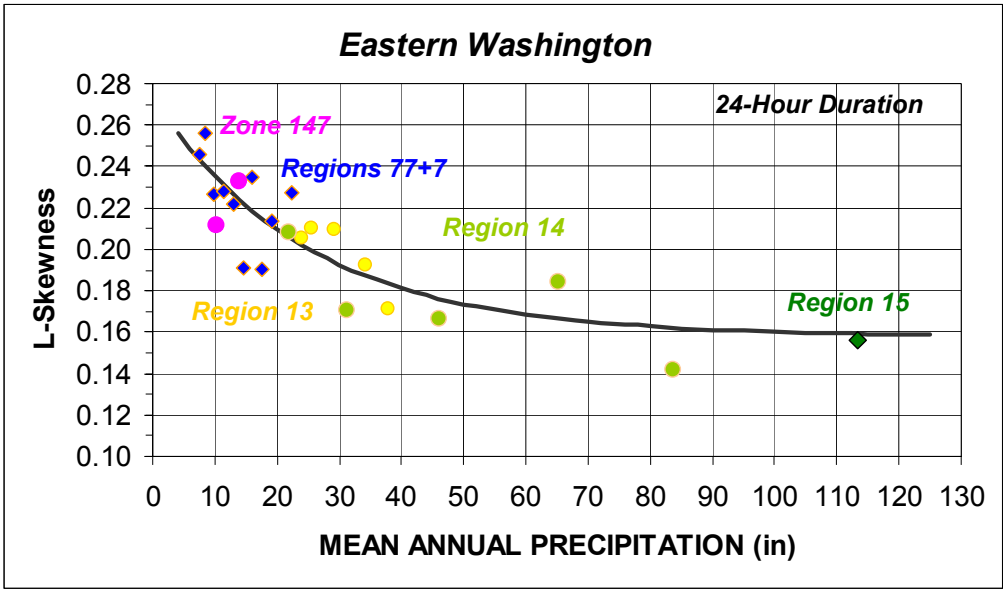


Figure 8 – Predictor Equation Solutions of Observed L-Skewness for Climatic Regions in Eastern Washington for 24-Hour Duration

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 that nearly all 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. 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
14 -147	7	7	6	5
77 -7 -13	15	14	12	14
TOTAL	**22**	**21**	**18**	**19**

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[9,28] 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 22 sub-regions at the 24-hour duration is shown in Figure 9. Nearness to the GEV distribution is clearly evident and consistent with the goodness-of-fit test results listed in Table 5.

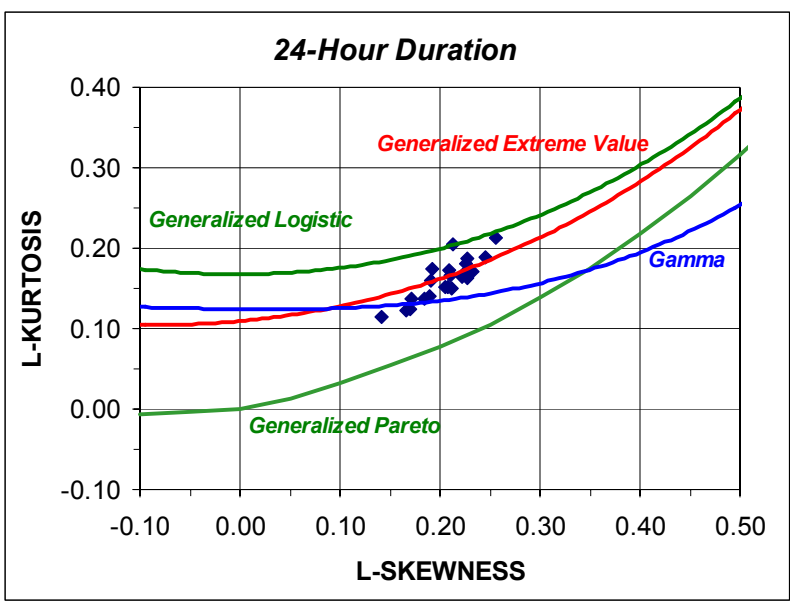


Figure 9 – L-Moment Ratio Plot for Sub-Regions for 24-Hour Duration

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: ξ, α, κ, 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[5]) was taken wherein the shape parameter h was computed as the average value from the group of sub-region solutions. An average value of 0.004 was computed with a standard error of estimation of approximately $\pm$ 0.064 for the eastern Washington study area. This compares with an h value of -0.05 that was found in the prior studies in western Washington[28], eastern British Columbia[25] and eastern Oregon[26]. A nominal h value of -0.05 was adopted for eastern Washington which is consistent with the findings of the prior studies and within one standard deviation of the sample average. This produces a regional growth curve slightly steeper than the GEV for very rare events and essentially matches the GEV out through about the 500-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 8 to 12 gages, 300 to 450 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 10 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 10 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 REGION	NUMBER OF SUB-REGIONS	HOURLY GAGES	STATION-YEARS OF RECORD
14	3	19	763
Zone 147	1	8	396
77	1	13	508
7	3	19	814
13	2	24	854
TOTAL	**10**	**83**	**3,335**

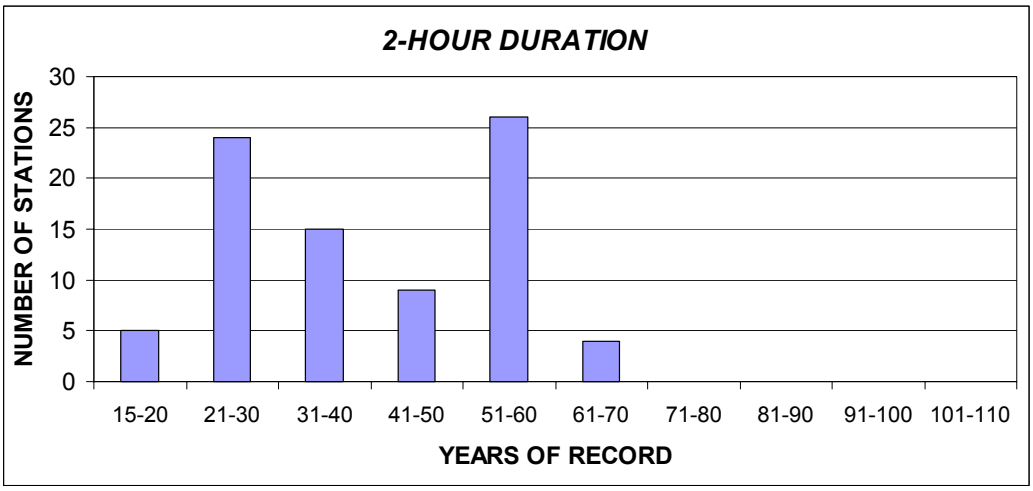


Figure 10 – Histogram of Station Record Lengths for 2-Hour Annual Maxima

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 Figure 11. The predictor equation for L-Skewness is listed in Table 8 and graphically depicted in Figure 12.

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

$L\text{-}Cv = \alpha * MAP^2 + \beta * MAP + \delta$					
REGIONS	**APPLICABILITY**	**ALPHA**	**BETA**	**DELTA**	**STANDARDIZED RMSE**
14 – 147 77 – 7 -13	All Areas	0.1500	-0.0300	0.1200	5.1%

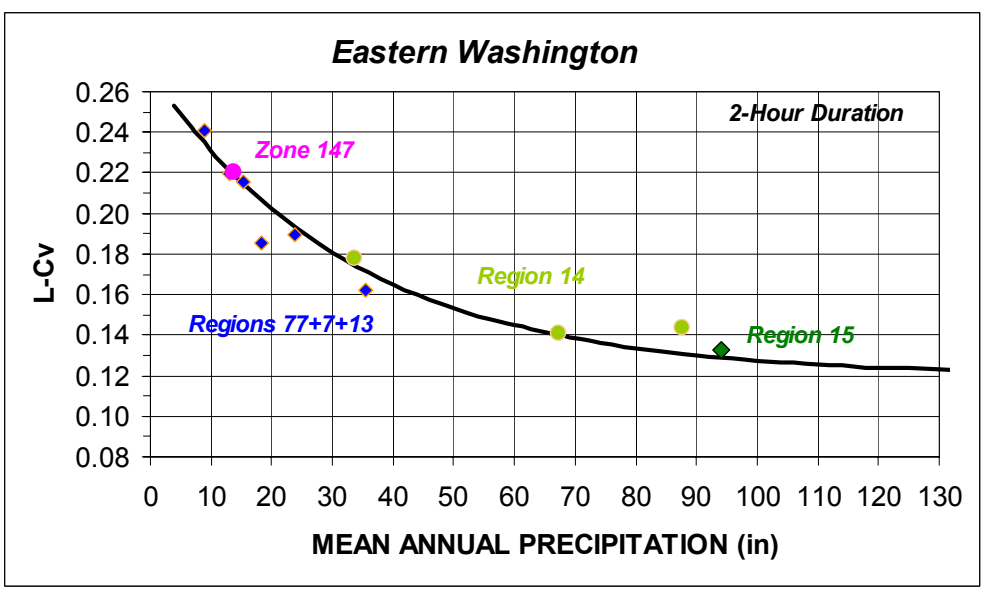


Figure 11 – Predictor Equation Solutions of Observed L-Cv
for Climatic Regions in Eastern Washington for 2-Hour Duration

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

*L-Skewness = α * EXP [-β * MAP] + δ*					
REGIONS	**APPLICABILITY**	**ALPHA**	**BETA**	**DELTA**	**STANDARDIZED RMSE**
14 – 147 77 – 7 -13	All Areas	0.1900	-0.0250	0.1700	10.3%

There is greater variability in the L-skewness measures than for L-Cv. L-skewness measures are inherently more variable, particularly for the sample sizes of precipitation annual maxima that are commonly available. 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.

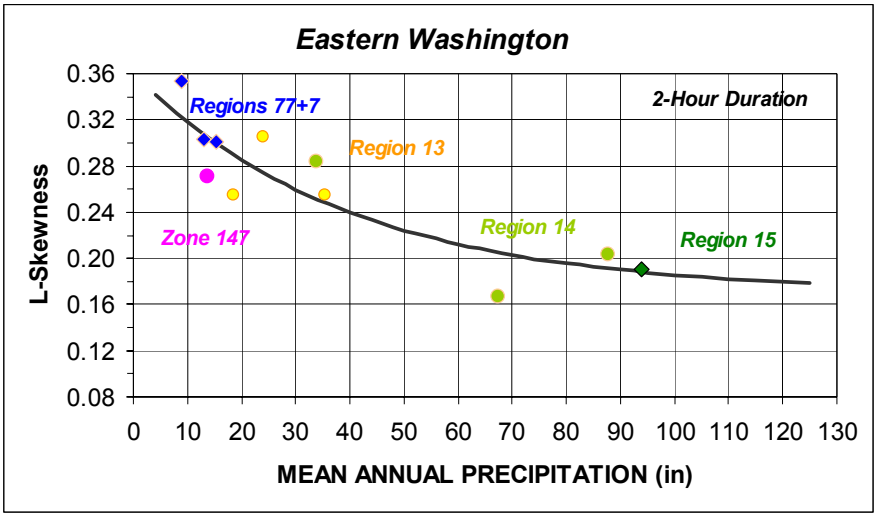


Figure 12 – Predictor Equation Solutions of Observed L-Skewness for All Climatic Regions in Eastern Washington for 2-Hour Duration

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. As was the case for the 24-hour duration, mean annual precipitation was found to be a suitable 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 $\leq$ 2.00	HOMOGENEOUS SUB-REGIONS H2 $\leq$ 1.00	SUB-REGIONS ACCEPTING GEV DISTRIBUTION
14 -147	4	3	4	4
77 -7 -13	6	5	4	6
TOTAL	**10**	**8**	**8**	**10**

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 10 sub-regions at the 2-hour duration is shown in Figure 13. 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.

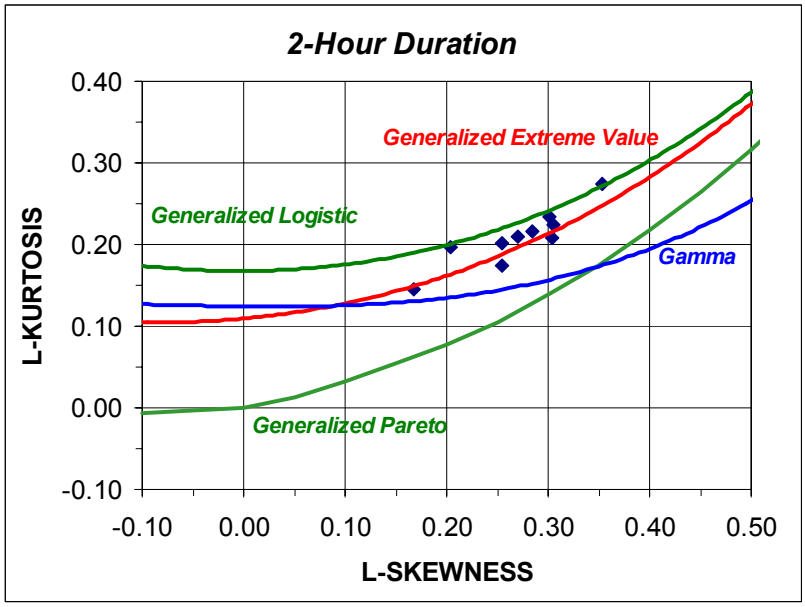


Figure 13 – L-Moment Ratio Plot for Sub-Regions for 2-Hour Duration

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[5]) was taken wherein the shape parameter *h* was computed as the median value from the group of sub-region solutions. A median value of -0.190 was computed with a standard error of estimation of approximately $\pm$ 0.115 for the eastern Washington study area. Based on this information, a nominal *h* value of -0.15 was adopted, which matches the value for western Washington[28] and is well within one standard deviation of the sample value. This produces a regional growth curve somewhat steeper than the GEV for very rare events and essentially matches the GEV distribution up to about 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 (ξ, α, and κ) 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 3, 4 and Tables 7, 8. 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 is needed to adjust the gage sample mean to account for precipitation measurement and reporting on a fixed time interval rather than on a continuous basis. The at-site mean is computed from the gage mean as:

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

where the correction factor (C_{nop}) varies with the length of the observational period (i.e. 2-hours and 24-hours). A correction factor of 1.13 has been estimated from theoretical considerations (Weiss[34]) and also been found in numerous studies (Miller et al[16]). The value of 1.13 is commonly taken as a standard in humid environments subjected to numerous storms each year where the typical duration of storms significantly exceeds the observational period.

In arid and semi-arid areas there may be few noteworthy storms each year and the duration of the storms may be significantly less than the length of the daily observational period. In these cases, it is possible that the correction factor for converting from maximum daily statistics to maximum 24-hour precipitation statistics is something less than conventional value of 1.13. A separate investigation was conducted to determine an appropriate correction factor for use with daily gages because many storms have durations less than 24-hours in the arid and semi-arid areas of eastern Washington. Correction factors for daily measurements in eastern Washington were obtained by comparison of gage mean values at sites having both daily and hourly gages for a common period of measurement (years). This allowed direct comparisons to be made of the computed gage mean values. The results of these analyses are listed in Table 10 and the plot of gage means for daily annual maxima and 24-hour annual maxima is shown in Figure 14.

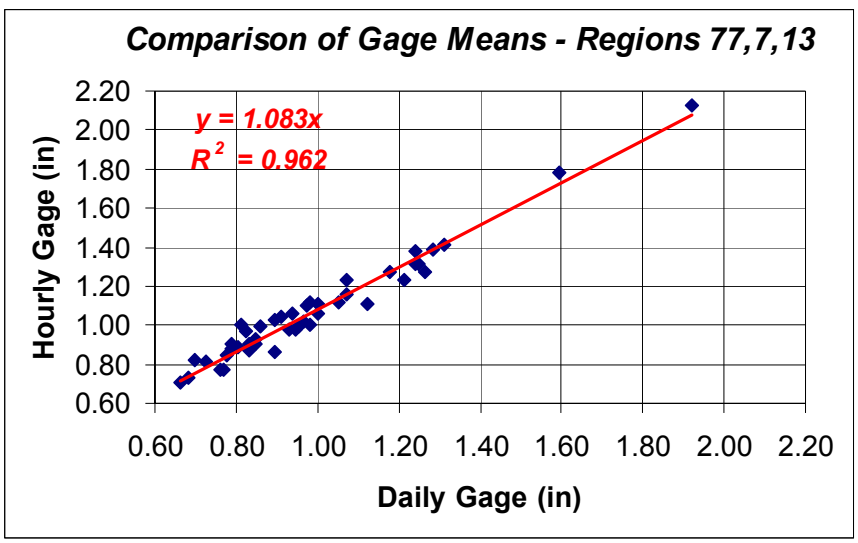


Figure 14 – Comparison of Gage Mean Values for Co-Located Daily and Hourly Gages for a Common Reporting Period for Regions 77, 7 and 13.

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

GAGE TYPE	DURATION	
	2-Hour	24-Hour
Regions 14 – 147 Daily and Snotel Gages	n/a	1.11
Regions 77 – 7 -13 Daily and Snotel Gages	n/a	1.08
Western Washington Daily and Snotel Gages	n/a	1.13
Automated Gage Hourly Reporting	1.04	1.00
Automated Gage 15-Minute Reporting	1.00	1.00

This procedure can be explained by an example using an existing gaged site. The Spokane Airport has an automated gage and is located in Region 7 (Okanogan, Spokane, Palouse). The mean annual precipitation for the site is 17.0-inches. For the 24-hour duration, the regional value of L-Cv is 0.170, which is obtained from Equation 2b and parameter values from Table 3. The regional value of L-Skewness is 0.216, which is obtained from Equation 2a and parameter values from Table 4. 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[9,12], yields:

$$\xi = 0.8573, \quad \alpha = 0.2226, \quad \kappa = -0.0823, \quad \text{and} \quad h = -0.05.$$

Use of Equation 3 yields the regional growth curve depicted in Figure 15a. Spokane Airport has an hourly gage with a gage mean of 1.06-inches for the 24-hour duration for 54-years of record. Use of Equation 4 with a correction factor of 1.00 for the 24-hour duration yields an at-site mean value of 1.06-inches. 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 15b. The observed 24-hour annual maxima for the Spokane Airport site for the period from 1948-2003 are also depicted in Figure 15b for a comparison of the regional solution and the observed annual maxima data. These computations are incorporated in the precipitation spatial mapping products that are described in the following sections.

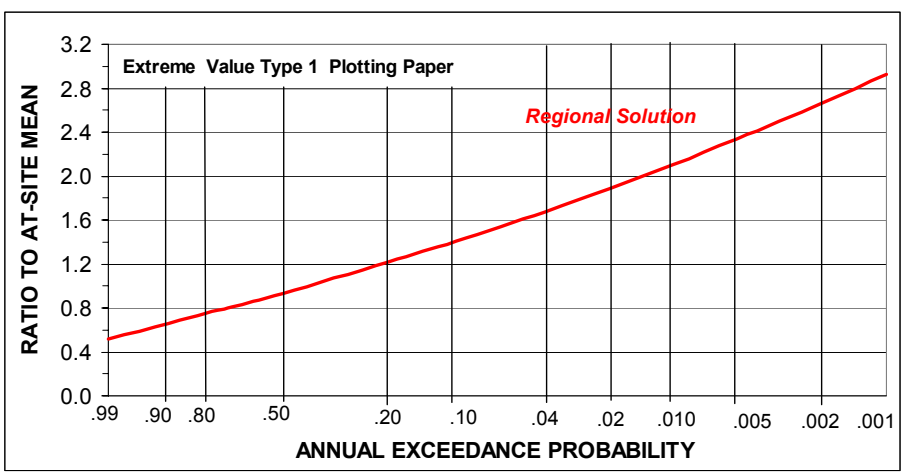


Figure 15a – Regional Growth Curve for Spokane Airport for 24-Hour Duration

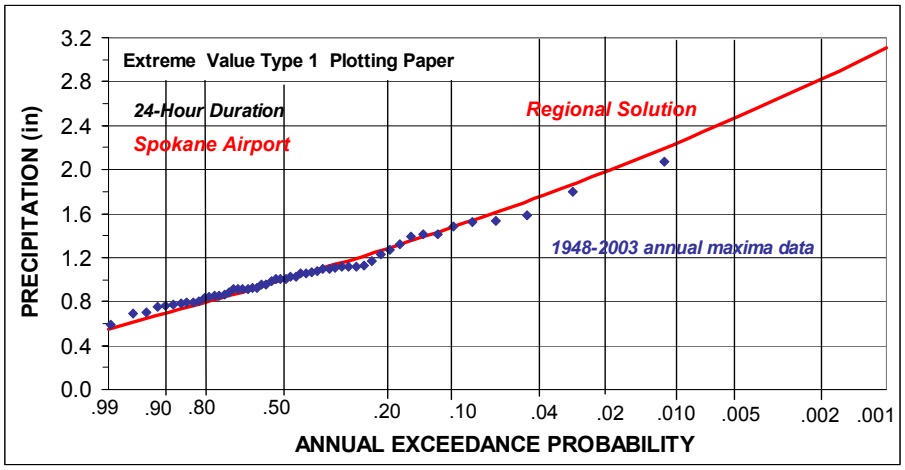


Figure 15b – Precipitation Magnitude-Frequency Curve for Spokane Airport for 24-Hour Duration

SPATIAL MAPPING OF PRECIPITATION-FREQUENCY INFORMATION

Products from the PRISM model[4] 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 (Stedinger[29]) using the conversion developed by Langbein[15]. 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 L-Cv and L-Skewness 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 1971 to 2000 has been completed for the study area by Oregon Climate Service using the PRISM model[4,20]. 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 0.50 minutes per grid-cell for the study area (about 0.23 mi^2). This resolution yields a study area domain that is a matrix of 1080 rows by 540 columns, 583,200 grid-cells for eastern Washington.

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 involved first developing relationships between at-site means computed at precipitation measurement stations and climatic/physiographic factors. An example of this type of relationship is depicted in Figure 16 for the eastern slopes of the Cascade Mountains. These relationships were then used to populate the grid-cells in the study area domain with the values predicted from the applicable regression equation based on the climatic and physiographic factors representative of each grid-cell. At-site mean values for grid-cells within transition zones 154 and 147 were computed as a weighted average of the at-site mean values in the same manner had the grid-cell been located in the adjoining regions. This provided continuity with at-site mean values at region boundaries and provided a smooth transition between adjoining regions.

Residuals were then computed for each of the station at-site means that quantify the magnitude of difference between mapped values and station values. This allowed analyses to be conducted of the residuals to identify if there was a coherent spatial pattern to the magnitude and sign of the residuals. When coherent residual patterns were encountered, they were used to adjust the original estimates. Lastly, standard bias and root mean square error measures were 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 17a,b, respectively.

