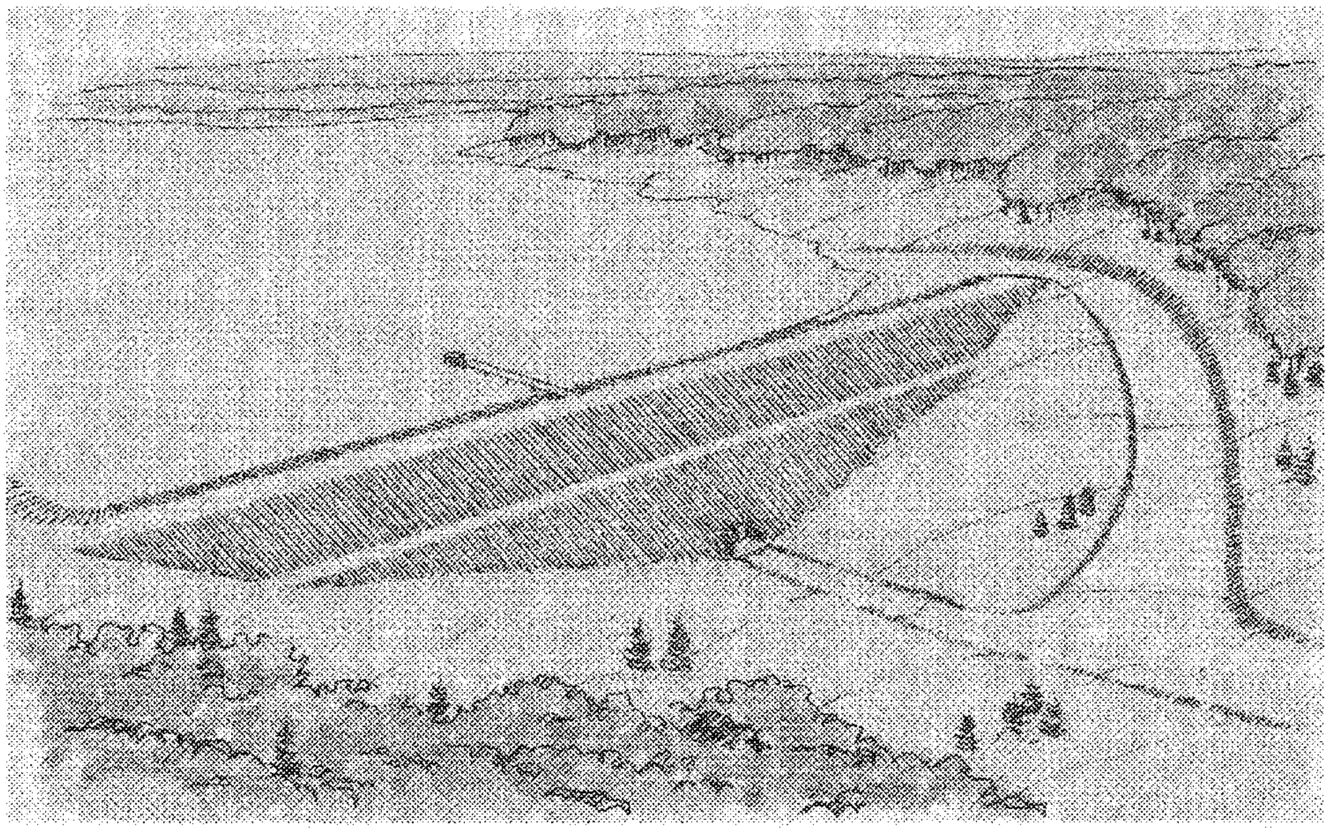

Dam Safety Guidelines

Technical Note 3:

Design Storm Construction

WASHINGTON STATE DEPARTMENT OF ECOLOGY

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WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

DAM SAFETY GUIDELINES

TECHNICAL NOTE 3

DESIGN STORM CONSTRUCTION

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for

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October 2009 (Revised)
92-55G

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

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

OVERVIEW

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

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

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

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

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

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

1. INTRODUCTION

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

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

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

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

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

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

1.1 TERMINOLOGY

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

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

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

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

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

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

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

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

Hyetograph - A graphical representation of precipitation as it occurs with time. It may be for a specific location or represent an average over a specified area. It may be discretized or continuous over time, displaying either precipitation intensities, incremental precipitation or accumulated precipitation.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1.2 GENERAL GUIDANCE IN APPLYING CANDIDATE DESIGN STORMS

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

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

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

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

1.2.1 Western Washington

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

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

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

1.2.2 Eastern Washington

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

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

1.2.3 Design Storm Spatial Distribution

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

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

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

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

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

WATERSHED SIZE	STORM INTERDURATION									
	¼-HR	1-HR	2-HR	3-HR	6-HR	12-HR	18-HR	24-HR	48-HR	72-HR
Short-Duration Storm										
1-mi²	100%	100%	100%	100%	100%	-	-	-	-	-
2-mi²	93%	97%	98%	98%	99%	-	-	-	-	-
5-mi²	80%	88%	90%	91%	92%	-	-	-	-	-
10-mi²	69%	79%	82%	83%	85%	-	-	-	-	-
Intermediate-Duration Storm										
10-mi²	100%	100%	100%	100%	100%	100%	100%	-	-	-
20-mi²	85%	94%	95%	95%	96%	97%	97%	-	-	-
50-mi²	76%	84%	86%	88%	91%	93%	93%	-	-	-
100-mi²	67%	75%	79%	83%	85%	88%	88%	-	-	-
Long-Duration Storm										
10-mi²	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
20-mi²	85%	94%	95%	95%	96%	97%	97%	98%	98%	98%
50-mi²	76%	84%	86%	88%	91%	93%	93%	95%	95%	95%
100-mi²	67%	75%	79%	83%	85%	88%	88%	92%	92%	92%

2. SELECTING THE DESIGN STEP

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

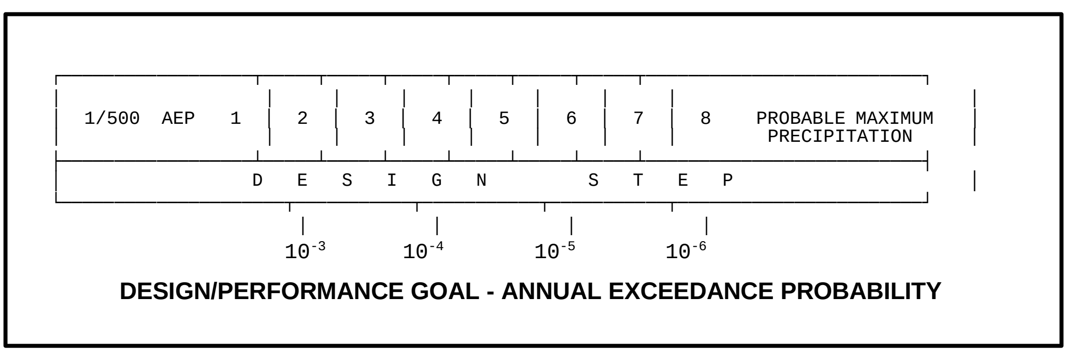

Figure 1 – Design Step Format as Applied to Design Storms

2.1 RELATION OF DESIGN STEP TO PROBABLE MAXIMUM PRECIPITATION

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

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

2.1.1 Constraints on Applying PMP and Design Step

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

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

3. COMPUTING PRECIPITATION FOR SCALING CANDIDATE DESIGN STORMS

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

3.1 COMPUTING PRECIPITATION-FREQUENCY RELATIONSHIPS

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

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

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

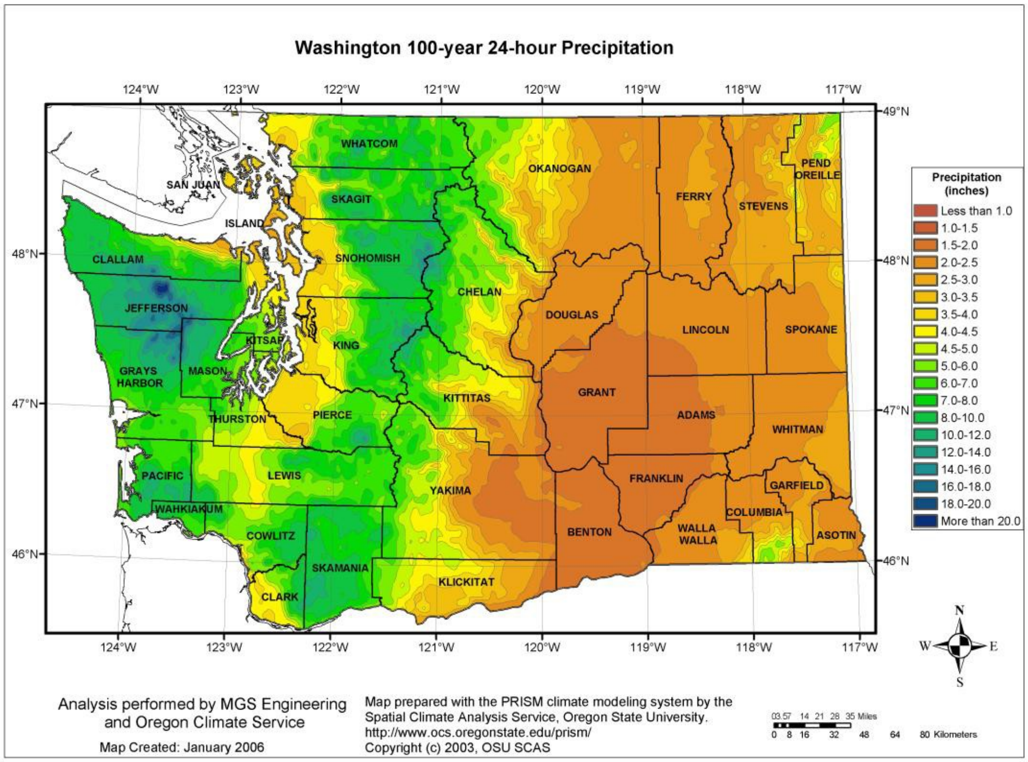

Figure 2 – Color-Shaded Isopluvial Map of 24-Hour Precipitation Maxima for Washington State, 100-Year Recurrence Interval