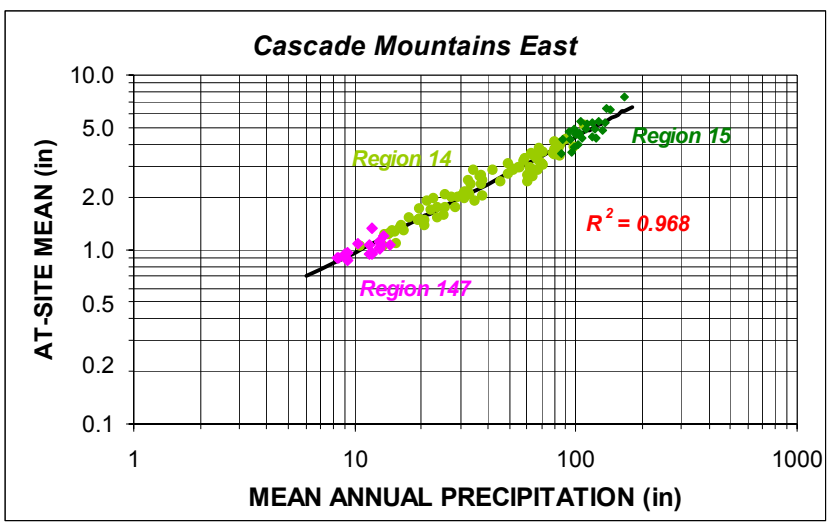


Figure 16 – Example Relationship of 24-Hour At-Site Mean with Mean Annual Precipitation for Eastern Cascade Mountains (Regions 14 and 147)

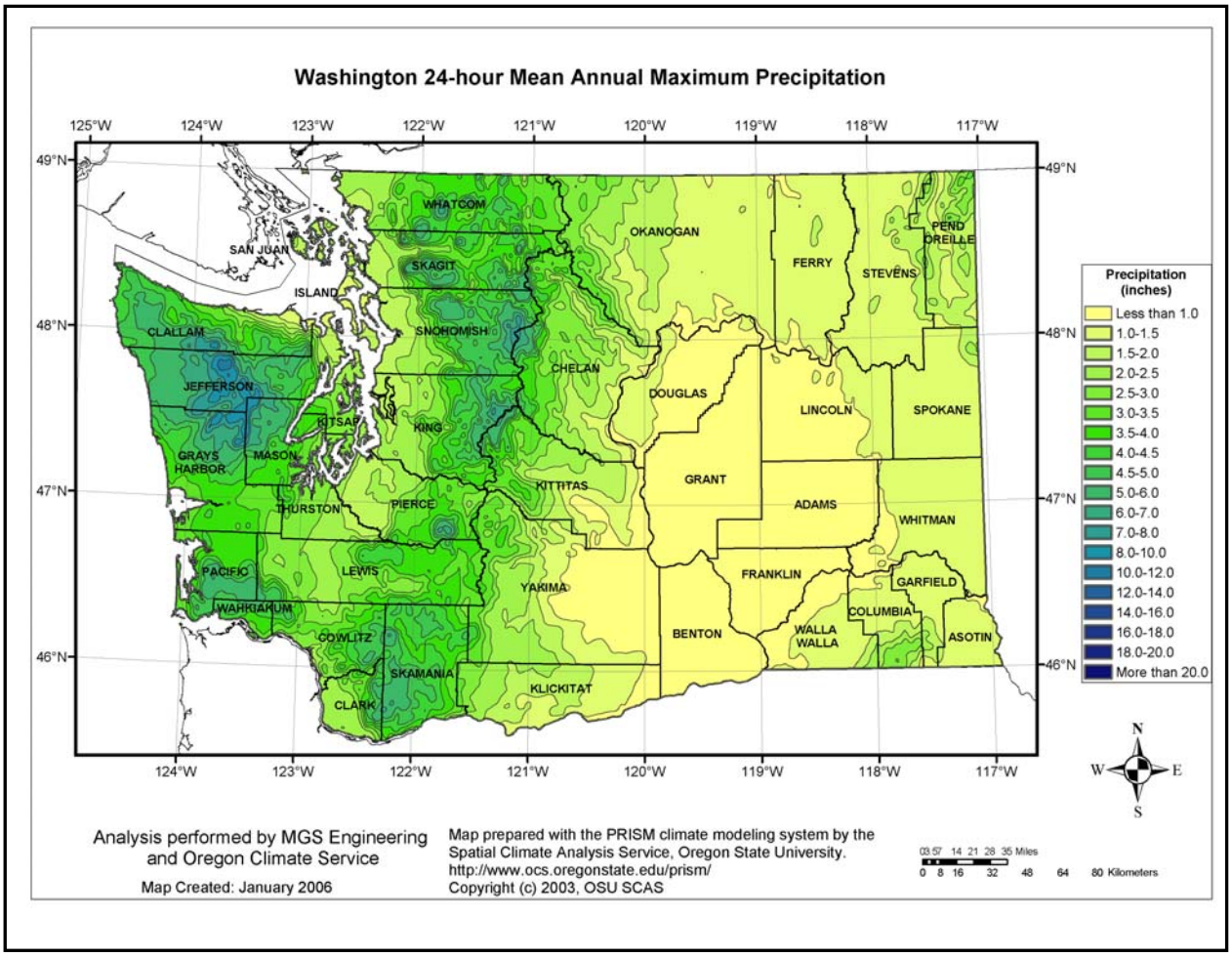


Figure 17a – Map of At-Site Means (Mean Annual Maxima) for 24-Hour Duration for Washington Study Area

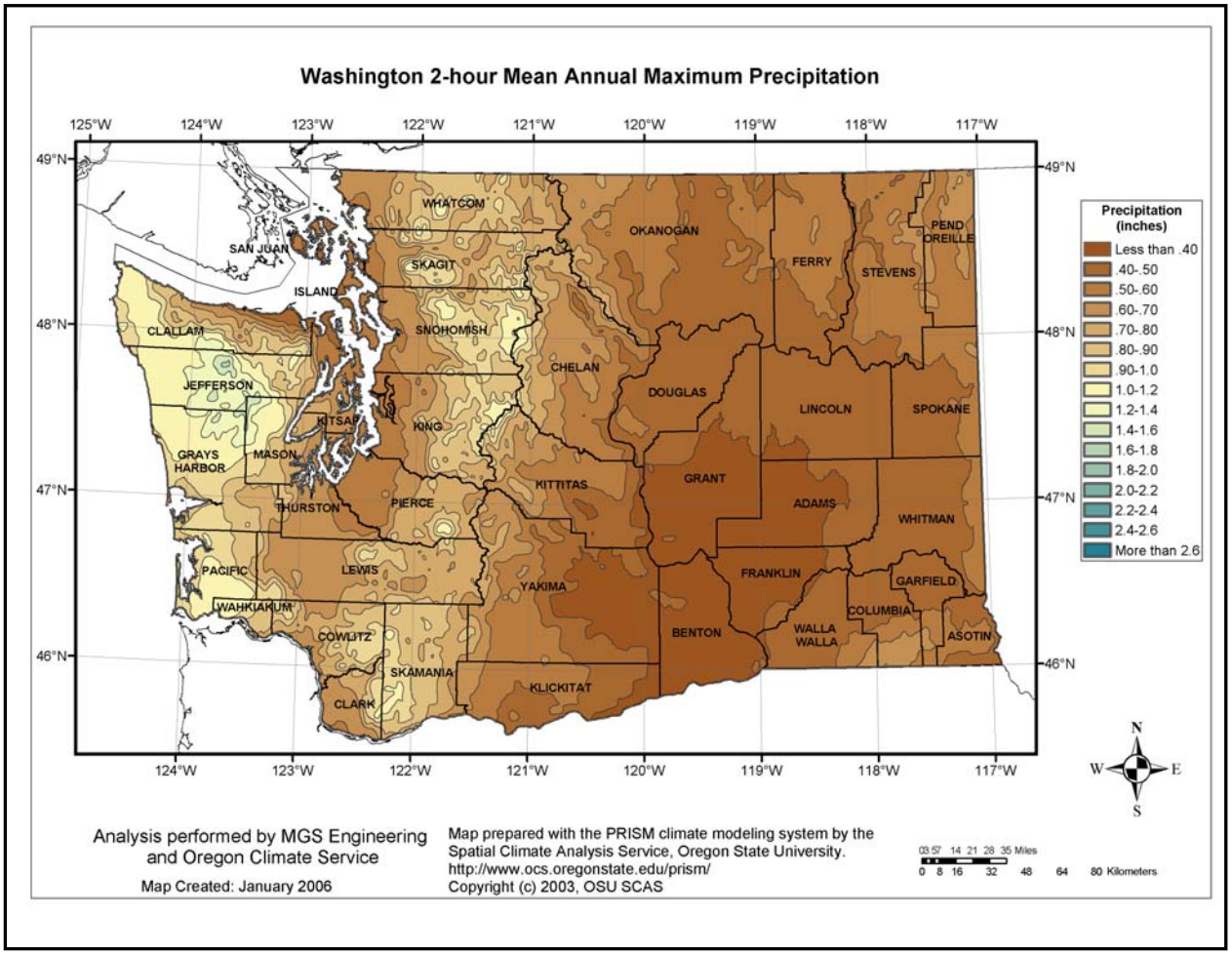


Figure 17b – Map of At-Site Means (Mean Annual Maxima) for 2-Hour Duration for Washington Study Area

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 the 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 (Helsel and Hirsch[6]) 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 Station At-Site Means for 24-Hour Duration

WESTERN WASHINGTON	FINAL MAPPED VALUES	
	Bias	***RMSE***
Region 5 – Coastal Lowlands	-0.6%	3.8%
Region 151 – Windward Faces Coastal Mountains	+1.1%	4.0%
Region 142 – Leeward Areas Coastal Mountains	+2.9%	6.9%
Region 32 – Interior Lowlands - West	-0.6%	8.1%
Region 31 – Interior Lowlands - East	-0.6%	4.0%
Region 15 – West Face of Cascade Mountains	-0.5%	5.6%
EASTERN WASHINGTON		
Region 14 – East Face of Cascade Mountains	-0.0%	5.0%
Zone 147 – Transition Zone Cascade Foothills	+1.2%	5.6%
Region 77 – Central Basin	+0.0%	2.9%
Region 7 – Okanogan, Spokane, Palouse	-0.1%	3.4%
Region 13 – Eastern Mountains	+0.0%	4.8%
All Regions	**+0.1%**	**4.9%**

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

WESTERN WASHINGTON	FINAL MAPPED VALUES	
	Bias	***RMSE***
Region 5 – Coastal Lowlands	+0.2%	2.3%
Region 151 – Windward Faces Coastal Mountains	+1.5%	7.8%
Region 142 – Leeward Areas Coastal Mountains	-1.2%	2.5%
Region 32 – Interior Lowlands - West	-0.4%	2.8%
Region 31 – Interior Lowlands - East	-0.8%	3.9%
Region 15 – West Face of Cascade Mountains	-0.9%	3.7%
EASTERN WASHINGTON		
Region 14 – East Face of Cascade Mountains	-0.5%	4.6%
Zone 147 – Transition Zone Cascade Foothills	-0.1%	3.4%
Region 77 – Central Basin	+0.1%	6.7%
Region 7 – Okanogan, Spokane, Palouse	+0.9%	5.1%
Region 13 – Eastern Mountains	-1.5%	5.3%
All Regions	**-0.5%**	**4.5%**

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 3 and 4) developed in the regional precipitation-frequency analysis. Population of the grid-cells within transition zones 154 and 147 was accomplished as a weighted average of the L-moment ratio values had the grid-cell been located in the adjoining climatic regions. The weights were based on the nearness of a given grid-cell to the boundaries of the transition zone. This provided continuity at the region boundaries and a smooth transition between region boundaries within the transition zones.

Color-shaded maps of L-Cv and L-Skewness values are depicted in Figures 18a,b and 19a,b for the 24-hour and 2-hour durations, respectively. Separate gridded data files are included as electronic files with this report (Appendix A).

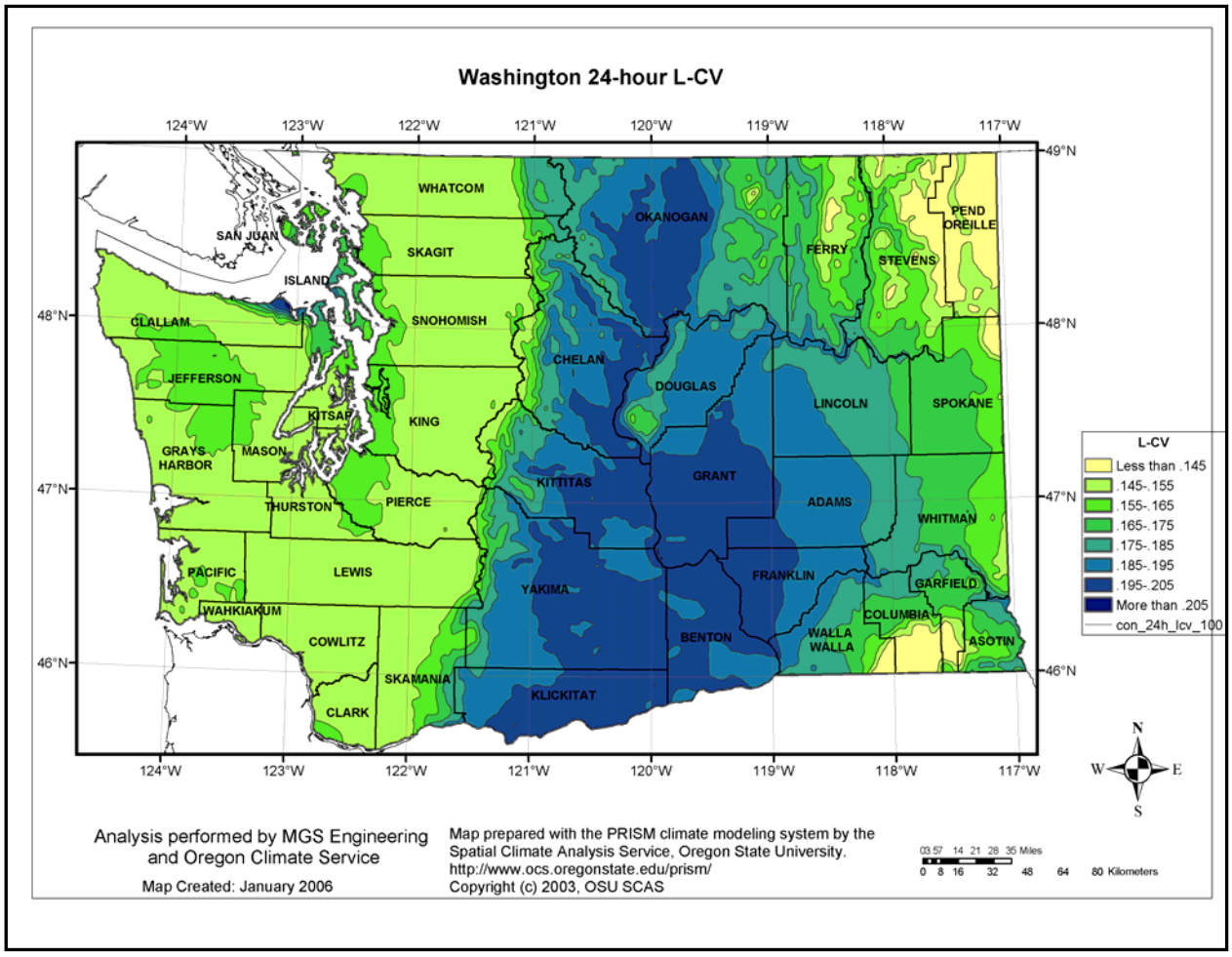


Figure 18a – Statewide Variation of L-Cv for 24-Hour Precipitation Annual Maxima

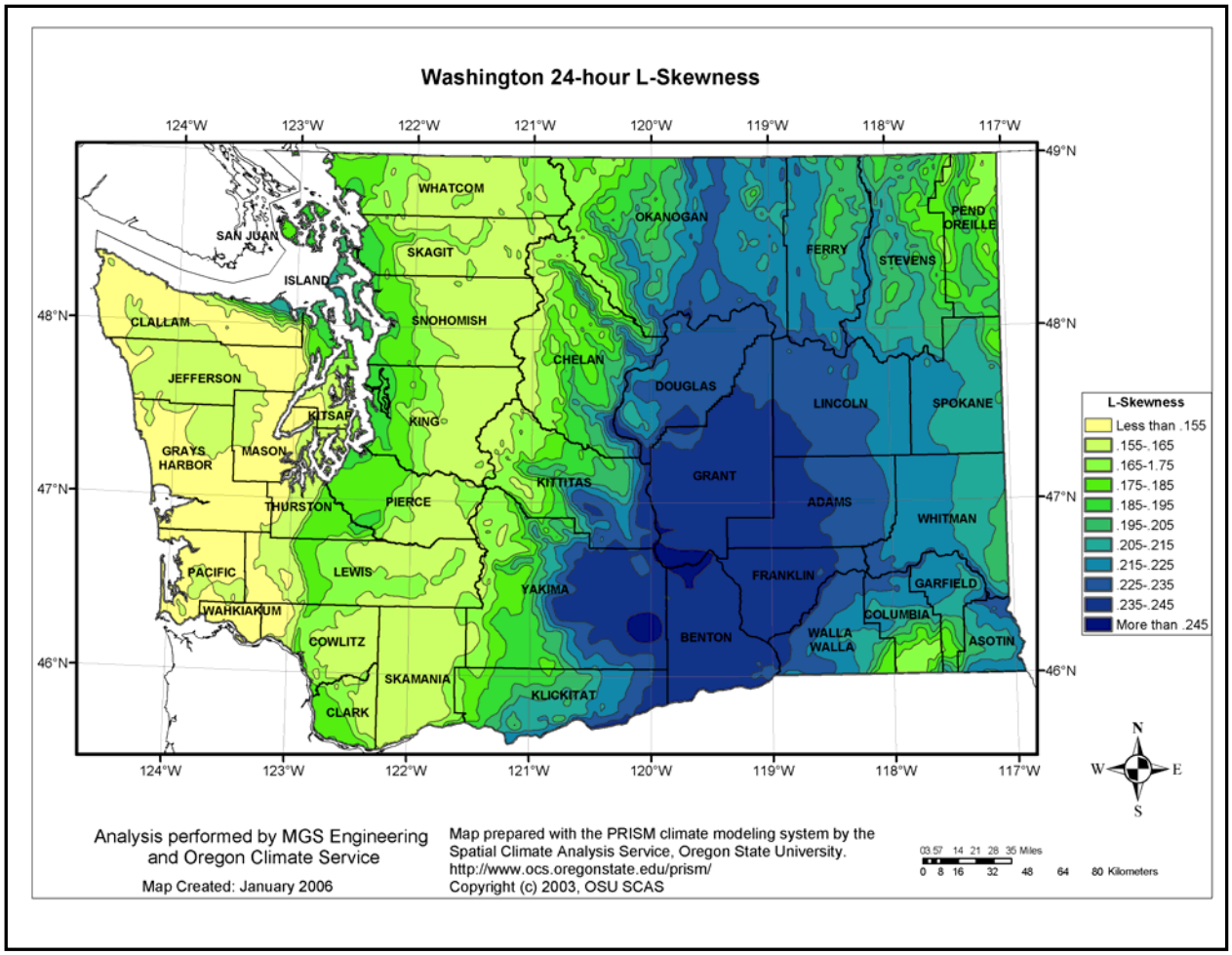


Figure 18b – Statewide Variation of L-Skewness for 24-Hour Precipitation Annual Maxima

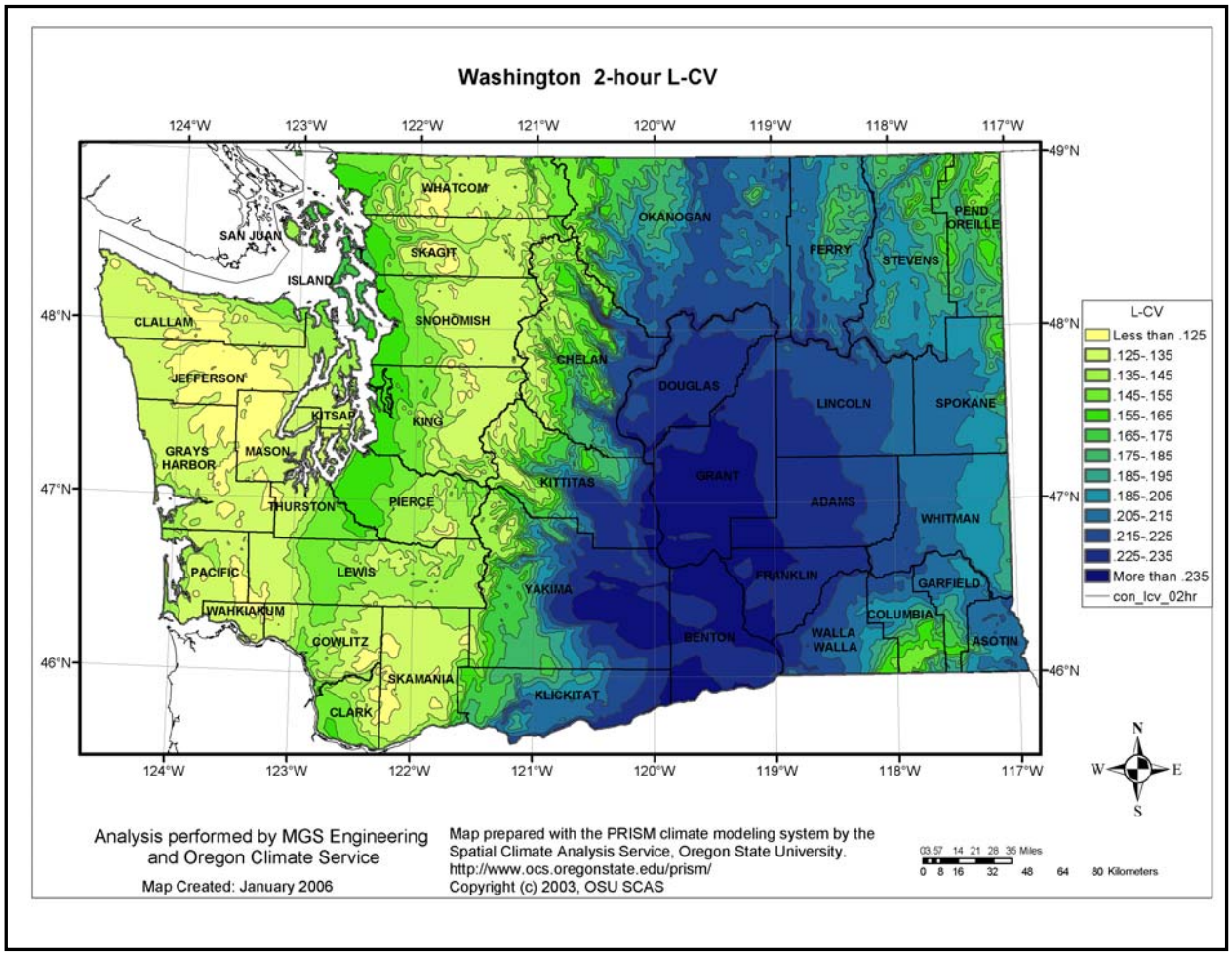


Figure 19a – Statewide Variation of L-Cv for 2-Hour Precipitation Annual Maxima

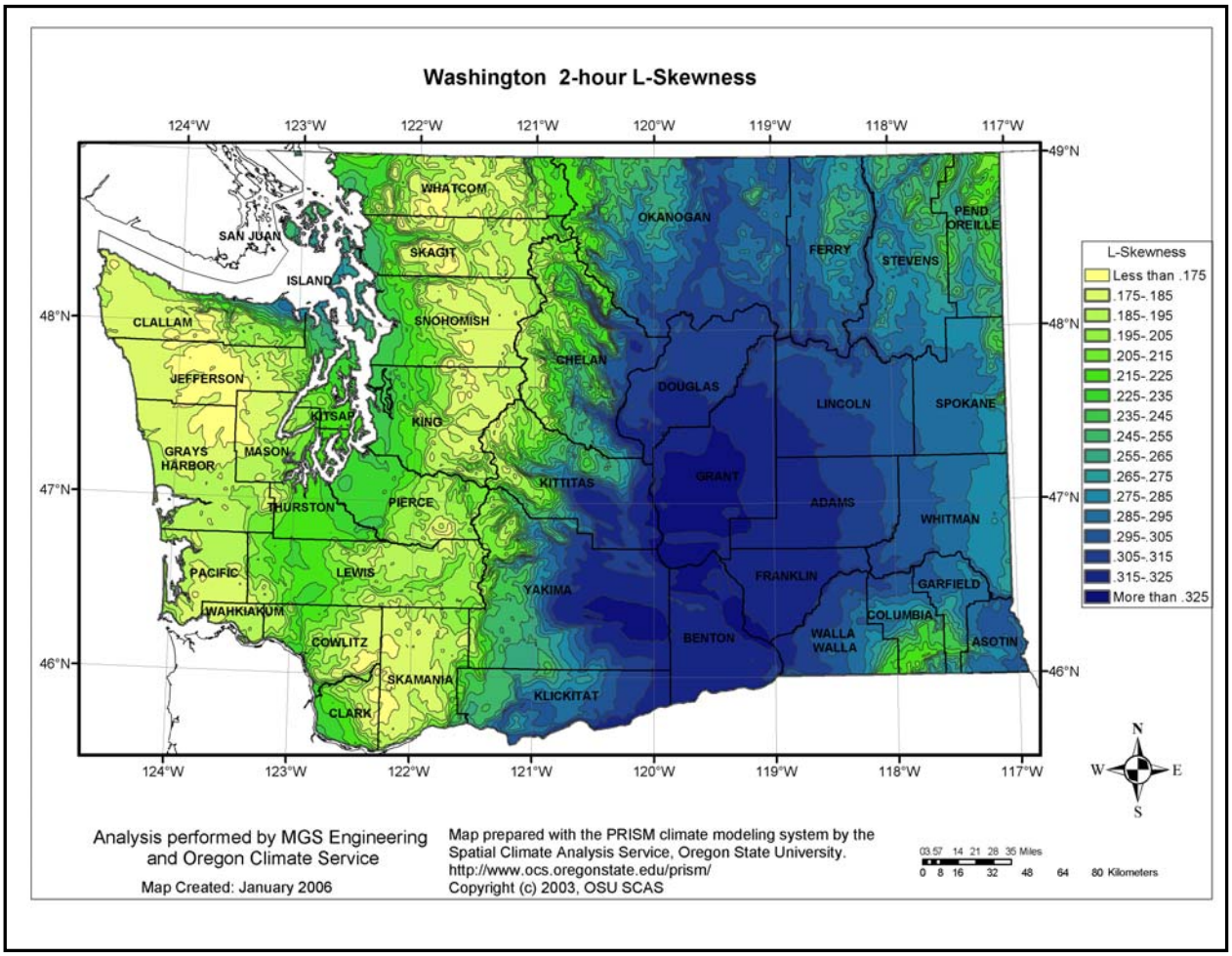


Figure 19b – Statewide Variation of L-Skewness for 2-Hour Precipitation Annual Maxima

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 20, 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. 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. Additional information on areal reduction factors can be found in articles by Bell[1], Meyers and Zehr[17], and Siriwardena and Weinmann[30].