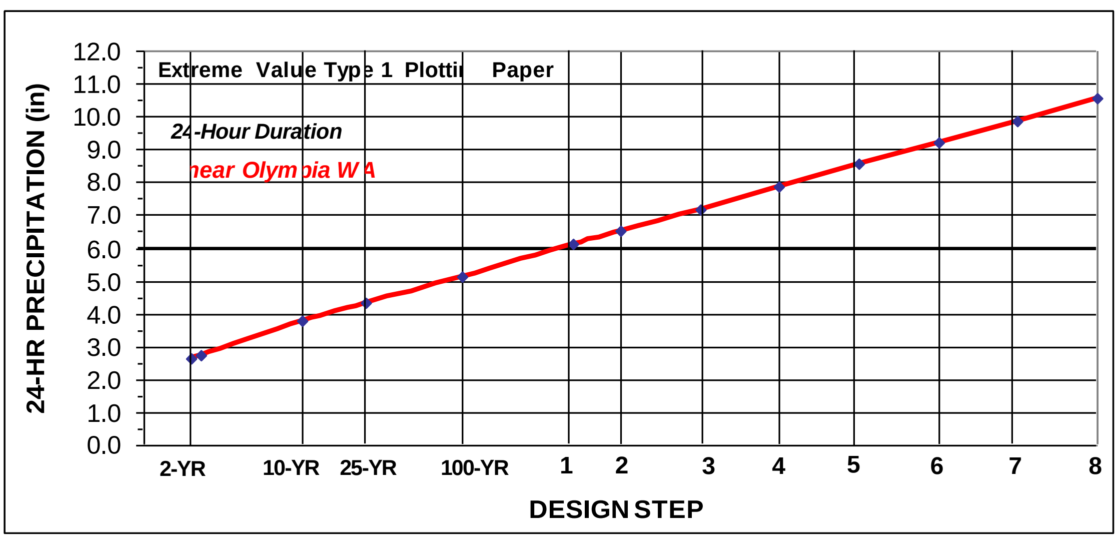

Figure 3 – Precipitation-Frequency Relationship for 24-hour Precipitation Maxima for a Site near Olympia, Washington

3.1.1 Large Watersheds

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

3.1.2 Design Usage

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

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

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

where:

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

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

4. DEVELOPING CANDIDATE DESIGN STORMS

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

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

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

4.1 DIMENSIONLESS DESIGN HYETOGRAPHS

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

4.1.1 Dimensionless Design Hyetographs Organized by Climatic Region

Climatic regions are geographic areas with similar climatic and topographic characteristics that result in storms having similar storm characteristics. One of the major changes that affected this Technical Note was a refinement of the climatic region delineation contained in the 2006 regional precipitation-frequency analysis (Schaefer et al[20, 21]). This required regrouping of the 252 historical storms that were analyzed in Ecology Report 89-51 (Schaefer[19]). Similarly, the 142 historical storms observed in the period from 1986-2006 were grouped according to the new climatic regions, and analyzed according to procedures described in the report 89-51. Separate analyses were then conducted for each climatic region for each of the three storm durations.

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

Climatic Regions for Western Washington

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

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

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

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

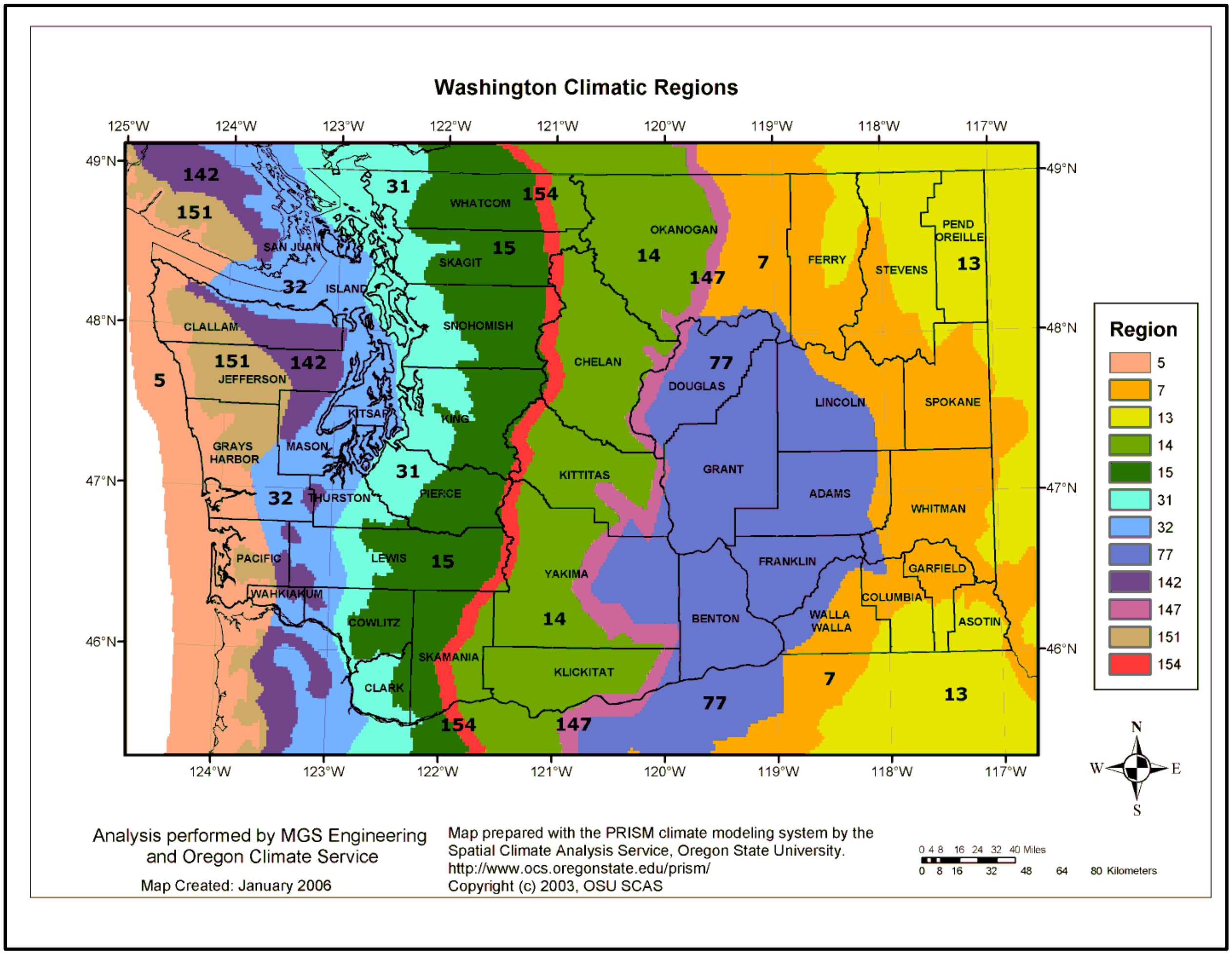

Figure 4 – Delineation of Climatic Regions and Transition Zones for Washington State and Surrounding Areas

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

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

Climatic Regions[3] for Eastern Washington

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

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

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

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

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

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

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

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

4.1.2 Changes Made in Updating Dimensionless Design Hyetographs

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

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

4.1.3 Short-Duration Design Storms

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

4.1.4 Intermediate-Duration Design Storms

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

4.1.5 Long-Duration Design Storms

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

4.1.6 Intensity Index Format for Dimensionless Design Hyetographs

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

4.1.7 Dimensionless Depth-Duration Curves for Large Watersheds

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

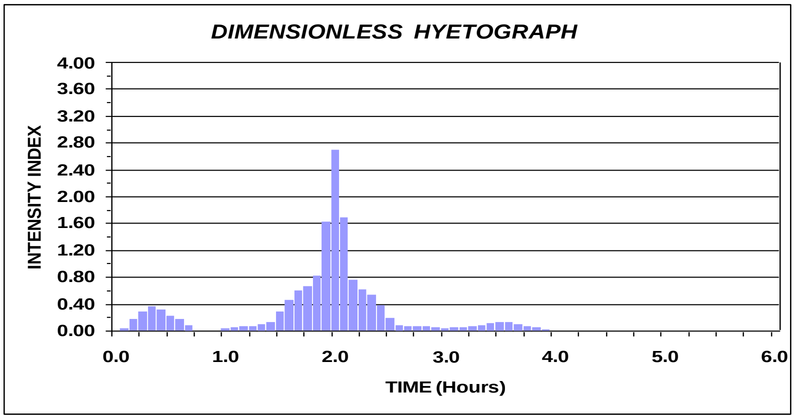

Figure 5 – Short-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 5, 15, 31, 32, 142, 151, and Transition Zone 154