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.

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%	7% - 10%
24-HOUR	4% - 7%	7% - 10%

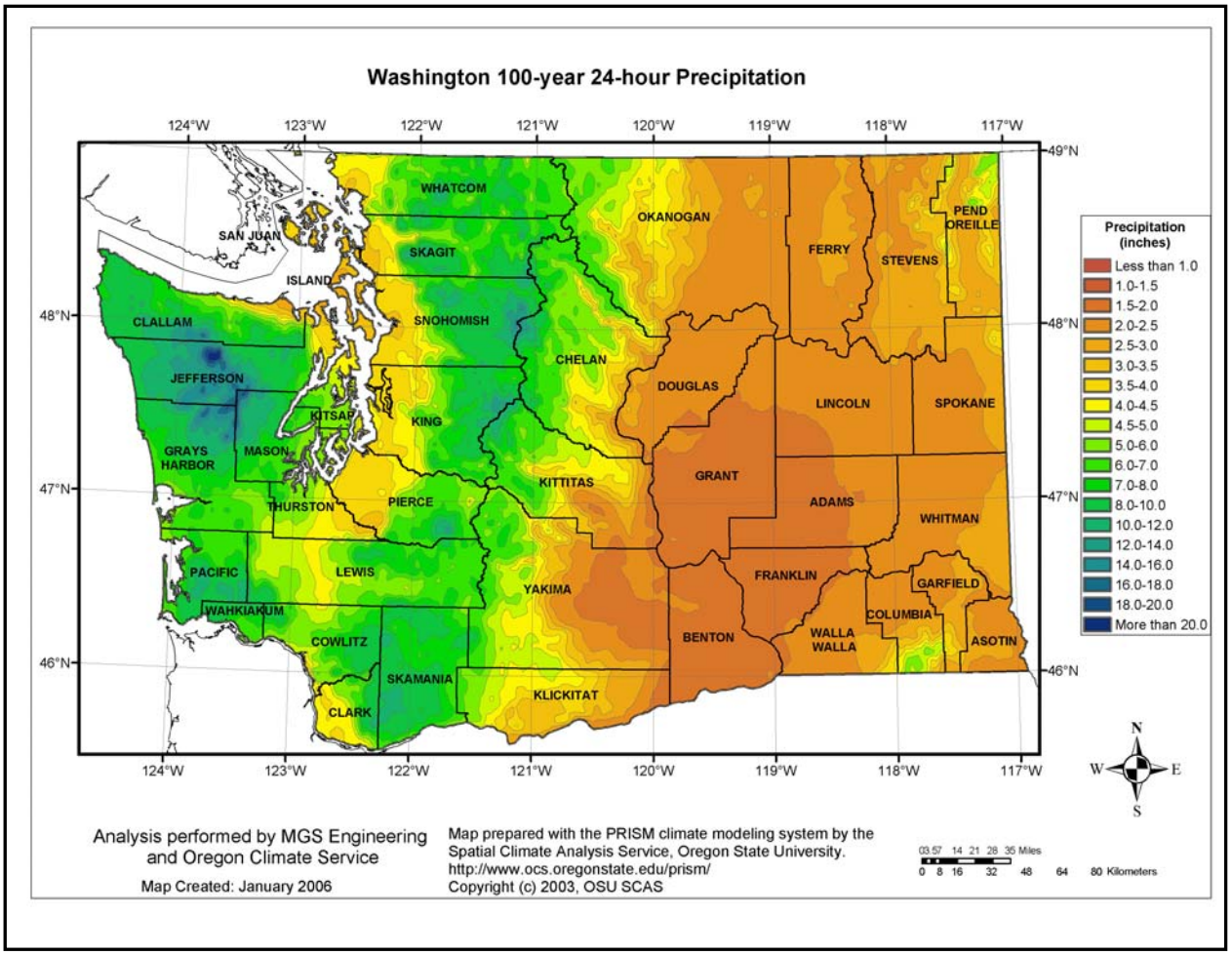


Figure 20 – Isopluvial Map of 24-Hour Precipitation for 100-Year Recurrence Interval for Washington State

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 four climatic regions (14, 77, 7, 13). 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 about 3 calendar days) were removed before constructing the frequency histograms for each climatic region. The results of the seasonality analyses are discussed below.

Seasonality of 24-Hour Extreme Events

Well-defined seasonal patterns are apparent for storms that are rare at the 24-hour duration on the east slopes of the Cascade Mountains (Figure 21a). 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. There is a rapid transition in seasonality of storms at the foothills of the Cascade Mountains into the Central Basin where arid and semi-arid Regions 77 and 7 show both a winter and spring-summer seasonality pattern (Figure 21b). It should be noted that the spring-summer period has the greater proportion of extreme storms in these arid and semi-arid areas.

The mountainous areas in northeastern and southeastern Washington show a bi-modal seasonality pattern (Figure 21c) with both winter and spring-summer periods have a similar proportion of extreme storms at the 24-hour duration.

Seasonality of 2-Hour Extreme Events

Storms which are extreme at the 2-hour duration have distinctively different seasonality patterns on the east slopes of the Cascade Mountains versus areas further east. Extreme storms on the east slopes of the Cascades have a bi-modal pattern with extreme storms occurring in both the winter and summer seasons at the 2-hour duration (Figure 22a). 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 storm events and are associated with large-scale weather systems having more widespread areal coverage.

Further east, the vast majority of extreme storms occur in the late-spring and summer season (Figures 22b,c). These storm events are typically associated with localized thunderstorms that may or may not be associated with an organized weather system.

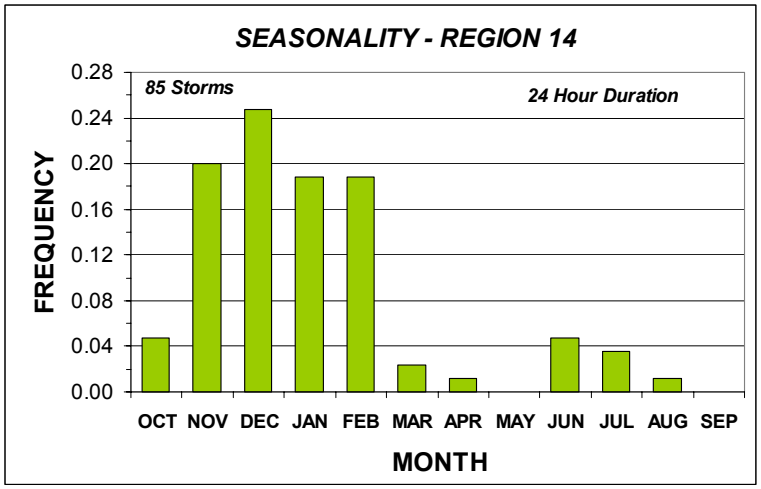


Figure 21a – Seasonality of Extreme Storms in Region 14 for the 24-Hour Duration
(East Slopes Cascade Mountains)

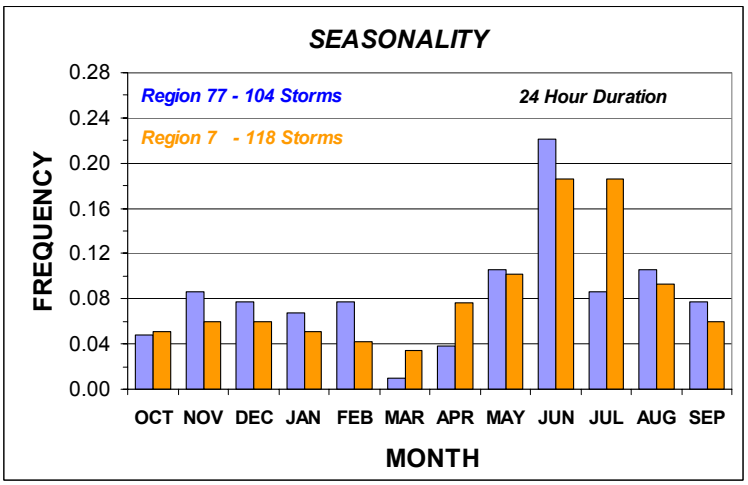


Figure 21b – Seasonality of Extreme Storms in Region 77 and Region 7 for the 24-Hour Duration
(Central Basin and Okanogan, Spokane, Palouse)

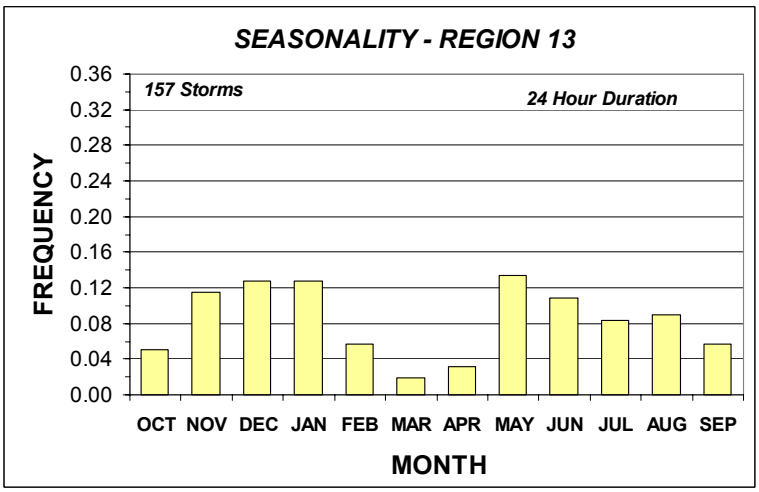


Figure 21c – Seasonality of Extreme Storms in Region 13 for the 24-Hour Duration
(Northeastern and Blue Mountains)

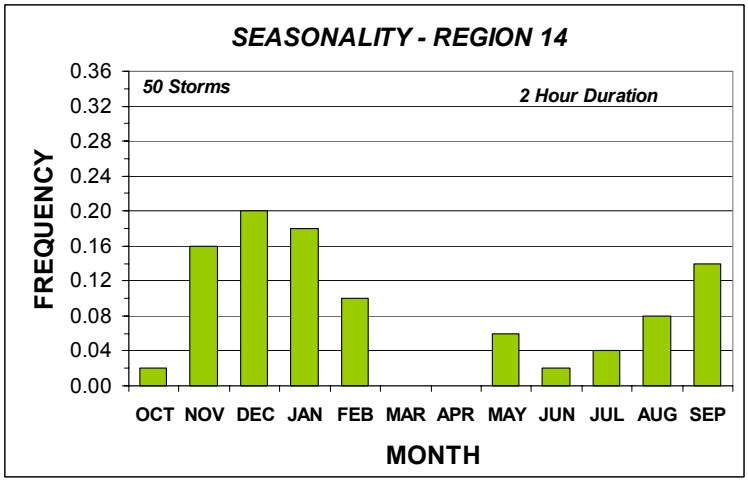


Figure 22a – Seasonality of Extreme Storms in Region 14 for the 2-Hour Duration (East Slopes Cascade Mountains)

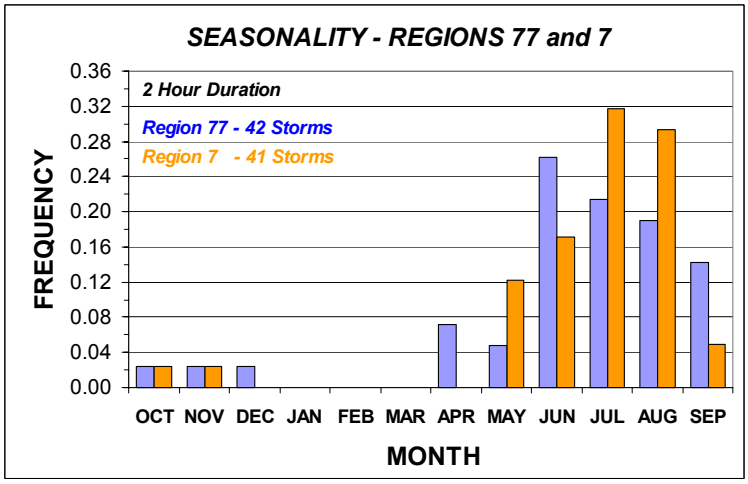


Figure 22b – Seasonality of Extreme Storms in Regions 77 and 7 for the 2-Hour Duration (Central Basin and Okanogan, Spokane, Palouse)

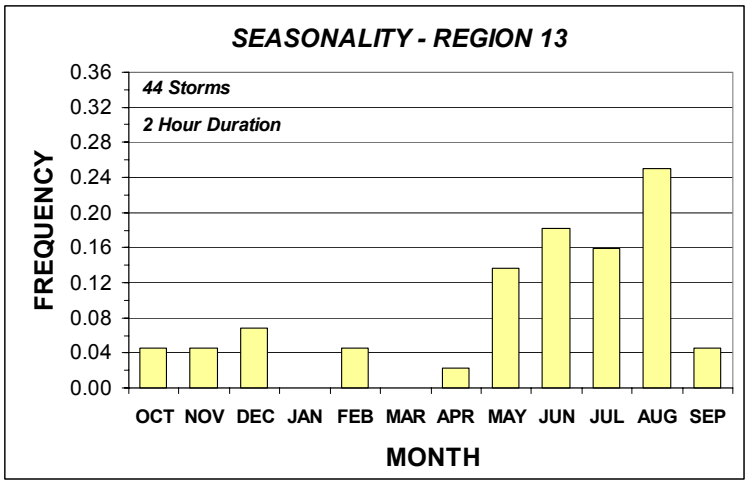


Figure 22c – Seasonality of Extreme Storms in Region 13 for the 2-Hour Duration (Northeastern and Blue Mountains)

CATALOG OF EXTREME STORMS

A catalog of extreme storms is contained in Appendix C. 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. Bell FC, The Areal Reduction Factors in Rainfall-Frequency Estimation, Natural Environmental Research Council, (NERC), Report 35, Institute of Hydrology, Wallingford UK, 1976.
2. Cunnane C, Unbiased Plotting Positions - A Review, Journal of Hydrology, 37, 205-222, 1978. **
3. Dalrymple D, Flood Frequency Analysis, USGS, Water Supply Paper 1543-A, 1960.
4. Daly C, PRISM, Parameter-Elevation Regression on Independent Slopes Model, Oregon State University, Oregon Climate Service, 1994.
5. 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.
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. 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.

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 United States, prepared with PRISM Model for NRCS, Corvallis Oregon, 2005.

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, Stochastic Modeling of Extreme Floods for A.R. Bowman Dam, MGS Engineering Consultants, November 1997.

27. 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.

28. 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.

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

30. 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.

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

32. 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.
33. Wallis JR, Hydrologic Problems Connected with Oil-Shale Development, Environmental Systems and Management, S. Rinaldi, Editor, North Holland, Amsterdam, pp. 85-102, 1982.
34. Weiss LL, Ratio of True to Fixed Interval Maximum Rainfall, Journal Hydraulics, ASCE, 90(HY1), pp77-82, 1964.

** related subjects not referenced in report or appendices

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[4,20] (in)
1100120	AGASSIZ CDA	BC	49.2500	121.7667	49	1889	1995	107	14	DY	67.6
45-0184	ANATONE	WA	46.1333	117.1333	3573	1948	1982	35	13	DY	20.1
45-0217	APPLETON	WA	45.8167	121.2667	2334	1960	1985	26	14	DY	33.3
19D02S	ARBUCKLE MTN	OR	45.1833	119.2500	5400	1979	2002	24	13	DY	35.2
35-0265	ARLINGTON	OR	45.7167	120.2000	277	1948	2003	56	147	HR	9.2
45-0294	ASOTIN 14 SW	WA	46.2000	117.2500	3500	1976	2003	28	13	DY	16.6
10-0667	BAYVIEW MODEL BASIN	ID	47.9667	116.5667	2075	1948	2003	56	13	DY	25.5
16A08S	BEAR MOUNTAIN	ID	48.3000	116.0833	5400	1982	2002	21	13	DY	90.0
35-0571	BEAR SPRINGS RS	OR	45.1167	121.5333	3360	1961	2003	43	14	HR	31.5
18D09S	BEAVER RESERVOIR	OR	45.1333	118.2167	5150	1981	2002	22	13	DY	31.6
1130770	BEAVERDELL	BC	49.4167	119.1000	2559	1925	1982	58	7	DY	17.8
1130771	BEAVERDELL NORTH	BC	49.4833	119.0500	2749	1975	1995	21	7	DY	18.8
45-0628	BENTON CITY 2 NW	WA	46.2833	119.5000	679	1938	1964	27	77	DY	8.5
10-0789	BENTON DAM	ID	48.3500	116.8000	2641	1948	1977	30	13	HR	36.3
45-0668	BICKLETON	WA	45.9833	120.3000	3015	1927	2003	77	14	DY	13.7
20B02S	BLEWETT PASS	WA	47.3500	120.6833	4270	1982	2002	21	14	DY	33.6
35-0858	BOARDMAN	OR	45.8333	119.7000	300	1971	2003	33	77	DY	8.5
10-1079	BONNERS FERRY	ID	48.6833	116.3167	1770	1907	2003	97	13	DY	22.7
1140905	BOSWELL	BC	49.4833	116.7500	1879	1911	1940	30	13	DY	19.7
45-0839	BOUNDARY	WA	49.0000	117.6333	1391	1941	1959	19	13	HR	23.5
45-0849	BOUNDARY SWITCHYARD	WA	48.9667	117.3500	2500	1971	2003	33	13	HR	28.5
16D09S	BRUNDAGE RESERVOIR	ID	45.0500	116.1333	6300	1987	2002	16	13	DY	51.4
45-0969	BUMPING LAKE	WA	46.8667	121.3000	3440	1910	1966	57	14	DY	49.4
21C38S	BUMPING RIDGE	WA	46.8167	121.3333	4600	1979	2002	24	14	DY	63.1
17A01S	BUNCHGRASS MDW	WA	48.6833	117.1667	5000	1984	2002	19	13	DY	51.2
10-1363	CABINET GORGE	ID	48.0833	116.0500	2260	1957	2003	47	13	DY	31.9
10-1370	CALDER	ID	47.2667	116.1833	2096	1971	2003	33	13	HR	30.7
1131410	CARMI	BC	49.5000	119.0833	4084	1939	1969	31	7	DY	22.1
45-1160	CARSON FISH HATCHERY	WA	45.8667	121.9667	1134	1977	2000	24	14	HR	90.4
1141455	CASTLEGAR A	BC	49.3000	117.6333	1623	1965	1995	31	13	DY	28.8
1141457	CASTLEGAR BCHPA DAM	BC	49.3500	117.7833	1561	1969	1995	27	13	DY	23.5
45-1257	CENTERVILLE 2 SW	WA	45.7333	120.9500	1650	1941	1956	16	14	HR	16.1
45-1350	CHELAN	WA	47.8167	120.0333	1120	1939	2003	65	147	DY	13.0
45-1362	CHENEY	WA	47.4833	117.5833	2402	1939	1956	18	7	DY	17.9
45-1381	CHESAW	WA	48.9500	119.0500	2871	1939	1959	21	7	DY	15.3
45-1395	CHEWELAH	WA	48.2667	117.7167	1670	1926	2003	78	13	DY	21.7
45-1400	CHIEF JOSEPH DAM	WA	47.9833	119.6500	820	1951	2003	53	77	HR	11.1
1101530	CHILLIWACK	BC	49.1667	121.9333	19	1896	1995	100	14	DY	70.7
45-1426	CHIWAWA RIVER	WA	48.0333	120.8333	2713	1935	1958	24	14	DY	58.5
21D13S	CLACKAMAS LAKE	OR	45.0833	121.7500	3400	1981	2002	22	14	DY	55.1
10-1831	CLARKIA RANGER STATI	ID	47.0000	116.2500	2860	1948	2001	54	13	HR	38.9
45-1504	CLE ELUM	WA	47.1833	120.9333	1920	1901	2003	103	14	DY	23.6
21D12S	CLEAR LAKE	OR	45.2000	121.7167	3500	1981	2002	22	14	DY	60.9
10-1956	COEUR D'ALENE	ID	47.6667	116.8000	2133	1909	2003	95	13	DY	26.1
45-1586	COLFAX	WA	46.8833	117.3500	1980	1933	1994	62	7	DY	19.8
1141800	COLUMBIA GARDENS	BC	49.0500	117.6000	1420	1937	1970	34	13	DY	26.0
45-1630	COLVILLE	WA	48.5333	117.9000	1657	1901	2003	103	13	DY	19.4
45-1666	CONCONULLY	WA	48.5333	119.7333	2320	1901	2003	103	14	DY	14.8
35-1765	CONDON	OR	45.2167	120.1667	2840	1928	2003	76	7	DY	14.1
45-1690	CONNELL 1 W	WA	46.6500	118.8667	1020	1960	2003	44	77	HR	8.8
45-1691	CONNELL 12 SE	WA	46.5000	118.7833	1078	1951	2003	53	77	DY	10.2
35-1852	CORNUCOPIA	OR	45.0000	117.2000	4705	1950	1973	24	13	DY	48.1
21B13S	CORRAL PASS	WA	47.0167	121.4667	6000	1982	2002	21	14	DY	63.6
10-2159	COTTONWOOD 2 WSW	ID	46.0333	116.3833	3945	1948	2003	56	13	HR	22.5
45-1767	COULEE DAM 1 SW	WA	47.9500	119.0000	1700	1936	2003	68	77	DY	11.1
18D08S	COUNTY LINE	OR	45.1833	118.5333	4800	1981	2002	22	13	DY	24.6
35-1926	COVE 1 E	OR	45.2833	117.7833	3130	1948	2002	55	13	DY	24.1
10-2246	CRAIGMONT	ID	46.2333	116.4833	3750	1980	1996	17	13	DY	22.4
1142130	CRESCENT VALLEY	BC	49.4500	117.5667	2001	1939	1965	27	13	DY	30.9
1142160	CRESTON	BC	49.1000	116.5167	1958	1912	1995	84	13	DY	23.4
1142164	CRESTON WPCC	BC	49.1000	116.5333	1765	1980	1995	16	13	DY	23.6
1102220	CULTUS LAKE	BC	49.0833	121.9833	150	1931	1994	64	14	DY	62.7
45-1972	DALLESPORT 10N	WA	45.7500	121.1500	1919	1951	1980	30	14	DY	23.7
45-1968	DALLESPORT 1N CAA AP	WA	45.6167	121.1500	222	1944	1985	42	14	DY	14.3
45-2007	DAVENPORT	WA	47.6500	118.1333	2440	1909	2003	95	7	DY	14.2
45-2030	DAYTON 1 WSW	WA	46.3000	118.0000	1557	1931	2003	73	7	DY	19.6
45-2037	DAYTON 9 SE	WA	46.2167	117.8500	2343	1940	1977	38	13	HR	32.7
1142400	DEER PARK	BC	49.4167	118.0500	1591	1924	1995	72	13	DY	20.0
45-2066	DEER PARK 2 E	WA	47.9667	117.4333	2201	1912	1977	66	13	DY	22.6
45-2157	DIABLO DAM	WA	48.7000	121.1333	891	1944	2003	60	14	HR	84.3
45-2175	DISAUTEL 9 NE	WA	48.4333	119.1000	3491	1953	1979	27	7	DY	16.3
45-2197	DIXIE 4 SE	WA	46.0833	118.1000	2250	1940	2003	64	13	HR	39.6