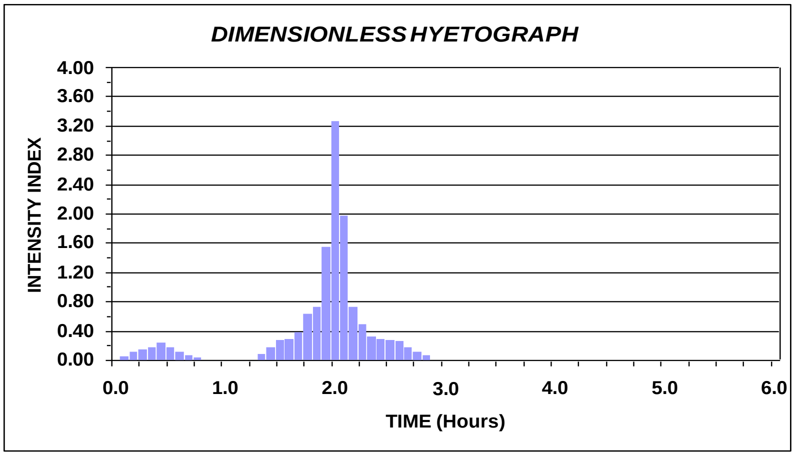

Figure 6 – Short-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 13, 14 and Transition Zone 147

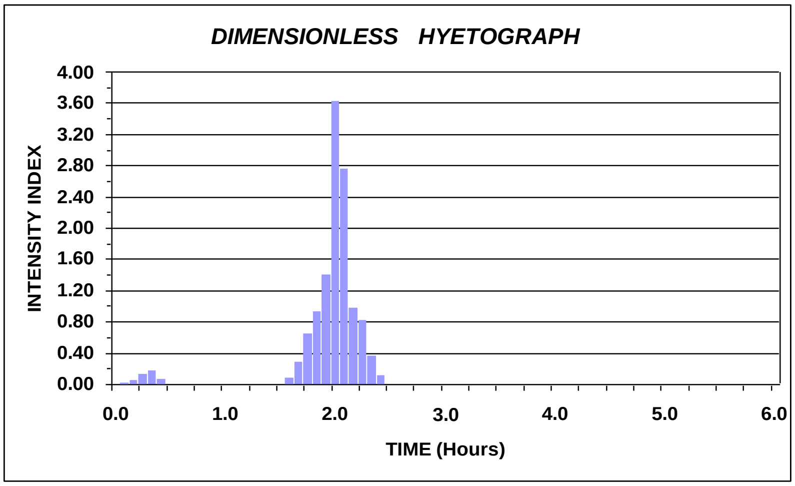

Figure 7 – Short-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7 and 77

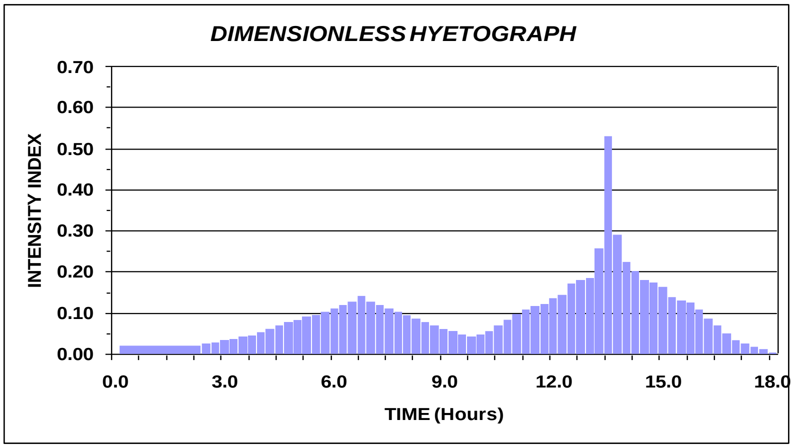

Figure 8 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Region 5

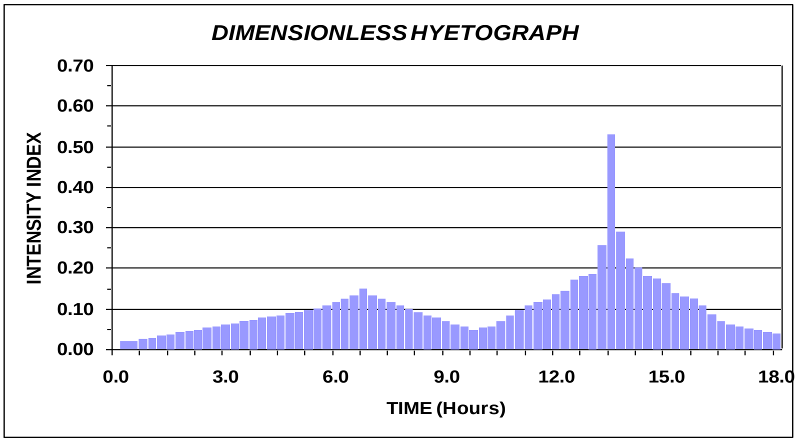

Figure 9 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 15, 151, 142 and Transition Zone 154

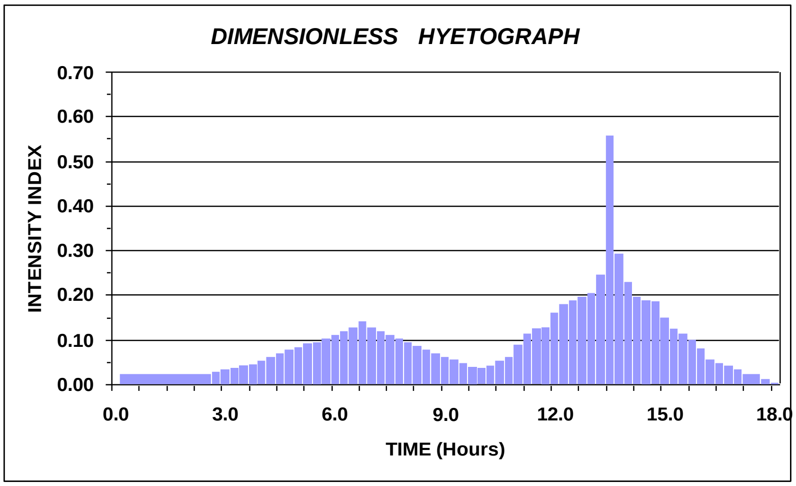

Figure 10 – Intermediate-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 31, 32

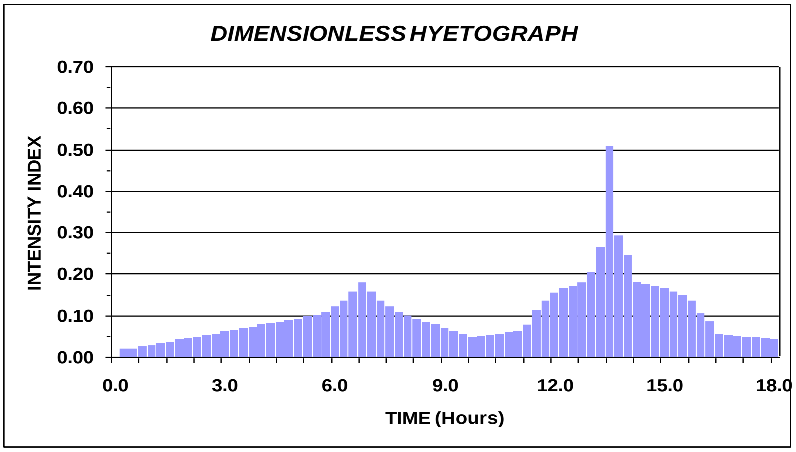

Figure 11 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 14

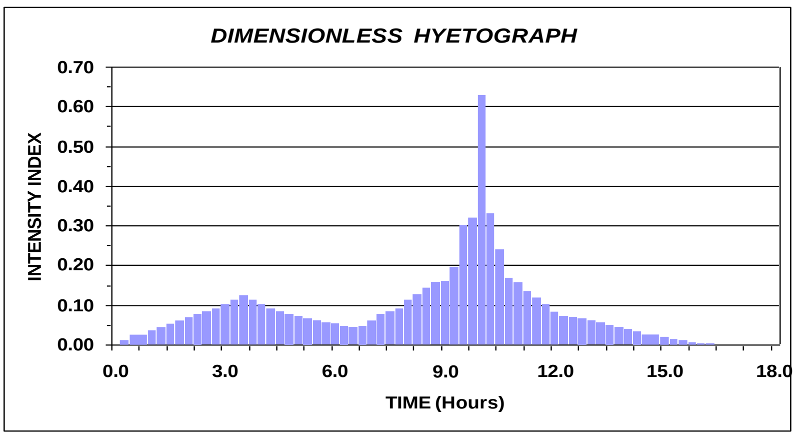

Figure 12 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7 and 77

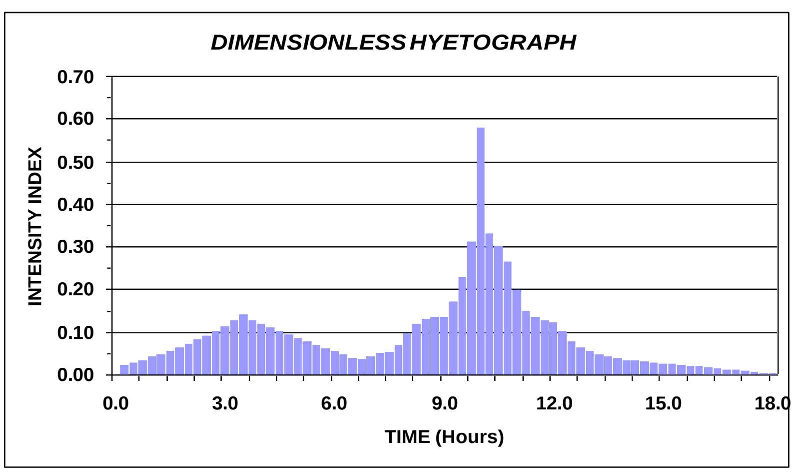

Figure 13 – Intermediate-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 13