STATION ID	STATION NAME	STATE	LAT	LONG	ELEV (ft)	YEAR START	YEAR END	YEARS OPEN	RGN	GAGE TYPE	PRISM MAP[4,20] (in)
35-2440	DUFUR	OR	45.4500	121.1167	1330	1928	2003	76	14	DY	13.5
10-2845	DWORSHAK FISH HATCHE	ID	46.5000	116.3167	995	1967	2003	37	13	HR	25.4
45-2384	EASTON	WA	47.2333	121.1833	2170	1941	2003	63	14	HR	49.7
35-2564	ECHO	OR	45.7500	119.1833	659	1948	1971	24	77	DY	10.6
35-2597	ELGIN	OR	45.5500	117.9167	2655	1948	2003	56	13	DY	23.9
16C20S	ELK BUTTE	ID	46.8500	116.1167	5690	1983	2002	20	13	DY	63.3
10-2892	ELK RIVER 1 S	ID	46.7667	116.1667	2918	1952	2003	52	13	DY	36.8
45-2505	ELLENSBURG	WA	46.9667	120.5333	1480	1901	2003	103	147	DY	9.1
45-2542	ELTOPIA 8 WSW	WA	46.3833	119.1500	700	1954	2003	50	77	DY	8.8
18D04S	EMIGRANT SPRINGS	OR	45.5500	118.4500	3925	1981	2002	22	13	DY	35.4
10-2966	ENAVILLE	ID	47.5500	116.2500	2120	1972	2003	32	13	HR	27.7
45-2563	ENTIAT FISH HATCHERY	WA	47.6833	120.3167	960	1989	2003	15	147	DY	13.2
45-2609	EPHRATA	WA	47.3167	119.5667	1362	1931	1971	41	77	DY	8.3
45-2614	EPHRATA AIRPORT	WA	47.3000	119.5000	1250	1950	2003	54	77	DY	7.6
45-2706	EWAN	WA	47.1167	117.7333	1722	1940	1974	35	7	DY	16.0
21B04S	FISH LAKE	WA	47.5167	121.0667	3371	1982	2002	21	14	DY	66.3
35-3121	FRIEND 1 W	OR	45.3500	121.2667	2441	1949	1976	28	14	DY	16.6
45-3183	GLENWOOD	WA	46.0167	121.2833	1896	1941	2003	63	14	HR	32.6
45-3222	GOLDENDALE	WA	45.8167	120.8167	1657	1906	2003	98	14	DY	16.3
1133270	GRAND FORKS	BC	49.0333	118.4667	1745	1910	1995	86	7	DY	19.3
10-3771	GRANGEVILLE	ID	45.9167	116.1167	3350	1948	2003	56	13	DY	25.0
21C10S	GREEN LAKE	WA	46.5500	121.1667	6000	1983	2002	20	14	DY	37.9
21D01S	GREENPOINT	OR	45.6167	121.7000	3200	1980	2002	23	14	DY	68.6
1133300	GREENWOOD	BC	49.1000	118.6833	2503	1911	1977	67	7	DY	17.1
20B11S	GROUSE CAMP	WA	47.2667	120.4833	5380	1983	2002	20	14	DY	31.2
35-3644	HARDMAN	OR	45.1667	119.6833	3583	1962	1975	14	7	DY	15.6
45-3515	HARRINGTON 1 NW	WA	47.4833	118.2500	2190	1942	2003	62	77	HR	13.6
45-3502	HARRINGTON 5 S	WA	47.4167	118.2500	2172	1923	1982	60	77	DY	13.3
45-3529	HARTLINE	WA	47.6833	119.1000	1910	1927	2003	77	77	DY	10.7
20A05S	HARTS PASS	WA	48.7167	120.6500	6500	1984	2002	19	14	DY	52.1
45-3546	HATTON 9 SE	WA	46.7167	118.6500	1510	1918	2003	86	77	DY	10.2
35-3827	HEPPNER	OR	45.3500	119.5500	1885	1928	2003	76	7	DY	14.3
35-3830	HEPPNER 5 SSE	OR	45.2833	119.5167	3240	1975	2003	29	7	HR	15.9
35-3847	HERMISTON 1 SE	OR	45.8167	119.2500	640	1928	2003	76	77	DY	9.7
18D19S	HIGH RIDGE	OR	45.6833	118.1000	4980	1979	2002	24	13	DY	50.8
45-3730	HOLDEN VILLAGE	WA	48.1833	120.7667	3220	1938	2003	66	14	DY	45.7
35-4003	HOOD RIVER EXP STN	OR	45.6833	121.5167	500	1928	2003	76	14	DY	30.7
35-4008	HOOD RIVER TUCKER BR	OR	45.6500	121.5333	383	1941	2003	63	14	HR	32.0
1113540	HOPE A	BC	49.3667	121.4833	127	1934	1995	62	14	DY	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
45-3883	ICE HARBOR DAM	WA	46.2333	118.8667	368	1957	2003	47	77	DY	10.4
45-3903	INCHELIUM 2 NW	WA	48.3167	118.2167	1690	1953	1975	23	7	DY	17.0
35-4161	IONE 18 S	OR	45.3167	119.8500	2130	1948	2003	56	7	DY	12.6
45-3975	IRENE MOUNTAIN WAUCO	WA	48.8167	118.9000	2703	1909	1988	80	7	DY	14.7
45-4035	JOHN DAY DAM	WA	45.7167	120.7000	190	1959	1972	14	14	HR	10.5
45-4077	KAHLOTUS 5 SSW	WA	46.5833	118.6000	1552	1936	1996	61	77	DY	10.7
10-4793	KAMIAH	ID	46.2167	116.0333	1230	1948	2003	56	13	DY	24.2
10-4831	KELLOGG	ID	47.5167	116.1167	2320	1905	2003	99	13	DY	40.4
45-4154	KENNEWICK	WA	46.2000	119.1000	390	1946	2003	58	77	DY	7.8
45-4159	KENNEWICK 10 SW	WA	46.1333	119.3000	1503	1950	1974	25	77	DY	9.9
35-4411	KENT	OR	45.1833	120.6833	2710	1948	2003	56	77	DY	12.5
1124112	KEREMEOS 2	BC	49.2167	119.8167	1427	1924	1995	72	147	DY	11.9
1144230	KINGSGATE	BC	49.0000	116.1833	2690	1924	1962	39	13	DY	30.2
35-4622	LA GRANDE	OR	45.3167	118.0667	2755	1948	2003	56	13	DY	17.0
45-4338	LACROSSE	WA	46.8000	117.8667	1450	1931	2003	73	7	DY	14.9
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	37.2
45-4406	LAKE KACHESS	WA	47.2667	121.2000	2270	1908	1977	70	14	DY	51.3
45-4414	LAKE KEECHELUS	WA	47.3167	121.3333	2480	1908	1977	70	14	DY	64.8
45-4446	LAKE WENATCHEE	WA	47.8333	120.7833	2005	1914	2003	90	14	DY	34.3
45-4549	LAURIER	WA	49.0000	118.2333	1644	1910	1987	78	13	DY	20.7
45-4572	LEAVENWORTH 3 S	WA	47.5500	120.6667	1128	1914	2003	90	14	DY	25.7
45-4601	LEMANASKY LAKE 3	WA	48.7167	119.6167	3500	1935	1959	25	14	DY	20.7
10-5241	LEWISTON AP	ID	46.3667	117.0000	1436	1950	2003	54	7	HR	17.1
45-4679	LIND 3 NE	WA	46.9833	118.5667	1630	1931	2003	73	77	DY	10.0
45-4702	LITTLE GOOSE DAM	WA	46.5833	118.0333	702	1964	1979	16	7	DY	12.6
21C39S	LOST HORSE	WA	46.3500	121.1167	5000	1991	2002	12	14	DY	34.8
15B14S	LOST LAKE	ID	47.0833	115.9667	6110	1982	2002	21	13	DY	79.0
45-4849	LUCERNE 1 N	WA	48.2333	120.6000	1200	1942	1989	48	14	HR	22.8
18D06S	LUCKY STRIKE	OR	45.2833	118.8500	5050	1979	2002	24	13	DY	28.2
20A23S	LYMAN LAKE	WA	48.2000	120.9167	5900	1980	2002	23	14	DY	80.7
1134735	LYNCH CREEK	BC	49.2500	118.4333	1801	1924	1948	25	7	DY	18.4
19D03S	MADISON BUTTE	OR	45.1000	119.5000	5250	1981	2002	22	13	DY	22.2
45-4971	MANSFIELD	WA	47.8167	119.6333	2270	1926	1978	53	77	DY	11.6
45-5133	MAZAMA	WA	48.6000	120.4333	2170	1942	2003	62	14	HR	22.2
45-5128	MAZAMA 6 SE	WA	48.5333	120.3333	1962	1936	1977	42	14	DY	20.9

STATION ID	STATION NAME	STATE	LAT	LONG	ELEV (ft)	YEAR START	YEAR END	YEARS OPEN	RGN	GAGE TYPE	PRISM MAP[4,20] (in)
45-5231	MCNARY DAM	WA	45.9333	119.2833	361	1955	2003	49	77	DY	8.3
35-5396	MEACHAM WSO AIRPORT	OR	45.5000	118.4000	4050	1948	1976	29	13	HR	33.4
45-5317	METALINE FALLS	WA	48.8667	117.3667	2113	1926	1965	40	13	DY	29.4
45-5326	METHOW 2 S	WA	48.1000	120.0000	1150	1957	2003	47	147	DY	13.5
16B14S	MICA CREEK	ID	47.1500	116.2667	4750	1991	2002	12	13	DY	55.7
35-5545	MIKKALO 6 W	OR	45.4667	120.3500	1550	1948	1995	48	77	DY	10.9
45-5377	MILL CREEK	WA	46.0167	118.1167	2001	1926	1973	48	13	DY	45.8
45-5387	MILL CREEK DAM	WA	46.0667	118.2667	1175	1948	2003	56	7	DY	19.9
35-5593	MILTON FREEWATER	OR	45.9333	118.4000	970	1928	2003	76	7	DY	16.4
35-5610	MINAM 7 NE	OR	45.6833	117.6000	3615	1956	1985	30	13	DY	26.9
20A40S	MINERS RIDGE	WA	48.1667	120.9833	6200	1989	2002	14	14	DY	75.8
35-5726	MORGAN 3 NE	OR	45.5833	119.8833	951	1948	1980	33	77	DY	9.5
35-5734	MORO	OR	45.4667	120.7167	1870	1928	2003	76	147	DY	11.6
21C17S	MORSE LAKE	WA	46.9000	121.4833	5400	1979	2002	24	14	DY	80.0
10-6148	MOSCOW 5 NE	ID	46.7833	116.9167	3000	1972	2003	32	13	HR	31.9
10-6152	MOSCOW U OF I	ID	46.7167	116.9500	2660	1894	2003	110	13	DY	28.0
45-5613	MOSES LAKE 3 E	WA	47.1167	119.2000	1211	1947	1987	41	77	DY	8.5
16A04S	MOSQUITO RIDGE	ID	48.0500	116.2333	5200	1982	2002	21	13	DY	57.6
17D06S	MOSS SPRINGS	OR	45.2667	117.6833	5850	1981	2002	22	13	DY	50.5
45-5659	MOUNT ADAMS RANGER S	WA	46.0000	121.5333	1960	1925	2003	79	14	DY	42.4
45-5674	MOUNT SPOKANE SUMMIT	WA	47.9167	117.1167	5892	1945	1973	29	13	DY	44.2
45-5688	MOXEE CITY 10 E	WA	46.5000	120.1500	1550	1901	2003	103	77	DY	8.3
17D18S	MT. HOWARD	OR	45.2667	117.1667	7910	1981	2002	22	13	DY	44.5
21D35S	MUD RIDGE	OR	45.2500	121.7333	3800	1979	2002	24	14	DY	68.7
45-5731	NACHES 10 NW	WA	46.8667	120.7667	2280	1944	2003	60	147	HR	17.7
1145445	NELSON 2	BC	49.5000	117.2833	1981	1904	1982	79	13	DY	26.0
45-5832	NESPELEM 2 S	WA	48.1333	118.9833	1890	1915	1991	77	7	DY	13.2
45-5840	NEWHALEM	WA	48.6833	121.2500	525	1926	2003	78	14	DY	79.6
45-5844	NEWPORT	WA	48.1833	117.0333	2135	1927	2003	77	13	DY	26.3
10-6424	NEZPERCE	ID	46.2333	116.2333	3240	1948	2003	56	13	DY	21.5
45-5946	NORTHPORT	WA	48.9000	117.7833	1350	1920	2003	84	13	DY	23.4
45-6039	ODESSA	WA	47.3167	118.6833	1530	1903	2003	101	77	DY	10.6
1145730	OLD GLORY MOUNTAIN	BC	49.1500	117.9167	7700	1947	1967	21	13	DY	28.3
1125760	OLIVER	BC	49.1667	119.5500	1033	1955	1995	41	7	DY	11.9
1125766	OLIVER STP	BC	49.1833	119.5500	974	1924	1995	72	7	DY	12.1
45-6123	OMAK 4 N	WA	48.4500	119.5167	1301	1909	2003	95	147	DY	13.0
10-6681	OROFINO	ID	46.4833	116.2667	1320	1948	1982	35	13	DY	24.7
45-6187	OROVILLE 1 S	WA	48.9333	119.4333	932	1941	1971	31	147	HR	14.4
45-6188	OROVILLE 3 NW	WA	48.9667	119.5000	1060	1940	1970	31	147	DY	13.0
1125850	OSOYOOS	BC	49.0333	119.4333	974	1954	1995	42	147	DY	12.0
45-6215	OTHELLO 6 ESE	WA	46.7833	119.0333	1190	1941	2003	63	77	DY	8.6
20A12S	PARK CREEK RIDGE	WA	48.4500	120.9167	4600	1979	2002	24	14	DY	71.2
35-6466	PARKDALE 1 NNE	OR	45.5333	121.5833	1520	1928	2003	76	14	DY	37.1
45-6400	PASCO	WA	46.2167	119.1000	350	1942	2003	62	77	HR	7.8
35-6540	PENDLETON BR EXP STN	OR	45.7167	118.6167	1487	1956	2003	48	7	DY	17.4
35-6546	PENDLETON MUNICIPAL	OR	45.6833	118.8500	1486	1928	2003	76	7	DY	13.0
1126150	PENTICTON A	BC	49.4667	119.6000	1128	1907	1996	90	7	DY	12.1
45-6472	PESHASTIN TELEMETERI	WA	47.5667	120.6167	1028	1971	2003	33	14	HR	19.7
21C33S	PIGTAIL PEAK	WA	46.6167	121.4167	5900	1982	2002	21	14	DY	67.8
35-6634	PILOT ROCK 1 SE	OR	45.4667	118.8167	1720	1948	2003	56	7	DY	15.0
35-6636	PILOT ROCK 11 E	OR	45.5000	118.6000	1920	1978	2003	26	13	HR	24.2
35-6655	PINE GROVE 5 ENE	OR	45.1167	121.2500	2059	1969	1998	30	14	DY	17.7
45-6534	PLAIN	WA	47.7667	120.6500	1940	1939	2003	65	14	DY	29.5
45-6553	PLEASANT VIEW	WA	46.5167	118.3333	1670	1937	1979	43	77	DY	13.4
10-7188	PLUMMER 3 WSW	ID	47.3000	116.9500	2920	1940	2003	64	13	HR	25.5
45-6610	POMEROY	WA	46.4667	117.5833	1900	1904	2003	100	7	DY	17.6
20B24S	POPE RIDGE	WA	47.9833	120.5667	3540	1982	2002	21	14	DY	32.9
10-7264	PORTHILL	ID	48.9833	116.5000	1775	1948	2003	56	13	DY	21.4
21C14S	POTATO HILL	WA	46.3000	121.5000	4500	1982	2002	21	14	DY	71.4
10-7301	POTLATCH 3 NNE	ID	46.9500	116.8667	2600	1915	2002	88	13	DY	26.2
45-6747	PRIEST RAPIDS DAM	WA	46.6333	119.9000	460	1957	2003	47	77	DY	7.3
10-7386	PRIEST RIVER EXP STN	ID	48.3500	116.8333	2380	1912	2003	92	13	DY	30.6
45-6768	PROSSER	WA	46.2000	119.7500	830	1913	2003	91	77	DY	8.8
45-6789	PULLMAN 2 NW	WA	46.7500	117.1833	2545	1940	2003	64	7	HR	21.2
17B04S	QUARTZ PEAK	WA	47.8667	117.0833	4700	1987	2002	16	13	DY	42.5
45-6880	QUINCY 1 S	WA	47.2000	119.8500	1274	1941	2003	63	77	DY	7.8
20A09S	RAINY PASS	WA	48.5500	120.7167	4780	1982	2002	21	14	DY	70.4
21D04S	RED HILL	OR	45.4667	121.7000	4400	1979	2002	24	14	DY	109.2
45-6974	REPUBLIC	WA	48.6333	118.7333	2610	1901	2003	103	7	DY	16.7
45-7015	RICHLAND	WA	46.3000	119.2500	373	1948	2003	56	77	DY	7.7
10-7706	RIGGINS	ID	45.4167	116.3000	1800	1940	2003	64	13	DY	17.9
45-7038	RIMROCK TIETON DAM	WA	46.6500	121.1333	2733	1917	1977	61	14	DY	25.6
45-7059	RITZVILLE 1 SSE	WA	47.1000	118.3667	1830	1901	2003	103	77	DY	11.9
1146810	ROBSON	BC	49.3333	117.7000	1450	1946	1980	35	13	DY	27.5
1136812	ROCK CREEK	BC	49.0667	119.0167	2001	1912	1947	36	7	DY	13.2
45-7180	ROSALIA	WA	47.2167	117.3667	2400	1948	2003	56	7	DY	18.8
1106865	ROSEDALE	BC	49.1833	121.8000	36	1967	1988	22	14	DY	65.1