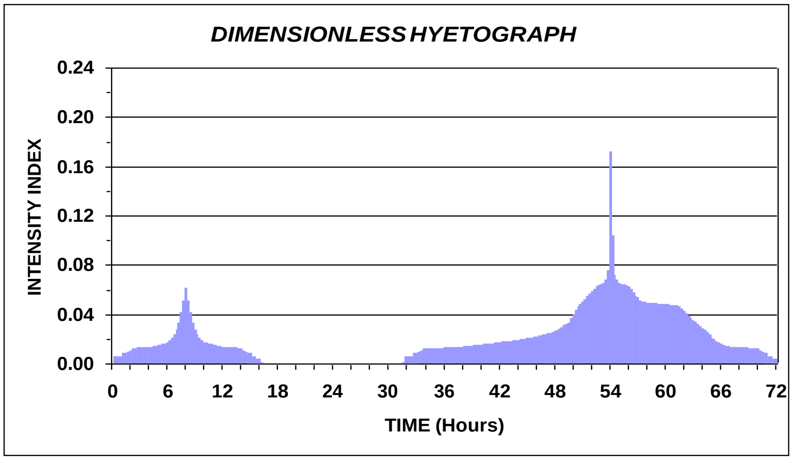

Figure 14 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Region 5

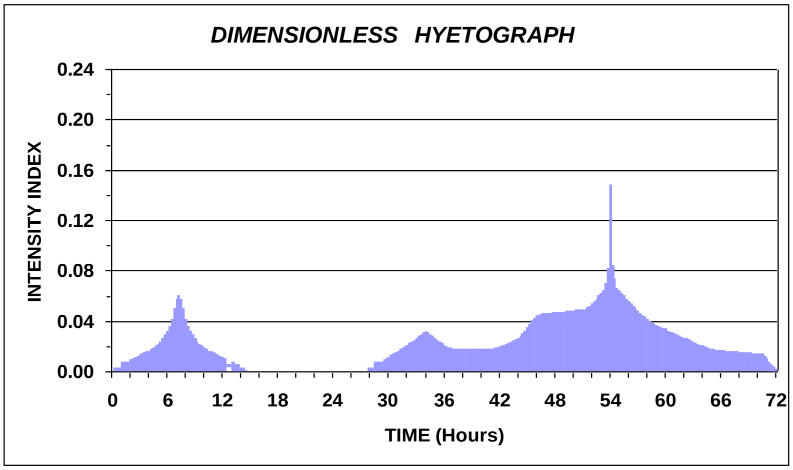

Figure 15 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 15, 142, 151 and Transition Zone 154

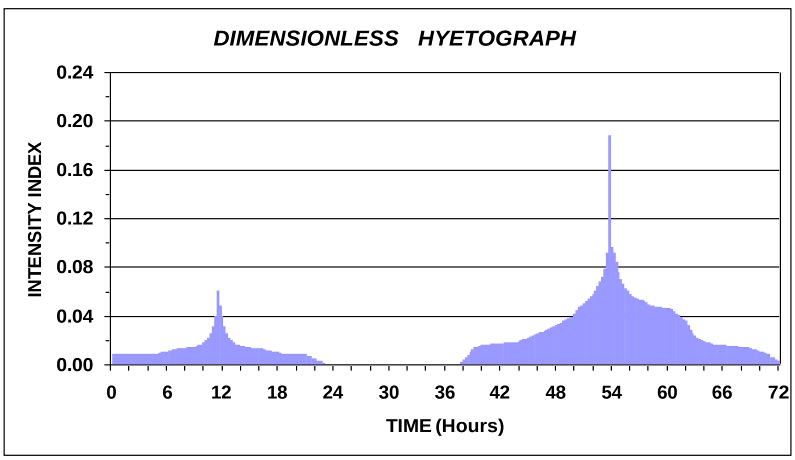

Figure 16 – Long-Duration Dimensionless Design Hyetograph for Western Washington, Climatic Regions 31, 32