STATION ID	STATION NAME	STATE	LAT	LONG	ELEV (ft)	YEAR START	YEAR END	YEARS OPEN	RGN	GAGE TYPE	PRISM MAP[4,20] (in)
45-7185	ROSS DAM	WA	48.7333	121.0500	1236	1960	2003	44	14	DY	58.7
1146870	ROSSLAND CITY YARD	BC	49.0833	117.8000	3408	1900	1995	96	13	DY	31.0
45-7267	SAINT JOHN	WA	47.0833	117.5833	1945	1963	2003	41	7	DY	17.6
10-8062	SAINT MARIES 1 W	ID	47.3000	116.5833	2320	1948	2003	56	13	DY	34.1
19A02S	SALMON MEADOWS	WA	48.6667	119.8333	4500	1982	2002	21	14	DY	25.4
10-8137	SANDPOINT EXP STATIO	ID	48.2833	116.5500	2100	1911	2003	93	13	DY	33.2
21B51S	SASSE RIDGE	WA	47.3667	121.0500	4200	1984	2002	19	14	DY	66.6
45-7342	SATUS PASS 2 SSW	WA	45.9500	120.6667	2610	1956	2003	48	14	HR	21.2
45-7379	SCENIC	WA	47.7000	121.1500	2221	1929	1970	42	14	DY	83.9
17D08S	SCHNEIDER MEADOWS	OR	45.0000	117.1500	5400	1981	2002	22	13	DY	46.8
16A10S	SCHWEITZER BASIN	ID	48.3667	116.6333	6090	1982	2002	21	13	DY	55.0
15D01S	SECESH SUMMIT	ID	45.1833	115.9667	6520	1982	2002	21	13	DY	51.7
16C01S	SHERWIN	ID	46.9500	116.3333	3200	1983	2002	20	13	DY	41.0
45-7690	SKAGIT POWER PLANT	WA	48.6833	121.2500	531	1931	1959	29	14	DY	79.6
1117410	SKAGIT RIVER	BC	49.0833	121.1667	1689	1936	1955	20	14	DY	65.1
45-7727	SMYRNA	WA	46.8333	119.6500	560	1951	2003	53	77	DY	8.1
1147620	SOUTH SLOCAN	BC	49.4667	117.5333	1499	1940	1995	56	13	DY	32.1
45-7933	SPOKANE	WA	47.6667	117.4167	1880	1954	1984	31	7	DY	17.9
45-7938	SPOKANE INTL AP	WA	47.6167	117.5167	2353	1889	2003	115	7	DY	17.3
45-7956	SPRAGUE	WA	47.3000	117.9833	1970	1942	1983	42	7	HR	15.5
45-8009	STAMPEDE PASS	WA	47.2833	121.3333	3958	1943	2003	61	14	HR	85.3
45-8059	STEHEKIN 4 NW	WA	48.3333	120.7167	1270	1931	2003	73	14	DY	37.7
45-8089	STEVENS PASS	WA	47.7333	121.0833	4070	1939	1994	56	14	DY	84.7
45-8115	STOCKDILL RANCH	WA	48.3667	120.3333	2201	1922	1964	43	14	DY	19.4
45-8207	SUNNYSIDE	WA	46.3167	120.0000	747	1942	2003	62	77	HR	7.2
21C13S	SURPRISE LAKES	WA	46.1000	121.7500	4250	1981	2002	22	14	DY	98.3
1147995	TARRYS	BC	49.3667	117.5667	1541	1924	1943	20	13	DY	25.3
17D07S	TAYLOR GREEN	OR	45.0333	117.5333	5740	1980	2002	23	13	DY	33.5
45-8348	TEKOA	WA	47.2167	117.0833	2495	1939	1980	42	7	DY	20.6
10-9029	TENSED	ID	47.1667	116.9167	2552	1964	1983	20	13	DY	25.1
35-8407	THE DALLES	OR	45.6000	121.2000	150	1948	2002	55	14	DY	15.2
20A07S	THUNDER BASIN	WA	48.5167	120.9833	4200	1988	2002	15	14	DY	74.6
45-8442	TIETON INTAKE	WA	46.6667	121.0000	2280	1920	1972	53	14	DY	19.7
35-8549	TOLLGATE	OR	45.7833	118.0833	4892	1948	1963	16	13	HR	55.4
45-8520	TONASKET 4 NNE	WA	48.7667	119.4167	960	1984	2003	20	147	DY	12.0
17C05S	TOUCHET #2	WA	46.1167	117.8500	5530	1981	1999	19	13	DY	55.1
45-8579	TRINIDAD 2 SSE	WA	47.2167	120.0000	561	1923	1962	40	77	DY	8.7
20B25S	TROUGH	WA	47.2333	120.3167	5300	1979	2002	24	14	DY	28.5
35-8717	TYGH VALLEY	OR	45.2333	121.1667	1115	1972	2003	32	14	HR	15.4
35-8726	UKIAH	OR	45.1333	118.9333	3400	1931	2003	73	7	DY	17.1
35-8734	UMATILLA	OR	45.9167	119.3500	269	1948	1966	19	77	DY	8.7
45-8688	UNDERWOOD 4 W	WA	45.7333	121.6000	1260	1941	1962	22	14	HR	37.5
35-8746	UNION EXPERIMENT STN	OR	45.2000	117.8667	2765	1928	2003	76	13	DY	15.5
20B07S	UPPER WHEELER	WA	47.2833	120.3667	4400	1982	2002	21	14	DY	27.5
35-8985	WALLA WALLA 13 ESE	OR	45.9833	118.0500	2400	1940	2003	64	13	HR	42.1
45-8926	WALLA WALLA 3 W	WA	46.0500	118.4000	801	1941	1962	22	7	HR	16.9
45-8928	WALLA WALLA FAA AIRP	WA	46.1000	118.2833	1166	1950	2001	52	7	DY	19.9
45-8931	WALLA WALLA WSO CITY	WA	46.0333	118.3333	949	1940	1988	49	7	HR	18.2
35-8997	WALLOWA	OR	45.5667	117.5167	2923	1948	2003	56	13	DY	17.5
1148670	WANETA	BC	49.0167	117.5833	1830	1913	1977	65	13	DY	26.8
45-8959	WAPATO	WA	46.4333	120.4167	841	1935	2003	69	77	DY	8.1
1148700	WARFIELD	BC	49.1000	117.7500	1988	1928	1995	68	13	DY	29.1
45-9012	WATERVILLE	WA	47.6333	120.0667	2620	1901	2003	103	147	DY	11.6
45-9024	WAWAWAI	WA	46.6500	117.4000	702	1931	1966	36	7	DY	18.4
45-9058	WELLPINIT	WA	47.8833	117.9833	2490	1930	2003	74	7	DY	19.5
45-9074	WENATCHEE	WA	47.4167	120.3000	640	1925	2003	79	147	DY	9.3
45-9082	WENATCHEE AP	WA	47.3833	120.2000	1229	1960	2003	44	147	DY	8.5
45-9079	WENATCHEE EXP STN	WA	47.4333	120.3500	800	1943	1998	56	147	HR	10.4
16D08S	WEST BRANCH	ID	45.0667	116.4333	5560	1981	2002	22	13	DY	34.4
35-9213	WESTON	OR	45.8167	118.4167	1922	1953	2003	51	7	HR	18.6
35-9219	WESTON 5 ESE	OR	45.8000	118.3333	3202	1955	1983	29	13	DY	30.2
21C28S	WHITE PASS E.S.	WA	46.6333	121.3833	4500	1981	2002	22	14	DY	60.6
45-9191	WHITE SWAN RANGER ST	WA	46.3833	120.7167	971	1928	1981	54	147	DY	9.1
45-9200	WHITMAN MISSION	WA	46.0333	118.4500	632	1963	2003	41	7	HR	14.7
45-9238	WILBUR	WA	47.7500	118.6667	2230	1900	2003	104	77	DY	13.0
45-9327	WILSON CREEK	WA	47.4167	119.1167	1280	1931	1980	50	77	DY	9.3
10-9846	WINCHESTER	ID	46.2333	116.6167	3950	1948	2003	56	13	DY	25.1
45-9376	WINTHROP 1 WSW	WA	48.4500	120.1833	1755	1911	2003	93	14	DY	14.4
45-9397	WITHROW	WA	47.7167	119.8167	2533	1948	1975	28	77	HR	10.8
18D21S	WOLF CREEK	OR	45.0667	118.1333	5700	1979	2002	24	13	DY	26.6
45-9465	YAKIMA AIRPORT	WA	46.5667	120.5333	1064	1940	2003	64	147	HR	8.3

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[4,20] (in)
1100120	AGASSIZ CDA	BC	49.2500	121.7667	49	1960	1990	31	14	HR	68.0
35-0265	ARLINGTON	OR	45.7167	120.2000	277	1948	2003	56	147	HR	9.2
35-0571	BEAR SPRINGS RS	OR	45.1167	121.5333	3360	1961	2003	43	14	HR	31.5
10-0789	BENTON DAM	ID	48.3500	116.8000	2641	1948	1977	30	13	HR	36.3
10-1079	BONNERS FERRY	ID	48.6833	116.3167	1770	1948	2003	56	13	HR	22.7
45-0839	BOUNDARY	WA	49.0000	117.6333	1391	1941	1959	19	13	HR	23.5
45-0849	BOUNDARY SWITCHYARD	WA	48.9667	117.3500	2500	1971	2003	33	13	HR	28.5
10-1370	CALDER	ID	47.2667	116.1833	2096	1971	2003	33	13	HR	30.7
45-1160	CARSON FISH HATCHERY	WA	45.8667	121.9667	1134	1977	2000	24	14	HR	90.4
45-1395	CHEWELAH	WA	48.2667	117.7167	1670	1969	2003	35	13	HR	21.7
45-1400	CHIEF JOSEPH DAM	WA	47.9833	119.6500	820	1951	2003	53	77	HR	11.1
10-1831	CLARKIA RANGER STN	ID	47.0000	116.2500	2860	1948	2001	54	13	HR	38.9
10-1956	COEUR D'ALENE	ID	47.6667	116.8000	2133	1953	2003	51	13	HR	26.1
45-1630	COLVILLE	WA	48.5333	117.9000	1657	1942	2003	62	7	HR	19.4
35-1765	CONDON	OR	45.2167	120.1667	2840	1949	2003	55	7	HR	14.1
45-1690	CONNELL 1 W	WA	46.6500	118.8667	1020	1960	2003	44	77	HR	8.8
10-2159	COTTONWOOD 2 WSW	ID	46.0333	116.3833	3945	1948	2003	56	13	HR	22.5
45-1767	COULEE DAM 1 SW	WA	47.9500	119.0000	1700	1941	1979	39	77	HR	11.1
45-2030	DAYTON 1 WSW	WA	46.3000	118.0000	1557	1941	2003	63	7	HR	19.6
45-2037	DAYTON 9 SE	WA	46.2167	117.8500	2343	1941	1977	37	13	HR	32.7
45-2157	DIABLO DAM	WA	48.7000	121.1333	891	1944	2003	60	14	HR	84.3
45-2197	DIXIE 4 SE	WA	46.0833	118.1000	2250	1940	2003	64	13	HR	39.6
10-2845	DWORSHAK FISH HATCH	ID	46.5000	116.3167	995	1967	2003	37	13	HR	25.4
45-2384	EASTON	WA	47.2333	121.1833	2170	1941	2003	63	14	HR	49.7
10-2892	ELK RIVER 1 S	ID	46.7667	116.1667	2918	1971	2003	33	13	HR	36.8
45-2505	ELLENSBURG	WA	46.9667	120.5333	1480	1941	2003	63	147	HR	9.1
10-2966	ENAVILLE	ID	47.5500	116.2500	2120	1972	2003	32	13	HR	27.7
45-3183	GLENWOOD	WA	46.0167	121.2833	1896	1942	2003	62	14	HR	32.6
45-3515	HARRINGTON 1 NW	WA	47.4833	118.2500	2190	1942	2003	62	77	HR	13.6
35-3830	HEPPNER 5 SSE	OR	45.2833	119.5167	3240	1975	2003	29	7	HR	15.9
35-4008	HOOD RIVER TUCKER BR	OR	45.6500	121.5333	383	1948	2003	56	14	HR	32.0
1113540	HOPE A	BC	49.3667	121.4833	127	1963	1995	33	14	HR	75.4
45-3883	ICE HARBOR DAM	WA	46.2333	118.8667	368	1957	1979	23	77	HR	10.4
35-4622	LA GRANDE	OR	45.3167	118.0667	2755	1966	2003	38	13	HR	17.0
35-4620	LA GRANDE CAA AIRPORT	OR	45.2833	118.0167	2707	1948	1966	19	13	HR	14.0
45-4446	LAKE WENATCHEE	WA	47.8333	120.8000	2005	1971	2003	33	14	HR	34.3
10-5241	LEWISTON AP	ID	46.3667	117.0000	1436	1950	2003	54	7	HR	17.1
45-4679	LIND 3 NE	WA	46.9833	118.5667	1630	1941	2003	63	77	HR	10.0
45-4702	LITTLE GOOSE DAM	WA	46.5833	118.0333	702	1964	1979	16	7	HR	12.6
45-4841	LOWER MONUMENTAL DM	WA	46.5500	118.5333	460	1963	1979	17	77	HR	10.6
45-4849	LUCERNE 1 N	WA	48.2333	120.6000	1200	1942	1989	48	14	HR	22.8
45-4999	MARBLEMOUNT R S	WA	48.5333	121.4500	348	1941	2003	63	14	HR	85.3
45-5133	MAZAMA	WA	48.6000	120.4333	2170	1942	2003	62	14	HR	22.2
45-5231	MCNARY DAM	WA	45.9333	119.2833	361	1955	1979	25	77	HR	8.3
35-5396	MEACHAM WSO AIRPORT	OR	45.5000	118.4000	4050	1948	1976	29	13	HR	33.4
45-5327	METHOW 2	WA	48.1333	120.0167	1165	1942	1979	38	147	HR	13.2
35-5734	MORO	OR	45.4667	120.7167	1870	1948	2003	56	147	HR	11.6
10-6148	MOSCOW 5 NE	ID	46.7833	116.9167	3000	1972	2003	32	13	HR	31.9
45-5659	MOUNT ADAMS RNGR STN	WA	46.0000	121.5333	1960	1971	2000	30	14	HR	42.4
45-5731	NACHES 10 NW	WA	46.8667	120.7667	2280	1944	2003	60	147	HR	17.7
45-5946	NORTHPORT	WA	48.9000	117.7833	1350	1961	2003	43	13	HR	23.4
45-6188	OROVILLE 3 NW	WA	48.9667	119.5000	1060	1941	1971	31	147	HR	13.0
45-6400	PASCO	WA	46.2167	119.1000	350	1942	2003	62	77	HR	7.8
35-6546	PENDLETON MUNICIPAL	OR	45.6833	118.8500	1486	1949	2003	55	7	HR	13.0
45-6472	PESHASTIN TELEMETERY	WA	47.5667	120.6167	1028	1971	2003	33	14	HR	19.7
35-6636	PILOT ROCK 11 E	OR	45.5000	118.6000	1920	1978	2003	26	13	HR	24.2
10-7188	PLUMMER 3 WSW	ID	47.3000	116.9500	2920	1948	2003	56	7	HR	25.5
10-7269	PORTHILL 1 SW	ID	48.9833	116.5000	1700	1971	2003	33	7	HR	21.4
45-6789	PULLMAN 2 NW	WA	46.7500	117.1833	2545	1941	2003	63	7	HR	21.2
45-6982	REPUBLIC RANGER STN	WA	48.6333	118.7333	2630	1941	2003	63	7	HR	16.7
10-8137	SANDPOINT EXP STATION	ID	48.2833	116.5500	2100	1952	2003	52	13	HR	33.2
45-7342	SATUS PASS 2 SSW	WA	45.9500	120.6667	2610	1956	2003	48	14	HR	21.2
45-7938	SPOKANE INTL AP	WA	47.6167	117.5167	2353	1948	2003	56	7	HR	17.3
45-7956	SPRAGUE	WA	47.3000	117.9833	1970	1942	1983	42	7	HR	15.5
45-8009	STAMPEDE PASS	WA	47.2833	121.3333	3958	1943	2003	61	14	HR	85.3
45-8059	STEHEKIN 4 NW	WA	48.3333	120.7167	1270	1976	2003	28	14	HR	37.7
45-8089	STEVENS PASS	WA	47.7333	121.0833	4070	1971	2000	30	14	HR	84.7
45-8207	SUNNYSIDE	WA	46.3167	120.0000	747	1942	2003	62	77	HR	7.2
45-8348	TEKOA	WA	47.2167	117.0833	2495	1972	2003	32	13	HR	20.6
35-8549	TOLLGATE	OR	45.7833	118.0833	4892	1948	1963	16	13	HR	55.4
35-8717	TYGH VALLEY	OR	45.2333	121.1667	1115	1972	2003	32	77	HR	15.4
35-8726	UKIAH	OR	45.1333	118.9333	3400	1971	2003	33	7	HR	17.1

STATION ID	STATION NAME	STATE	LAT	LONG	ELEV (ft)	YEAR START	YEAR END	YEARS OPEN	RGN	GAGE TYPE	PRISM MAP[4,20] (in)
45-8688	UNDERWOOD 4 W	WA	45.7333	121.6000	1260	1941	1962	22	14	HR	37.5
35-8746	UNION EXPERIMENT STN	OR	45.2000	117.8667	2765	1948	2003	56	13	HR	15.5
35-8985	WALLA WALLA 13 ESE	OR	45.9833	118.0500	2400	1948	2003	56	13	HR	42.1
45-8926	WALLA WALLA 3 W	WA	46.0500	118.4000	801	1941	1962	22	7	HR	16.9
45-8931	WALLA WALLA WSO CITY	WA	46.0333	118.3333	949	1940	1988	49	7	HR	18.2
45-9079	WENATCHEE EXP STN	WA	47.4333	120.3500	800	1943	1998	56	147	HR	10.4
35-9213	WESTON	OR	45.8167	118.4167	1922	1953	2003	51	7	HR	18.6
45-9200	WHITMAN MISSION	WA	46.0333	118.4500	632	1962	2003	42	7	HR	14.7
45-9327	WILSON CREEK	WA	47.4167	119.1167	1280	1941	1980	40	77	HR	9.3
45-9397	WITHROW	WA	47.7167	119.8167	2533	1948	1975	28	77	HR	10.8
45-9465	YAKIMA AIRPORT	WA	46.5667	120.5333	1064	1940	2003	64	147	HR	8.3

Appendix B

ISOPLUVIAL MAPS

FOR SELECTED RECURRENCE INTERVALS

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[15,29] 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 (png files) contained in this appendix are also included on the CD.

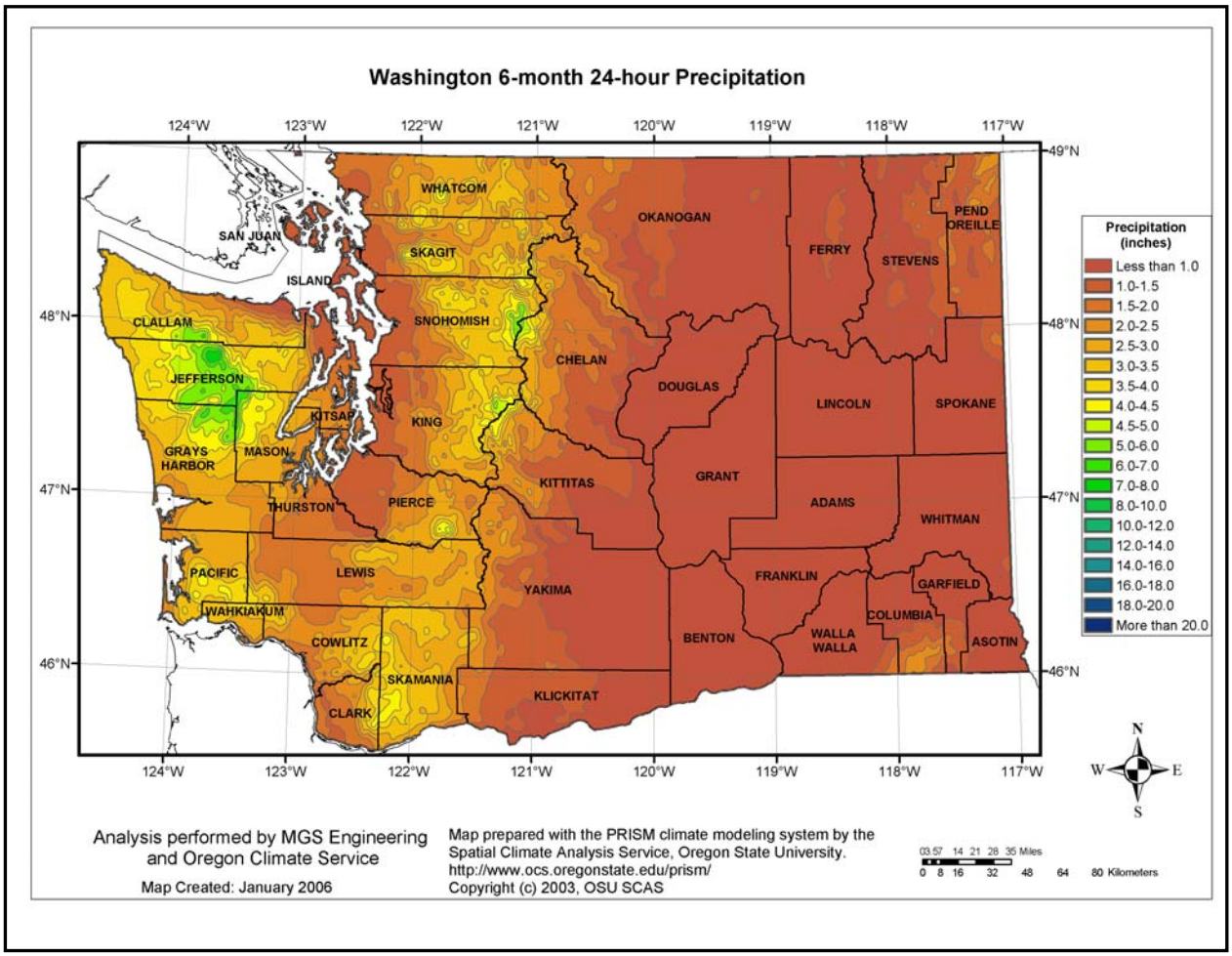


Figure B1 – Isopluvial Map of 24-Hour Precipitation for 6-Month Recurrence Interval

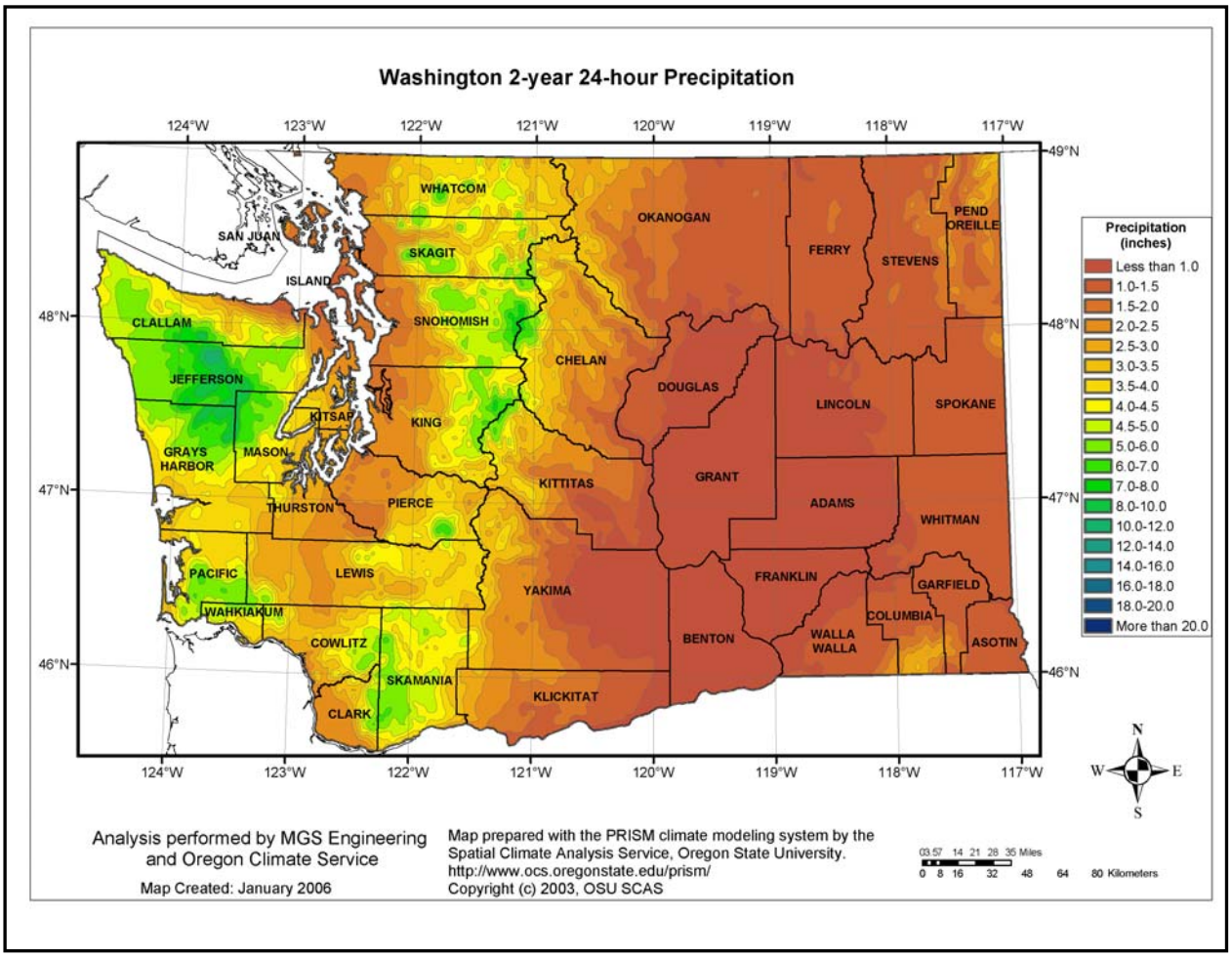


Figure B2 – Isopluvial Map of 24-Hour Precipitation for 2-Year Recurrence Interval

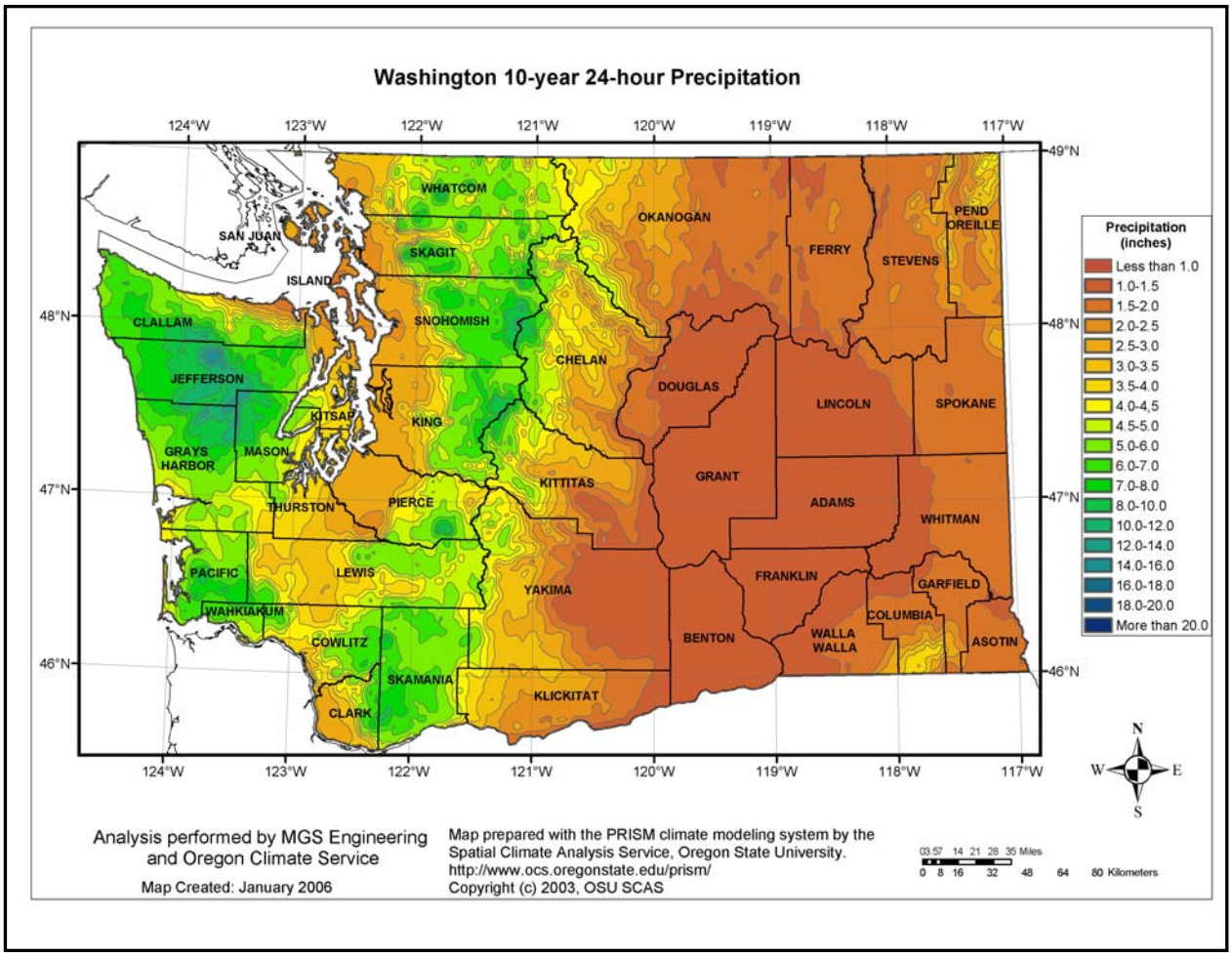


Figure B3 – Isopluvial Map of 24-Hour Precipitation for 10-Year Recurrence Interval

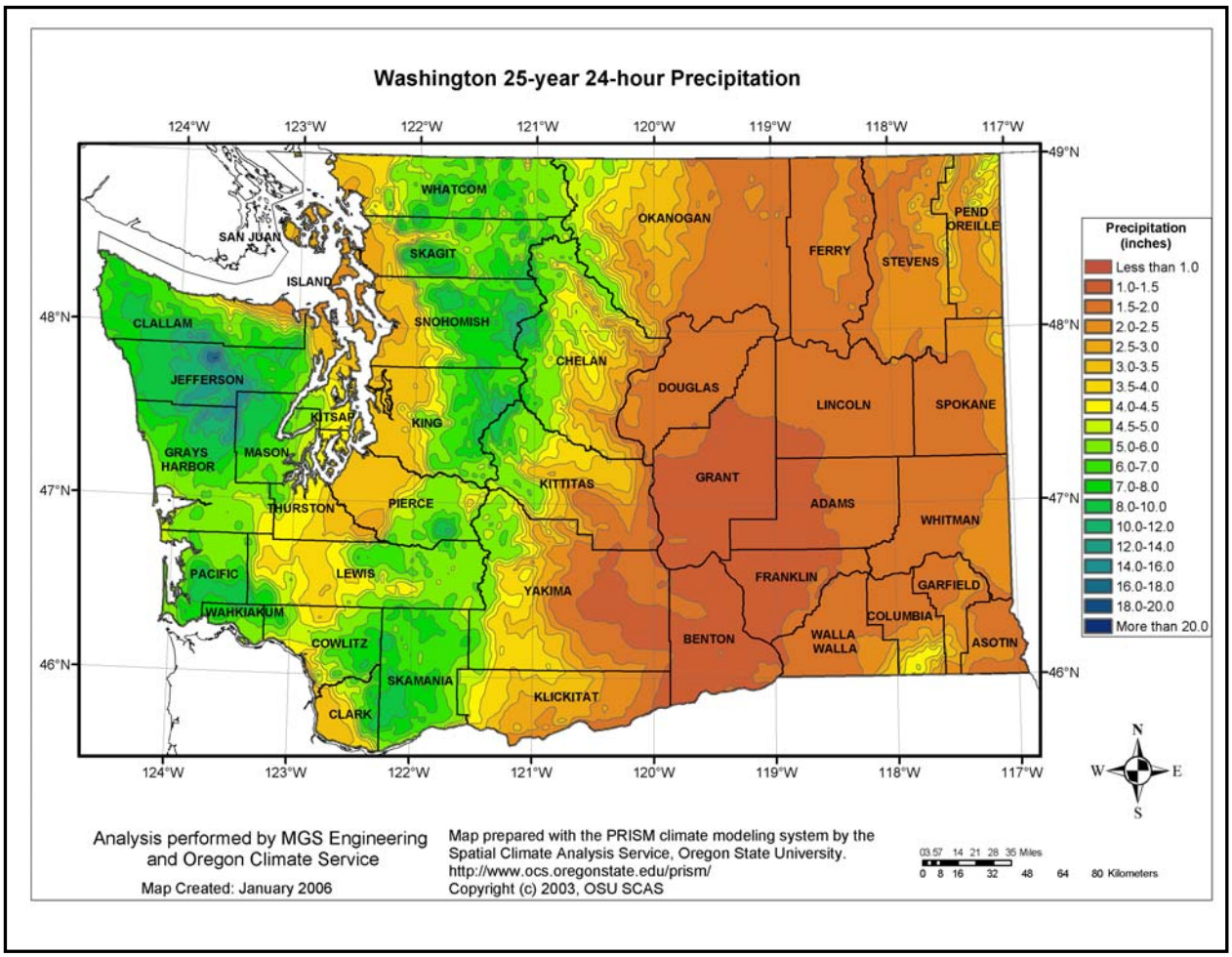


Figure B4 – Isopluvial Map of 24-Hour Precipitation for 25-Year Recurrence Interval

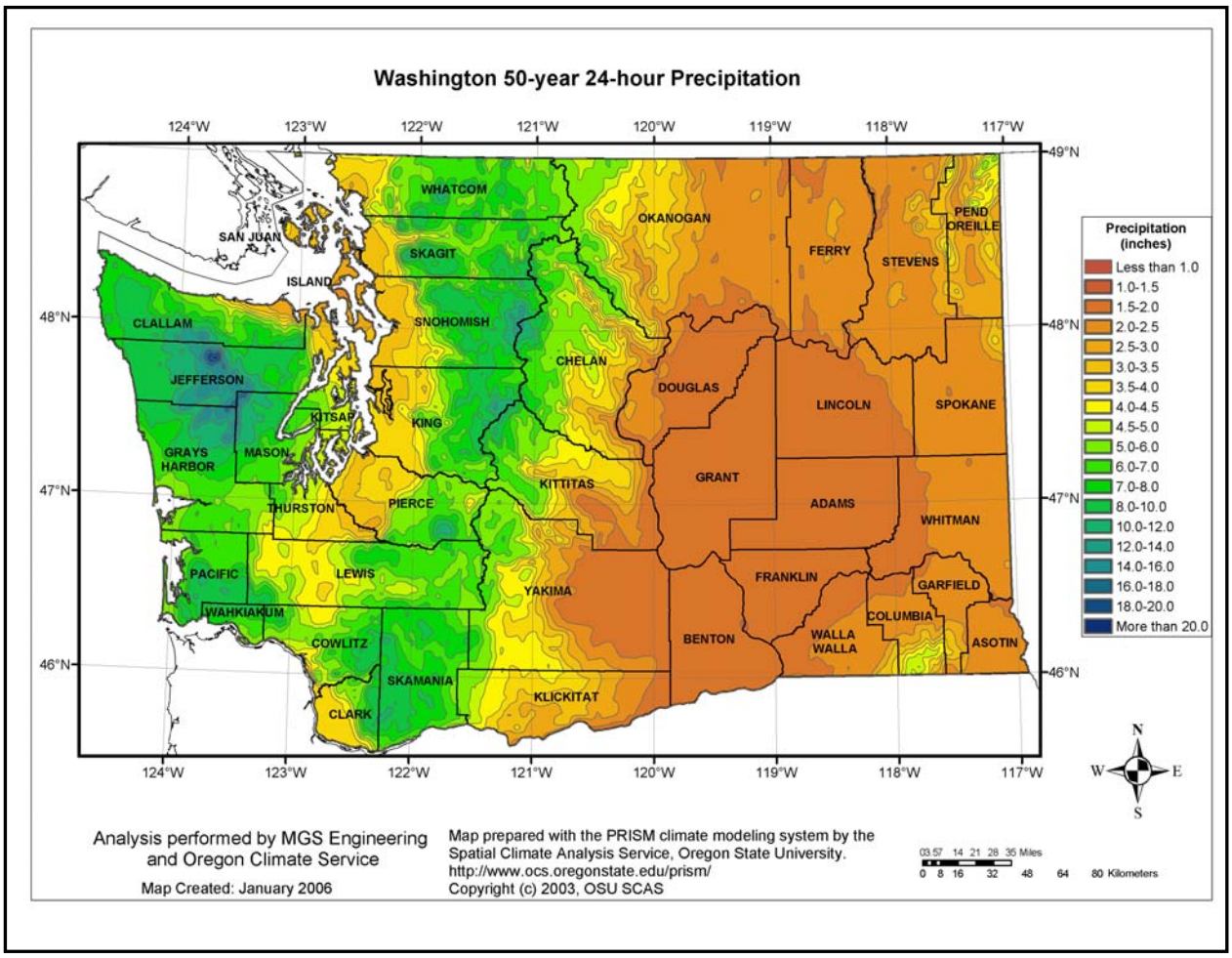


Figure B5 – Isopluvial Map of 24-Hour Precipitation for 50-Year Recurrence Interval

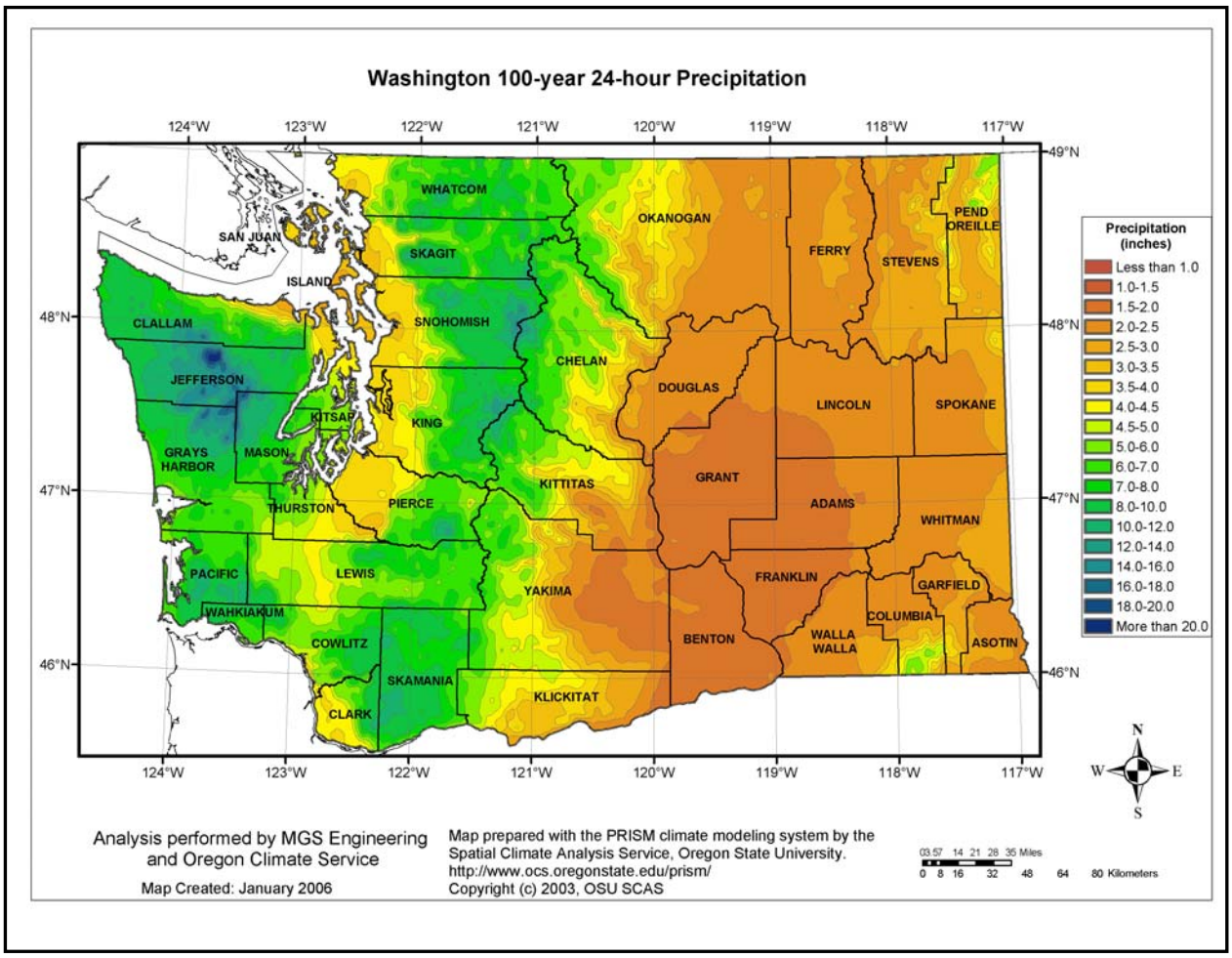


Figure B6 – Isopluvial Map of 24-Hour Precipitation for 100-Year Recurrence Interval

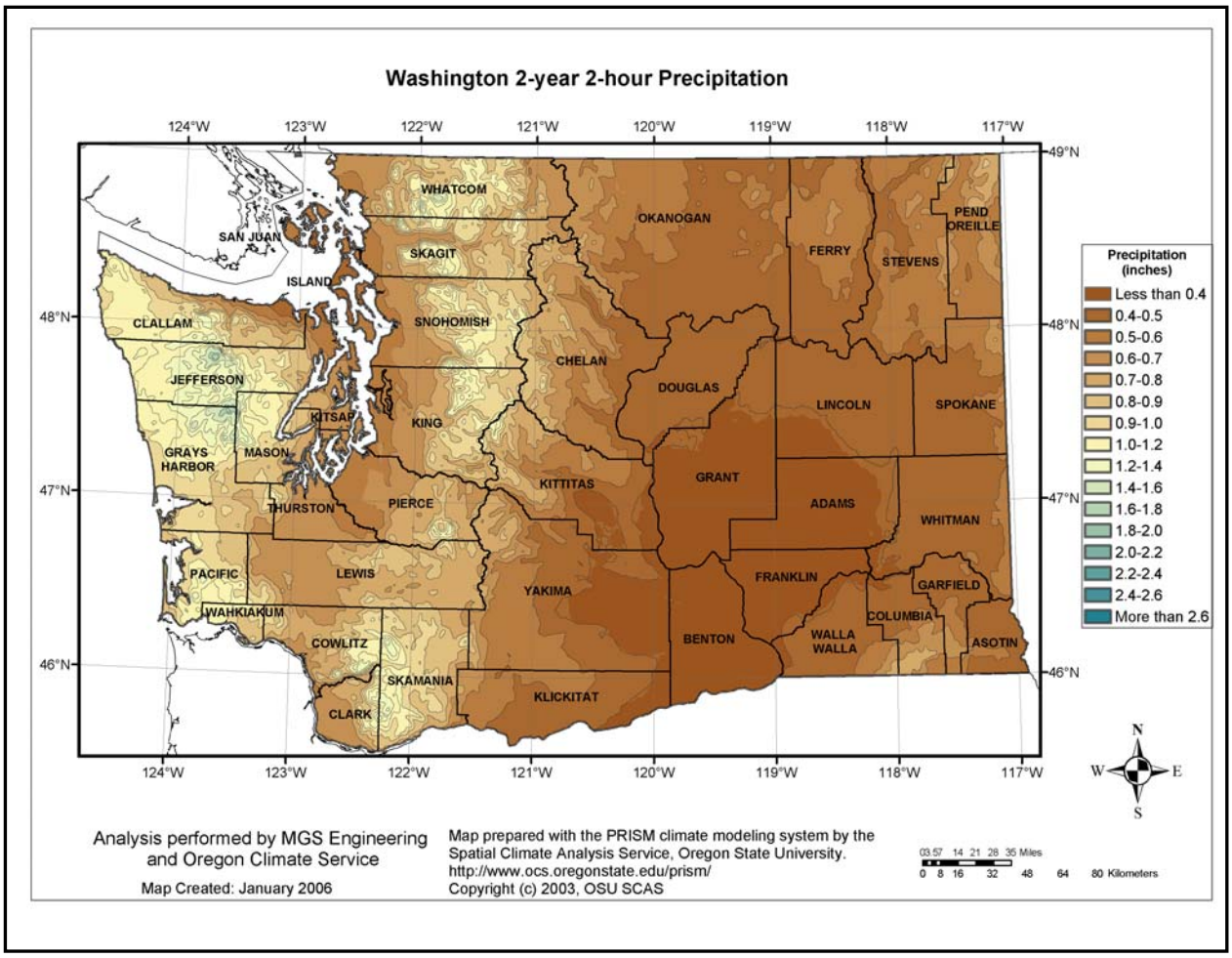


Figure B7 – Isopluvial Map of 2-Hour Precipitation for 2-Year Recurrence Interval

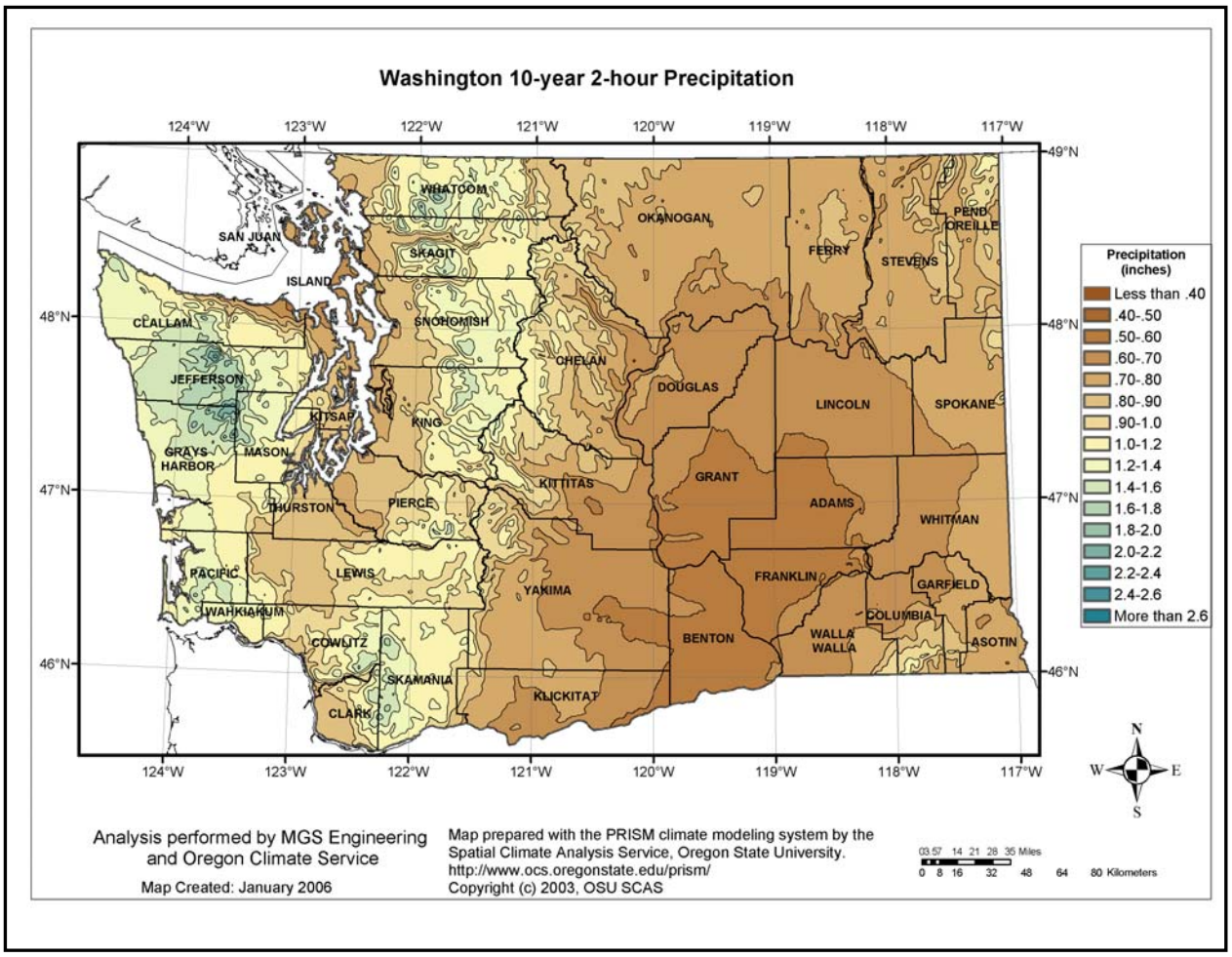


Figure B8 – Isopluvial Map of 2-Hour Precipitation for 10-Year Recurrence Interval

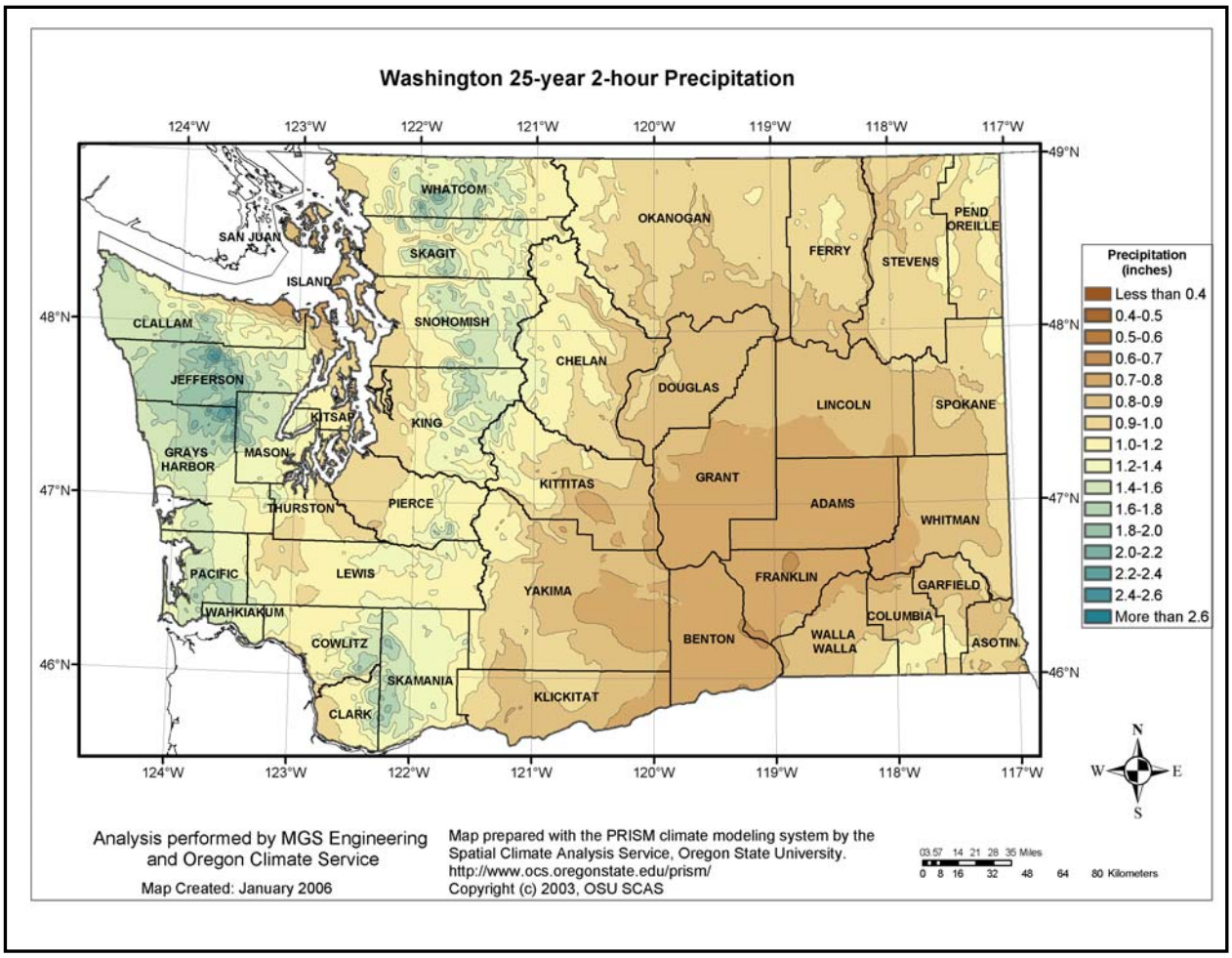


Figure B9 – Isopluvial Map of 2-Hour Precipitation for 25-Year Recurrence Interval

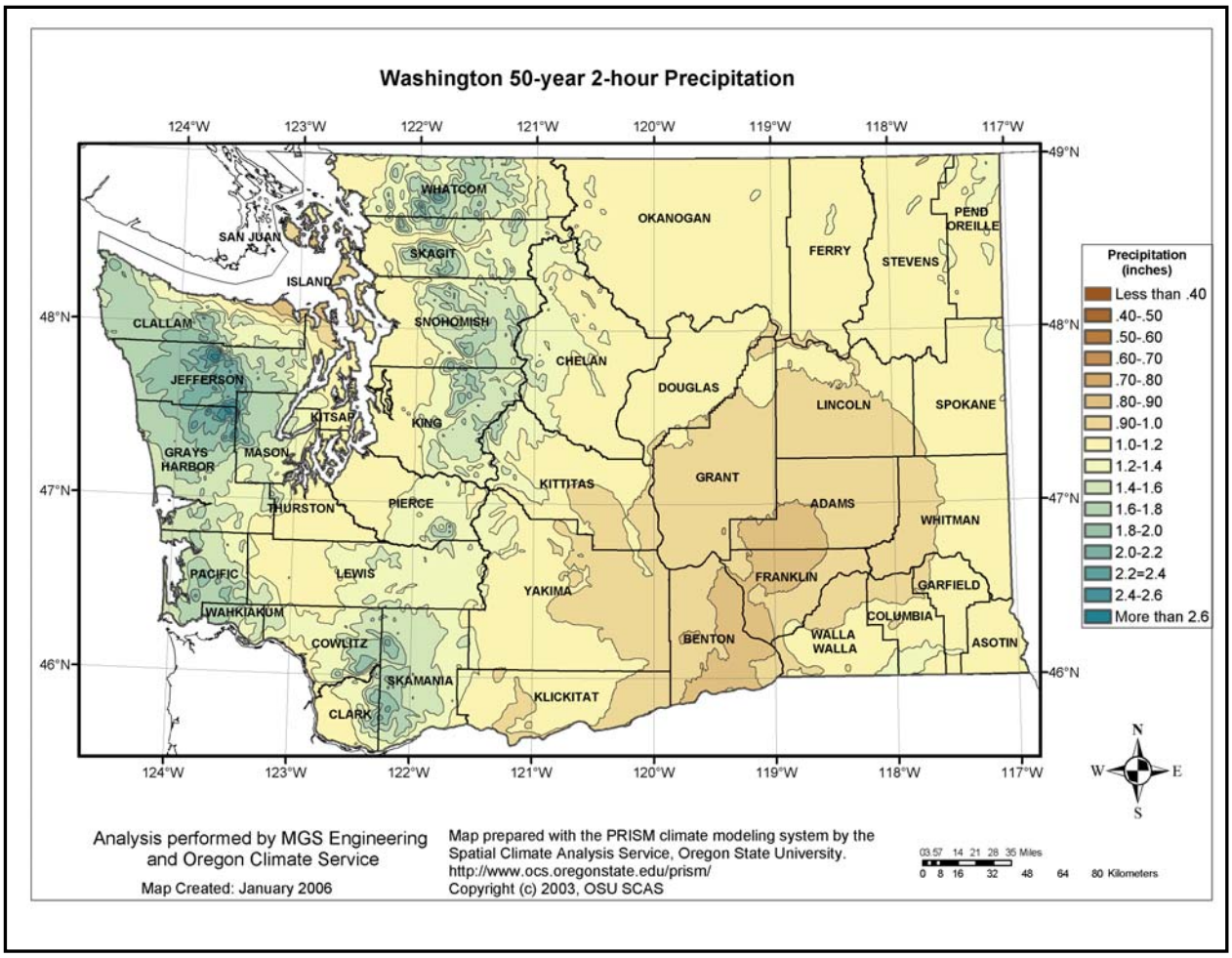


Figure B10 – Isopluvial Map of 2-Hour Precipitation for 50-Year Recurrence Interval

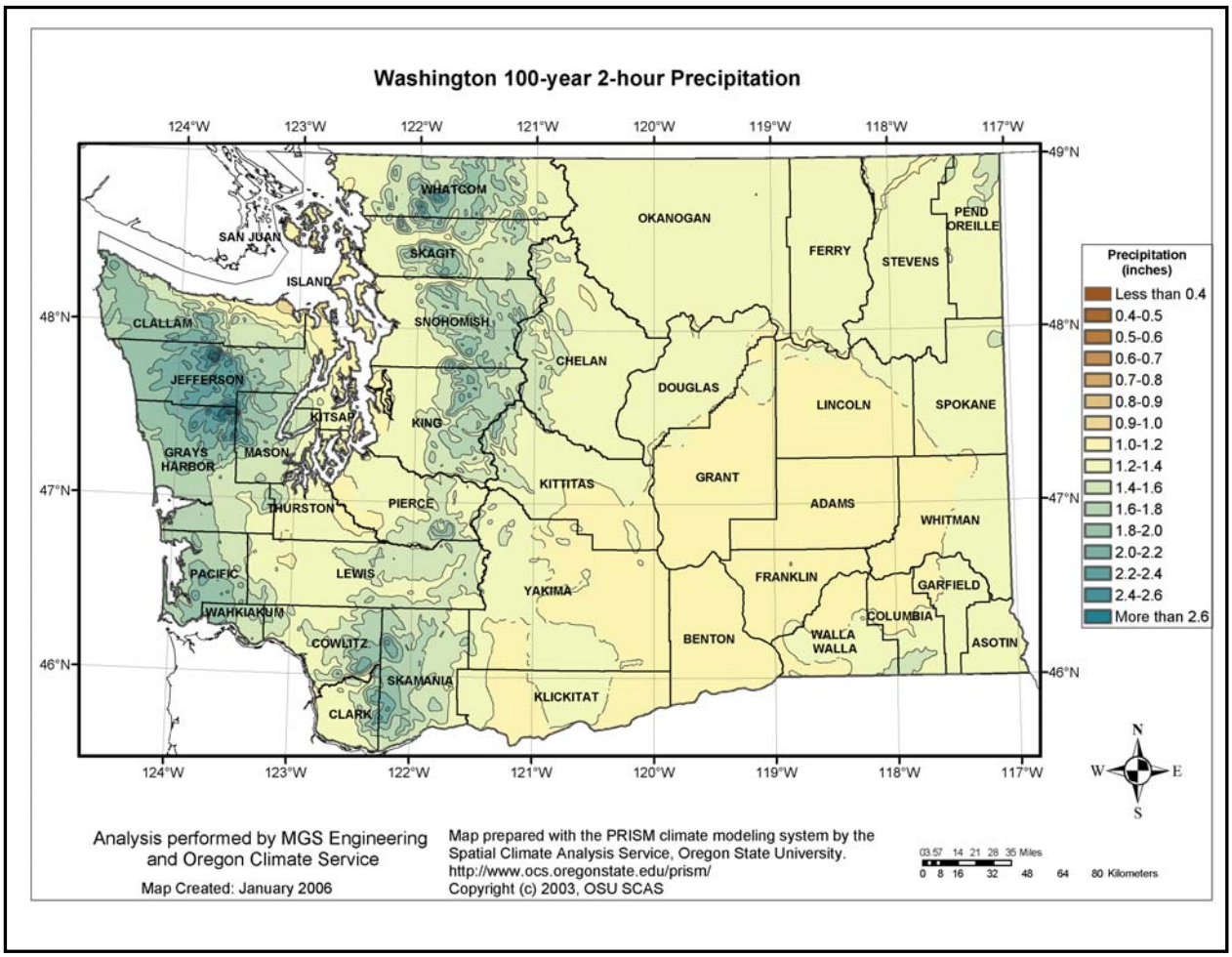


Figure B11 – Isopluvial Map of 2-Hour Precipitation for 100-Year Recurrence Interval

Appendix C

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 C1 - Catalog of Extreme Storms for Region 14 for 24-Hour Duration
(East Slopes of Cascade Mountains)

EXTREME STORMS AT 24-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-2157	DIABLO DAM	14	54	48.7	121.1	1.62	6.42	10	24	1945
45-8688	UNDERWOOD 4 W	14	22	45.7	121.6	1.52	4.04	12	11	1946
45-5327	METHOW 2	14	38	48.1	120.0	1.93	2.02	5	28	1948
45-2157	DIABLO DAM	14	54	48.7	121.1	1.90	7.53	2	16	1949
45-2157	DIABLO DAM	14	54	48.7	121.1	1.64	6.47	2	10	1951
45-5327	METHOW 2	14	38	48.1	120.0	1.69	1.77	8	28	1951
45-1257	CENTERVILLE 2 SW	14	14	45.7	121.0	1.77	2.36	1	9	1953
45-8009	STAMPEDE PASS	14	54	47.3	121.3	1.73	7.01	12	10	1956
45-3183	GLENWOOD	14	59	46.0	121.3	1.61	3.42	11	24	1960
45-8009	STAMPEDE PASS	14	54	47.3	121.3	1.96	7.94	11	20	1962
45-4035	JOHN DAY DAM	14	13	45.7	120.7	2.60	2.70	12	23	1964
45-5133	MAZAMA	14	60	48.6	120.4	1.85	3.10	1	11	1972
45-4849	LUCERNE 1 N	14	47	48.2	120.6	1.61	3.17	12	2	1975
45-8009	STAMPEDE PASS	14	54	47.3	121.3	1.95	7.90	12	2	1977
35-4008	HOOD RIVER TUCKER BR	14	61	45.7	121.5	1.73	3.70	12	13	1977
45-5133	MAZAMA	14	60	48.6	120.4	1.90	3.20	1	12	1980
45-8059	STEHEKIN 4 NW	14	19	48.3	120.7	1.83	5.00	1	23	1982
45-8089	STEVENS PASS	14	23	47.7	121.1	1.54	6.50	12	3	1982
45-4999	MARBLEMOUNT R S	14	59	48.5	121.5	1.82	6.20	2	24	1986
45-7342	SATUS PASS 2 SSW	14	39	46.0	120.7	2.06	3.90	12	10	1987
45-4446	LAKE WENATCHEE	14	30	47.8	120.8	1.83	5.30	1	9	1990
45-4999	MARBLEMOUNT R S	14	59	48.5	121.5	1.82	6.20	11	10	1990
45-2384	EASTON	14	58	47.2	121.2	2.08	6.40	11	24	1990
45-3183	GLENWOOD	14	59	46.0	121.3	1.79	3.80	10	27	1994
45-4999	MARBLEMOUNT R S	14	59	48.5	121.5	1.56	5.30	11	28	1995
35-4008	HOOD RIVER TUCKER BR	14	61	45.7	121.5	2.20	4.70	11	19	1996
45-7342	SATUS PASS 2 SSW	14	39	46.0	120.7	2.17	4.10	12	28	1998

Table C2 - Catalog of Extreme Storms for Transition Zone 147 for 24-Hour Duration
(Eastern Foothills of Cascade Mountains)

EXTREME STORMS AT 24-HOUR DURATION										
STATION ID	STATION NAME	TRANS ZONE	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-5327	METHOW 2	147	38	48.1	120.0	1.93	2.02	5	28	1948
45-9079	WENATCHEE EXP STN	147	55	47.4	120.4	1.77	1.91	6	11	1948
45-6187	OROVILLE 1 S	147	29	48.9	119.4	1.85	1.96	11	16	1950
45-5327	METHOW 2	147	38	48.1	120.0	1.69	1.77	8	28	1951
35-0265	ARLINGTON	147	52	45.7	120.2	2.56	2.22	12	23	1964
35-5734	MORO	147	54	45.5	120.7	1.78	1.60	1	21	1972
45-9079	WENATCHEE EXP STN	147	55	47.4	120.4	1.73	1.87	6	10	1972
45-9079	WENATCHEE EXP STN	147	55	47.4	120.4	1.90	2.06	8	19	1975
35-5734	MORO	147	54	45.5	120.7	1.78	1.60	5	11	1977
45-9465	YAKIMA AIRPORT	147	63	46.6	120.5	1.78	1.58	12	13	1977
45-9465	YAKIMA AIRPORT	147	63	46.6	120.5	1.76	1.56	6	30	1982
45-2505	ELLENSBURG	147	59	47.0	120.5	2.21	1.80	12	10	1987
35-0265	ARLINGTON	147	52	45.7	120.2	1.96	1.70	4	21	1988
45-9465	YAKIMA AIRPORT	147	63	46.6	120.5	1.96	1.74	8	21	1990
45-2505	ELLENSBURG	147	59	47.0	120.5	2.33	1.90	11	18	1996

Table C3 - Catalog of Extreme Storms for Region 77 for 24-Hour Duration (Central Basin)

EXTREME STORMS AT 24-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-4679	LIND 3 NE	77	59	47.0	118.6	1.99	1.53	6	26	1942
45-3515	HARRINGTON 1 NW	77	59	47.5	118.3	1.69	1.52	9	21	1945
45-8207	SUNNYSIDE	77	59	46.3	120.0	2.51	2.05	6	7	1947
45-1767	COULEE DAM 1 SW	77	38	48.0	119.0	1.89	1.66	5	28	1948
45-9079	WENATCHEE EXP STN	77	55	47.4	120.4	1.77	1.91	6	11	1948
45-3513	HARRINGTON 2 S	77	14	47.4	118.3	1.80	1.55	9	26	1948
45-9327	WILSON CREEK	77	39	47.4	119.1	1.90	1.54	6	19	1950
45-3883	ICE HARBOR DAM	77	21	46.2	118.9	2.55	2.55	6	6	1957
45-5231	MCNARY DAM	77	23	45.9	119.3	4.47	3.15	10	2	1957
45-4679	LIND 3 NE	77	59	47.0	118.6	1.63	1.25	2	1	1963
45-9327	WILSON CREEK	77	39	47.4	119.1	1.98	1.60	6	17	1965
45-8207	SUNNYSIDE	77	59	46.3	120.0	2.01	1.64	5	21	1972
45-9079	WENATCHEE EXP STN	77	55	47.4	120.4	1.73	1.87	6	10	1972
45-9397	WITHROW	77	24	47.7	119.8	1.72	1.62	8	16	1972
45-9079	WENATCHEE EXP STN	77	55	47.4	120.4	1.90	2.06	8	19	1975
45-6400	PASCO	77	57	46.2	119.1	1.92	1.41	8	30	1977
45-9465	YAKIMA AIRPORT	77	63	46.6	120.5	1.78	1.58	12	13	1977
45-6400	PASCO	77	57	46.2	119.1	2.18	1.60	9	13	1980
45-9465	YAKIMA AIRPORT	77	63	46.6	120.5	1.76	1.56	6	30	1982
45-8207	SUNNYSIDE	77	59	46.3	120.0	2.08	1.70	9	15	1986
45-1400	CHIEF JOSEPH DAM	77	51	48.0	119.7	1.61	1.50	9	18	1986
45-2505	ELLENSBURG	77	59	47.0	120.5	2.21	1.80	12	10	1987
45-9465	YAKIMA AIRPORT	77	63	46.6	120.5	1.96	1.74	8	21	1990
45-1400	CHIEF JOSEPH DAM	77	51	48.0	119.7	1.94	1.80	7	24	1992
45-4679	LIND 3 NE	77	59	47.0	118.6	1.82	1.40	7	23	1993
45-1690	CONNELL 1 W	77	40	46.7	118.9	1.78	1.30	5	16	1994
45-2505	ELLENSBURG	77	59	47.0	120.5	2.33	1.90	11	18	1996
45-3515	HARRINGTON 1 NW	77	59	47.5	118.3	1.55	1.40	4	14	2000

Table C4 - Catalog of Extreme Storms for Region 7 for 24-Hour Duration (Okanogan, Spokane, Palouse)

EXTREME STORMS AT 24-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-8926	WALLA WALLA 3 W	7	22	46.1	118.4	1.51	1.49	6	25	1942
45-7956	SPRAGUE	7	38	47.3	118.0	1.84	1.77	10	23	1943
45-7956	SPRAGUE	7	38	47.3	118.0	1.61	1.55	9	22	1945
45-6187	OROVILLE 1 S	7	29	48.9	119.4	1.85	1.96	11	16	1950
45-7938	SPOKANE INTL AP	7	54	47.6	117.5	1.49	1.58	12	18	1951
10-5241	LEWISTON AP	7	51	46.4	117.0	1.68	1.73	9	14	1955
35-3827	HEPPNER	7	33	45.4	119.6	2.23	2.18	10	2	1957
45-2035	DAYTON 1 WSW	7	50	46.3	118.0	1.68	1.95	1	27	1959
35-1765	CONDON	7	54	45.2	120.2	1.58	1.55	11	27	1962
45-7938	SPOKANE INTL AP	7	54	47.6	117.5	1.95	2.07	6	8	1964
45-4702	LITTLE GOOSE DAM	7	16	46.6	118.0	1.30	1.10	4	20	1970
45-8931	WALLA WALLA WSO CITY	7	47	46.0	118.3	1.56	1.91	5	27	1971
35-6546	PENDLETON MUNICIPAL	7	54	45.7	118.9	1.53	1.52	5	21	1972
35-8726	UKIAH	7	30	45.1	118.9	1.97	2.20	7	10	1975
45-8348	TEKOA	7	25	47.2	117.1	1.67	2.20	7	4	1978
35-3827	HEPPNER	7	33	45.4	119.6	1.53	1.50	8	22	1978
45-8931	WALLA WALLA WSO CITY	7	47	46.0	118.3	2.51	3.08	10	14	1980
35-6546	PENDLETON MUNICIPAL	7	54	45.7	118.9	1.89	1.88	10	29	1982
45-6982	REPUBLIC RANGER STN	7	60	48.6	118.7	2.29	2.70	8	11	1983
45-6982	REPUBLIC RANGER STN	7	60	48.6	118.7	1.70	2.00	7	27	1988
45-7938	SPOKANE INTL AP	7	54	47.6	117.5	1.70	1.80	7	25	1990
35-1765	CONDON	7	54	45.2	120.2	2.14	2.10	7	14	1993
45-9200	WHITMAN MISSION	7	37	46.0	118.5	1.80	2.00	8	16	1993
45-2035	DAYTON 1 WSW	7	50	46.3	118.0	1.90	2.20	11	1	1994
45-9200	WHITMAN MISSION	7	37	46.0	118.5	1.80	2.00	11	19	1996
45-6982	REPUBLIC RANGER STN	7	60	48.6	118.7	2.12	2.50	5	27	1998
10-5241	LEWISTON AP	7	51	46.4	117.0	1.85	1.90	7	11	1998

Table C5 - Catalog of Extreme Storms for Region 13 for 24-Hour Duration
(Northeastern Mountains and Blue Mountains)

EXTREME STORMS AT 24-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-2197	DIXIE 4 SE	13	63	46.1	118.1	1.50	2.44	6	6	1941
45-2197	DIXIE 4 SE	13	63	46.1	118.1	1.45	2.36	6	25	1942
35-8985	WALLA WALLA 13 ESE	13	60	46.0	118.1	1.76	4.06	12	28	1945
10-1079	BONNERS FERRY	13	61	48.7	116.3	1.99	2.75	11	18	1946
45-6789	PULLMAN 2 NW	13	59	46.8	117.2	1.64	2.09	9	16	1947
10-1956	COEUR D'ALENE	13	52	47.7	116.8	1.50	2.08	5	8	1948
10-2159	COTTONWOOD 2 WSW	13	49	46.0	116.4	1.67	2.12	8	2	1948
45-6789	PULLMAN 2 NW	13	59	46.8	117.2	1.95	2.48	8	11	1952
10-7188	PLUMMER 3 WSW	13	55	47.3	117.0	1.79	2.70	1	1	1954
45-1630	COLVILLE	13	54	48.5	117.9	2.59	2.73	5	13	1957
10-1956	COEUR D'ALENE	13	52	47.7	116.8	1.58	2.20	5	20	1957
45-0839	BOUNDARY	13	19	49.0	117.6	1.61	1.80	12	12	1958
35-8549	TOLLGATE	13	13	45.8	118.1	1.49	3.27	9	26	1959
45-6789	PULLMAN 2 NW	13	59	46.8	117.2	1.54	1.96	11	22	1961
35-5396	MEACHAM WSO AIRPORT	13	27	45.5	118.4	1.54	2.81	11	8	1963
45-2197	DIXIE 4 SE	13	63	46.1	118.1	1.66	2.70	11	24	1964
45-2037	DAYTON 9 SE	13	35	46.2	117.9	1.97	3.01	12	23	1964
10-7188	PLUMMER 3 WSW	13	55	47.3	117.0	1.71	2.58	6	18	1965
45-2037	DAYTON 9 SE	13	35	46.2	117.9	1.65	2.52	1	2	1966
10-1079	BONNERS FERRY	13	61	48.7	116.3	1.62	2.24	9	18	1968
35-8746	UNION EXPERIMENT STN	13	54	45.2	117.9	1.50	1.50	5	7	1970
10-0789	BENTON DAM	13	28	48.4	116.8	1.53	2.70	11	16	1973
10-1831	CLARKIA RANGER STATI	13	45	47.0	116.3	1.45	2.60	1	15	1974
10-1370	CALDER	13	30	47.3	116.2	1.86	2.90	12	2	1977
10-2845	DWORSHAK FISH HATCH	13	36	46.5	116.3	1.70	2.40	5	5	1979
10-7188	PLUMMER 3 WSW	13	55	47.3	117.0	2.52	3.80	5	26	1980
10-2892	ELK RIVER 1 S	13	30	46.8	116.2	1.92	3.60	1	23	1982
10-8137	SANDPOINT EXP STATIO	13	40	48.3	116.6	1.58	2.80	2	14	1982
35-8746	UNION EXPERIMENT STN	13	54	45.2	117.9	2.08	2.08	8	31	1984
45-0849	BOUNDARY SWITCHYRD	13	32	49.0	117.4	2.12	3.10	2	15	1986
35-4622	LA GRANDE	13	33	45.3	118.1	1.62	2.00	2	23	1986
10-2159	COTTONWOOD 2 WSW	13	49	46.0	116.4	1.65	2.10	5	29	1990
35-8746	UNION EXPERIMENT STN	13	54	45.2	117.9	1.59	1.59	5	19	1991
45-5946	NORTHPORT	13	41	48.9	117.8	2.05	2.30	6	13	1992
10-6148	MOSCOW 5 NE	13	26	46.8	116.9	1.57	2.50	8	22	1992
35-4622	LA GRANDE	13	33	45.3	118.1	1.87	2.30	8	16	1993
45-1630	COLVILLE	13	54	48.5	117.9	1.61	1.70	11	27	1996
45-1395	CHEWELAH	13	28	48.3	117.7	2.06	2.70	5	26	1998
45-1630	COLVILLE	13	54	48.5	117.9	1.80	1.90	6	25	1999
10-2845	DWORSHAK FISH HATCH	13	36	46.5	116.3	1.77	2.50	11	25	1999
10-1956	COEUR D'ALENE	13	52	47.7	116.8	1.44	2.00	4	14	2000
35-8985	WALLA WALLA 13 ESE	13	60	46.0	118.1	1.86	4.30	10	1	2000

Table C6a - Catalog of Extreme Storms for Region 14 for 2-Hour Duration for Cool Seasons (East Slopes of Cascade Mountains)

EXTREME STORMS AT 24-HOUR DURATION – COOL SEASONS										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-3183	GLENWOOD	14	58	46.0	121.3	1.75	0.79	12	8	1942
45-2157	DIABLO DAM	14	56	48.7	121.1	1.64	1.10	2	16	1949
45-8009	STAMPEDE PASS	14	54	47.3	121.3	1.88	1.39	11	22	1961
45-8009	STAMPEDE PASS	14	54	47.3	121.3	1.61	1.19	11	19	1962
45-2157	DIABLO DAM	14	56	48.7	121.1	1.79	1.20	12	8	1971
45-4999	MARBLEMOUNT R S	14	57	48.5	121.5	1.28	0.80	12	25	1972
45-4446	LAKE WENATCHEE	14	32	47.8	120.8	1.85	1.20	1	17	1975
35-4008	HOOD RIVER TUCKER BR	14	52	45.7	121.5	1.48	0.70	12	2	1977
45-3183	GLENWOOD	14	58	46.0	121.3	1.57	0.71	12	13	1977
45-5659	MOUNT ADAMS RNGR ST	14	27	46.0	121.5	2.04	1.30	1	13	1980
45-3183	GLENWOOD	14	58	46.0	121.3	1.33	0.60	12	25	1980
45-2384	EASTON	14	61	47.2	121.2	1.61	1.00	1	23	1982
45-3183	GLENWOOD	14	58	46.0	121.3	1.33	0.60	2	20	1982
45-4446	LAKE WENATCHEE	14	32	47.8	120.8	1.54	1.00	12	3	1982
45-6472	PESHASTIN TELEMETERI	14	29	47.6	120.6	1.53	0.80	1	4	1984
45-8089	STEVENS PASS	14	24	47.7	121.1	1.58	1.30	11	1	1985
45-4999	MARBLEMOUNT R S	14	57	48.5	121.5	1.28	0.80	2	23	1986
45-5133	MAZAMA	14	60	48.6	120.4	1.89	1.00	2	1	1987
45-4446	LAKE WENATCHEE	14	32	47.8	120.8	1.54	1.00	12	9	1987
45-4446	LAKE WENATCHEE	14	32	47.8	120.8	1.54	1.00	1	9	1990
45-4999	MARBLEMOUNT R S	14	57	48.5	121.5	1.28	0.80	11	9	1990
45-2384	EASTON	14	61	47.2	121.2	1.45	0.90	10	31	1994
35-4008	HOOD RIVER TUCKER BR	14	52	45.7	121.5	1.48	0.70	11	11	1995
45-4999	MARBLEMOUNT R S	14	57	48.5	121.5	1.28	0.80	11	28	1995
35-0571	BEAR SPRINGS RS	14	40	45.1	121.5	2.22	1.10	11	19	1996
45-8059	STEHEKIN 4 NW	14	23	48.3	120.7	1.85	1.20	12	29	1996
45-4999	MARBLEMOUNT R S	14	57	48.5	121.5	1.60	1.00	10	30	1997
45-2384	EASTON	14	61	47.2	121.2	1.45	0.90	1	15	1998
45-7342	SATUS PASS 2 SSW	14	43	46.0	120.7	2.07	1.10	12	27	1998
45-8009	STAMPEDE PASS	14	54	47.3	121.3	1.63	1.20	1	10	1999
45-2384	EASTON	14	61	47.2	121.2	1.45	0.90	2	3	1999
45-3183	GLENWOOD	14	58	46.0	121.3	1.33	0.60	1	16	2001
45-4446	LAKE WENATCHEE	14	32	47.8	120.8	1.54	1.00	1	3	2002

Table C6b - Catalog of Extreme Storms for Region 14 for 2-Hour Duration for Warm Seasons (East Slopes of Cascade Mountains)

EXTREME STORMS AT 24-HOUR DURATION – COOL SEASONS										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-8688	UNDERWOOD 4 W	14	21	45.7	121.6	1.64	0.91	9	27	1947
35-4008	HOOD RIVER TUCKER BR	14	52	45.7	121.5	2.12	1.00	5	20	1972
45-4999	MARBLEMOUNT R S	14	57	48.5	121.5	1.44	0.90	8	30	1982
45-7342	SATUS PASS 2 SSW	14	43	46.0	120.7	2.44	1.30	5	29	1983
45-2384	EASTON	14	61	47.2	121.2	2.90	1.80	8	26	1983
45-5133	MAZAMA	14	60	48.6	120.4	2.08	1.10	7	16	1985
45-4999	MARBLEMOUNT R S	14	57	48.5	121.5	1.28	0.80	9	5	1985
45-3183	GLENWOOD	14	58	46.0	121.3	1.33	0.60	9	9	1985
45-6472	PESHASTIN TELEMETERI	14	29	47.6	120.6	1.53	0.80	8	6	1991
45-2157	DIABLO DAM	14	56	48.7	121.1	1.49	1.00	7	20	1992
45-3183	GLENWOOD	14	58	46.0	121.3	1.33	0.60	6	30	1998
35-4008	HOOD RIVER TUCKER BR	14	52	45.7	121.5	3.39	1.60	9	18	1998
45-2384	EASTON	14	61	47.2	121.2	1.45	0.90	9	8	2000
35-0571	BEAR SPRINGS RS	14	40	45.1	121.5	2.02	1.00	9	14	2001

Table C7 - Catalog of Extreme Storms for Transition Zone 147 for 2-Hour Duration (Eastern Foothills of Cascade Mountains)

EXTREME STORMS AT 2-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-2505	ELLENSBURG	147	57	47.0	120.5	1.70	0.62	5	12	1943
45-9465	YAKIMA AIRPORT	147	63	46.6	120.5	2.28	0.90	8	19	1944
45-2505	ELLENSBURG	147	57	47.0	120.5	1.64	0.60	6	13	1946
45-5327	METHOW 2	147	38	48.1	120.0	2.28	1.08	8	10	1948
45-5327	METHOW 2	147	38	48.1	120.0	1.88	0.89	6	17	1950
45-9079	WENATCHEE EXP STN	147	54	47.4	120.4	2.79	1.29	8	10	1952
45-9079	WENATCHEE EXP STN	147	54	47.4	120.4	2.98	1.38	8	25	1956
45-5731	NACHES 10 NW	147	51	46.9	120.8	2.21	0.90	5	5	1957
35-5734	MORO	147	54	45.5	120.7	2.21	0.84	6	26	1958
45-6188	OROVILLE 3 NW	147	28	49.0	119.5	2.54	1.27	6	11	1964
35-5734	MORO	147	54	45.5	120.7	2.36	0.90	6	9	1972
45-2505	ELLENSBURG	147	57	47.0	120.5	1.64	0.60	4	20	1973
45-9465	YAKIMA AIRPORT	147	63	46.6	120.5	2.49	0.98	8	18	1975
45-9079	WENATCHEE EXP STN	147	54	47.4	120.4	2.38	1.10	10	31	1980
35-5734	MORO	147	54	45.5	120.7	2.10	0.80	9	27	1981
45-5731	NACHES 10 NW	147	51	46.9	120.8	2.95	1.20	7	7	1982
35-0265	ARLINGTON	147	51	45.7	120.2	2.02	0.69	9	19	1982
45-9465	YAKIMA AIRPORT	147	63	46.6	120.5	1.95	0.77	8	21	1990
45-2505	ELLENSBURG	147	57	47.0	120.5	1.64	0.60	7	24	1991
35-0265	ARLINGTON	147	51	45.7	120.2	2.35	0.80	4	29	1992
45-2505	ELLENSBURG	147	57	47.0	120.5	2.46	0.90	7	3	1998

Table C8 - Catalog of Extreme Storms for Region 77 for 2-Hour Duration (Central Basin)

EXTREME STORMS AT 2-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-8207	SUNNYSIDE	77	59	46.3	120.0	4.44	1.62	6	7	1947
45-3515	HARRINGTON 1 NW	77	61	47.5	118.3	2.57	1.03	6	10	1948
45-9327	WILSON CREEK	77	39	47.4	119.1	3.76	1.50	6	18	1950
45-3883	ICE HARBOR DAM	77	21	46.2	118.9	3.46	1.67	6	5	1957
45-6400	PASCO	77	57	46.2	119.1	1.84	0.58	6	6	1957
45-6400	PASCO	77	57	46.2	119.1	2.22	0.70	10	1	1957
45-5231	MCNARY DAM	77	23	45.9	119.3	3.35	0.97	10	1	1957
45-1767	COULEE DAM 1 SW	77	38	48.0	119.0	2.13	0.85	4	29	1961
45-1690	CONNELL 1 W	77	40	46.7	118.9	2.06	0.64	5	10	1961
45-1767	COULEE DAM 1 SW	77	38	48.0	119.0	1.83	0.73	9	16	1963
45-9327	WILSON CREEK	77	39	47.4	119.1	2.88	1.15	6	17	1965
45-4841	LWR MONUMENTAL DAM	77	16	46.6	118.5	2.13	0.75	9	13	1966
45-9397	WITHROW	77	23	47.7	119.8	1.84	0.94	8	14	1968
45-4679	LIND 3 NE	77	59	47.0	118.6	1.98	0.70	12	21	1969
45-3515	HARRINGTON 1 NW	77	61	47.5	118.3	1.75	0.70	7	20	1976
45-1690	CONNELL 1 W	77	40	46.7	118.9	1.93	0.60	8	30	1977
45-3515	HARRINGTON 1 NW	77	61	47.5	118.3	1.75	0.70	7	3	1978
45-6400	PASCO	77	57	46.2	119.1	2.22	0.70	9	13	1980
45-3515	HARRINGTON 1 NW	77	61	47.5	118.3	2.50	1.00	6	1	1982
35-8717	TYGH VALLEY	77	21	45.2	121.2	2.60	1.10	7	30	1985
45-8207	SUNNYSIDE	77	59	46.3	120.0	3.01	1.10	9	15	1986
45-1400	CHIEF JOSEPH DAM	77	51	48.0	119.7	2.42	1.00	7	25	1987
45-4679	LIND 3 NE	77	59	47.0	118.6	1.98	0.70	8	20	1990
45-8207	SUNNYSIDE	77	59	46.3	120.0	1.92	0.70	6	20	1991
45-1400	CHIEF JOSEPH DAM	77	51	48.0	119.7	2.66	1.10	7	9	1993
45-4679	LIND 3 NE	77	59	47.0	118.6	3.68	1.30	7	22	1993

Table C9 - Catalog of Extreme Storms for Region 7 for 24-Hour Duration
(Okanogan, Spokane, Palouse)

EXTREME STORMS AT 2-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
45-6982	REPUBLIC RANGER STN	7	60	48.6	118.7	2.67	1.43	8	23	1941
45-2030	DAYTON 1 WSW	7	60	46.3	118.0	1.86	0.79	7	8	1946
45-7956	SPRAGUE	7	38	47.3	118.0	1.92	0.72	6	17	1950
45-1630	COLVILLE	7	56	48.5	117.9	1.90	0.90	7	19	1950
45-6789	PULLMAN 2 NW	7	57	46.8	117.2	3.83	1.77	8	10	1952
45-8926	WALLA WALLA 3 W	7	22	46.1	118.4	1.68	0.69	5	7	1956
35-1765	CONDON	7	53	45.2	120.2	2.14	1.06	7	10	1956
45-1630	COLVILLE	7	56	48.5	117.9	1.77	0.84	5	13	1957
45-8931	WALLA WALLA WSO CITY	7	47	46.0	118.3	2.97	1.60	5	24	1958
45-2030	DAYTON 1 WSW	7	60	46.3	118.0	1.60	0.68	11	22	1960
35-1765	CONDON	7	53	45.2	120.2	2.14	1.06	6	16	1961
35-3827	HEPPNER	7	33	45.4	119.6	1.72	0.63	8	14	1961
45-6982	REPUBLIC RANGER STN	7	60	48.6	118.7	2.35	1.26	8	9	1962
45-6789	PULLMAN 2 NW	7	57	46.8	117.2	3.18	1.47	6	16	1963
45-7956	SPRAGUE	7	38	47.3	118.0	1.47	0.55	8	22	1965
10-5241	LEWISTON AP	7	50	46.4	117.0	2.64	1.26	6	9	1969
45-8931	WALLA WALLA WSO CITY	7	47	46.0	118.3	3.25	1.75	5	26	1971
45-4702	LITTLE GOOSE DAM	7	15	46.6	118.0	1.88	0.65	8	20	1972
45-7938	SPOKANE INTL AP	7	54	47.6	117.5	1.64	0.77	9	19	1973
45-7956	SPRAGUE	7	38	47.3	118.0	1.47	0.55	7	19	1974
35-8726	UKIAH	7	30	45.1	118.9	4.26	2.10	7	9	1975
45-7938	SPOKANE INTL AP	7	54	47.6	117.5	2.04	0.96	6	7	1977
45-9200	WHITMAN MISSION	7	39	46.0	118.5	2.28	0.94	8	5	1977
45-6789	PULLMAN 2 NW	7	57	46.8	117.2	1.51	0.70	8	26	1977
45-7938	SPOKANE INTL AP	7	54	47.6	117.5	1.64	0.77	7	1	1978
45-2030	DAYTON 1 WSW	7	60	46.3	118.0	2.83	1.20	7	7	1978
35-6546	PENDLETON MUNICIPAL	7	54	45.7	118.9	1.96	0.79	8	22	1978
10-7188	PLUMMER 3 WSW	7	48	47.3	117.0	2.55	1.30	5	25	1980
45-6982	REPUBLIC RANGER STN	7	60	48.6	118.7	2.61	1.40	8	10	1983
35-6546	PENDLETON MUNICIPAL	7	54	45.7	118.9	1.88	0.76	9	9	1985
45-1630	COLVILLE	7	56	48.5	117.9	2.74	1.30	8	9	1989
45-7938	SPOKANE INTL AP	7	54	47.6	117.5	1.79	0.84	7	24	1990
35-6546	PENDLETON MUNICIPAL	7	54	45.7	118.9	1.68	0.68	6	6	1991
45-9200	WHITMAN MISSION	7	39	46.0	118.5	1.94	0.80	7	22	1992
35-1765	CONDON	7	53	45.2	120.2	3.43	1.70	7	13	1993
35-3830	HEPPNER 5 SSE	7	28	45.3	119.5	2.63	1.10	7	19	1993
35-9213	WESTON	7	41	45.8	118.4	2.04	0.90	8	16	1993
10-5241	LEWISTON AP	7	50	46.4	117.0	3.37	1.61	7	10	1998
35-1765	CONDON	7	53	45.2	120.2	2.42	1.20	7	27	1998
35-9213	WESTON	7	41	45.8	118.4	1.59	0.70	10	8	2000
10-7269	PORTHILL 1 SW	7	29	49.0	116.5	1.83	0.80	7	8	2002

Table C10 - Catalog of Extreme Storms for Region 13 for 2-Hour Duration
(Northeastern Mountains and Blue Mountains)

EXTREME STORMS AT 2-HOUR DURATION										
STATION ID	STATION NAME	REGION	YEARS RECORD	LAT	LONG	RATIO TO MEAN	PRECIP (in)	MO N	DAY	YEAR
10-2159	COTTONWOOD 2 WSW	13	49	46.0	116.4	3.72	2.07	8	1	1948
45-2037	DAYTON 9 SE	13	34	46.2	117.9	1.54	0.74	9	15	1949
45-0839	BOUNDARY	13	18	49.0	117.6	1.56	0.68	7	10	1950
45-2197	DIXIE 4 SE	13	61	46.1	118.1	1.57	0.90	10	18	1953
35-8746	UNION EXPERIMENT STN	13	54	45.2	117.9	1.77	0.77	5	10	1958
10-1831	CLARKIA RANGER STATN	13	44	47.0	116.3	2.84	1.59	7	7	1958
10-0789	BENTON DAM	13	28	48.4	116.8	1.86	0.96	7	29	1958
45-2037	DAYTON 9 SE	13	34	46.2	117.9	1.48	0.71	12	3	1958
35-8549	TOLLGATE	13	12	45.8	118.1	1.31	0.70	11	21	1959
10-1079	BONNERS FERRY	13	54	48.7	116.3	2.17	0.99	9	10	1962
35-8746	UNION EXPERIMENT STN	13	54	45.2	117.9	2.55	1.11	6	16	1963
10-1831	CLARKIA RANGER STATN	13	44	47.0	116.3	2.39	1.34	12	4	1964
45-2197	DIXIE 4 SE	13	61	46.1	118.1	1.57	0.90	6	16	1965
35-8746	UNION EXPERIMENT STN	13	54	45.2	117.9	1.82	0.79	8	2	1965
35-4620	LA GRANDE CAA AIRPOR	13	17	45.3	118.0	2.03	0.87	8	24	1965
35-4622	LA GRANDE	13	32	45.3	118.1	1.73	0.77	5	10	1968
10-2845	DWORSHAK FISH HATCH	13	35	46.5	116.3	1.60	0.80	6	13	1971
10-2159	COTTONWOOD 2 WSW	13	49	46.0	116.4	1.87	1.04	7	31	1972
35-5396	MEACHAM WSO AIRPORT	13	26	45.5	118.4	1.66	0.88	7	8	1974
45-2197	DIXIE 4 SE	13	61	46.1	118.1	1.57	0.90	7	12	1975
10-2966	ENAVILLE	13	26	47.6	116.3	1.73	0.90	8	3	1976
10-8137	SANDPOINT EXP STATN	13	51	48.3	116.6	1.81	0.90	8	19	1976
10-8137	SANDPOINT EXP STATN	13	51	48.3	116.6	2.01	1.00	8	24	1977
10-1079	BONNERS FERRY	13	54	48.7	116.3	1.97	0.90	4	30	1979
10-2966	ENAVILLE	13	26	47.6	116.3	1.73	0.90	8	20	1979
45-8348	TEKOA	13	23	47.2	117.1	1.56	0.80	5	14	1981
10-6148	MOSCOW 5 NE	13	28	46.8	116.9	1.46	0.80	6	5	1981
10-2845	DWORSHAK FISH HATCH	13	35	46.5	116.3	1.60	0.80	2	16	1982
45-1395	CHEWELAH	13	29	48.3	117.7	1.81	1.00	7	20	1983
45-0849	BOUNDARY SWITCHYRD	13	29	49.0	117.4	2.18	1.20	10	25	1984
45-5946	NORTHPORT	13	42	48.9	117.8	1.86	0.90	5	27	1987
10-1079	BONNERS FERRY	13	54	48.7	116.3	1.75	0.80	6	15	1987
10-2845	DWORSHAK FISH HATCH	13	35	46.5	116.3	1.60	0.80	5	27	1989
35-8985	WALLA WALLA 13 ESE	13	51	46.0	118.1	2.28	1.60	6	6	1991
35-6636	PILOT ROCK 11 E	13	24	45.5	118.6	2.17	1.30	8	14	1991
10-6148	MOSCOW 5 NE	13	28	46.8	116.9	1.46	0.80	8	22	1992
35-4622	LA GRANDE	13	32	45.3	118.1	2.24	1.00	8	16	1993
35-8985	WALLA WALLA 13 ESE	13	51	46.0	118.1	1.85	1.30	11	8	1995
10-1370	CALDER	13	31	47.3	116.2	2.12	1.10	2	5	1996
10-1956	COEUR D'ALENE	13	39	47.7	116.8	1.81	0.90	6	30	1998
45-5946	NORTHPORT	13	42	48.9	117.8	2.28	1.10	7	11	1998
10-1956	COEUR D'ALENE	13	39	47.7	116.8	1.60	0.80	5	21	1999
45-8348	TEKOA	13	23	47.2	117.1	1.56	0.80	6	27	2001
10-2892	ELK RIVER 1 S	13	29	46.8	116.2	1.68	1.00	12	7	2001

Appendix D

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:

$$\text{Mean} = L_1 \tag{D1}$$

Scale, L-Cv (t_2):

$$t_2 = L_2/L_1 \tag{D2}$$

L-Skewness (t_3):

$$t_3 = L_3/L_2 \tag{D3}$$

L-Kurtosis (t_4):

$$t_4 = L_4/L_2 \tag{D4}$$

where:

$$L_1 = \beta_0 \tag{D5}$$

$$L_2 = 2\beta_1 - \beta_0 \tag{D6}$$

$$L_3 = 6\beta_2 - 6\beta_1 + \beta_0 \tag{D7}$$

$$L_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \tag{D8}$$

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

$$\beta_0 = n^{-1} \sum_{j=1}^{n} x_j \tag{D9}$$

$$\beta_1 = n^{-1} \sum_{j=2}^{n} x_j \, [(j-1)/(n-1)] \tag{D10}$$

$$\beta_2 = n^{-1} \sum_{j=3}^{n} x_j \, [(j-1)(j-2)]/[(n-1)(n-2)] \tag{D11}$$

$$\beta_3 = n^{-1} \sum_{j=4}^{n} x_j \, [(j-1)(j-2)(j-3)]/[(n-1)(n-2)(n-3)] \tag{D12}$$

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:

$$n_R = \sum_{i=1}^{N} n_i \tag{D13}$$

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

$$L_1^R = 1 \tag{D14}$$

Regional L-Cv (t_2^R):

$$t_2^R = n_R^{-1} \sum_{i=1}^{N} n_i \, t_2^i \tag{D15}$$

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):

$$t_4^R = n_R^{-1} \sum_{i=1}^{N} n_i \, t_4^i \tag{D17}$$

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:

$$\text{bias } t_3^R = 4N(.10 - t_4^R) / n_R \tag{D18}$$

$$\text{bias } t_4^R = 4N(.15 - t_4^R) / n_R \tag{D19}$$

Appendix E

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.