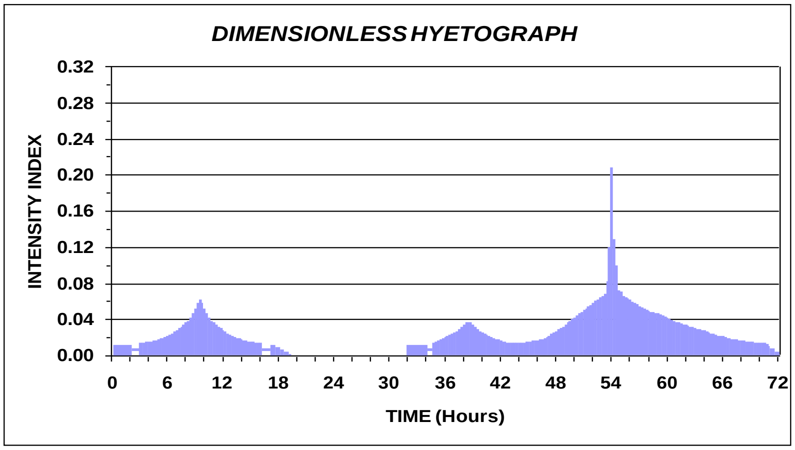

Figure 17 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 14

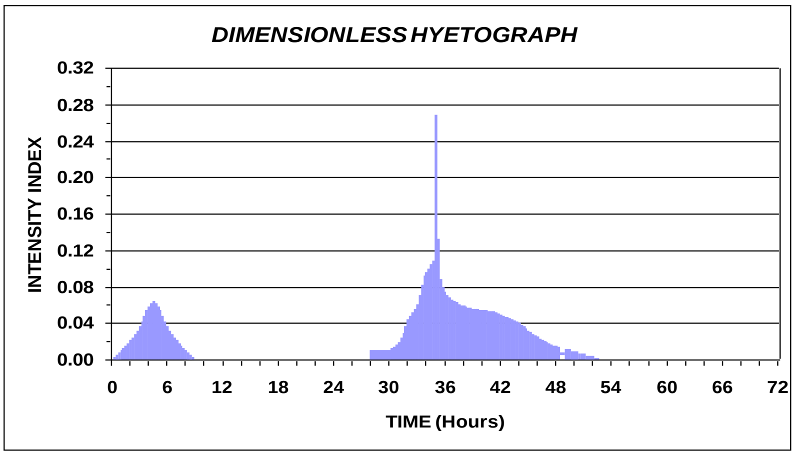

Figure 18 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Regions 7, 77

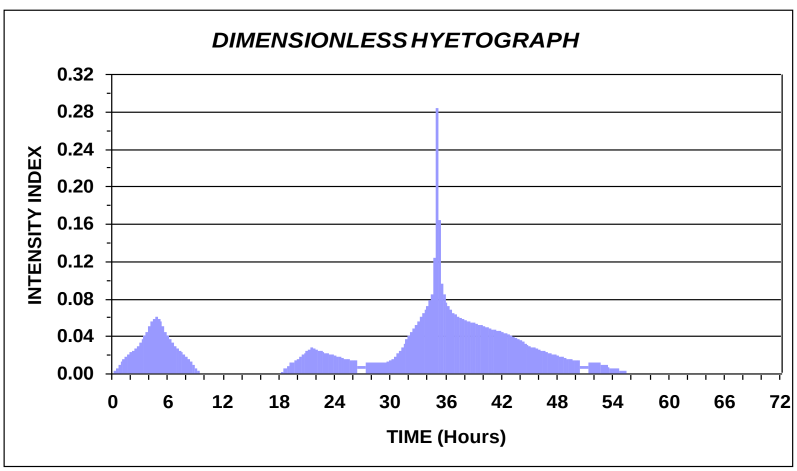

Figure 19 – Long-Duration Dimensionless Design Hyetograph for Eastern Washington, Climatic Region 13

4.2 ASSEMBLING CANDIDATE DESIGN STORMS FOR SMALL WATERSHEDS

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

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

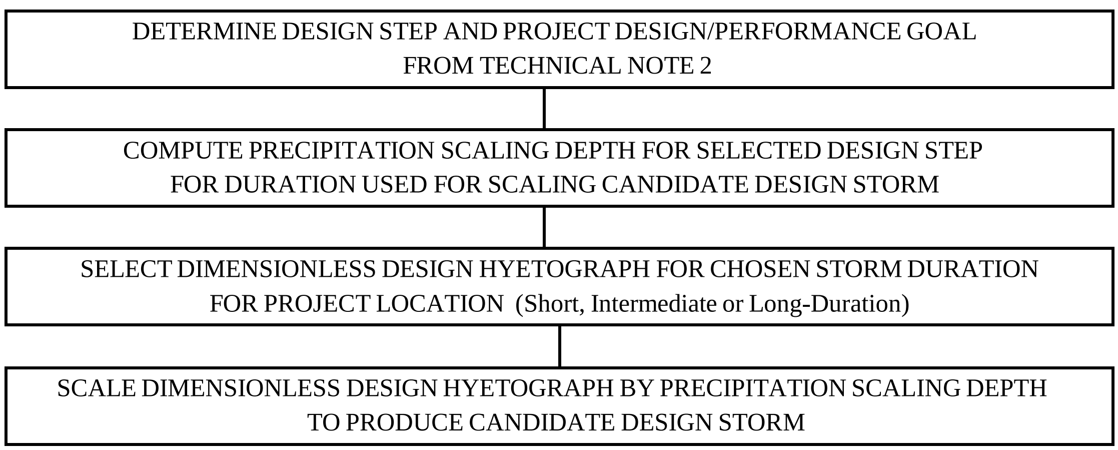

Figure 20 – Flowchart for Construction of a Candidate Design Storm for Small Watersheds

4.2.1 Example Assembly of Short-Duration Candidate Design Storm

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

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

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

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

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

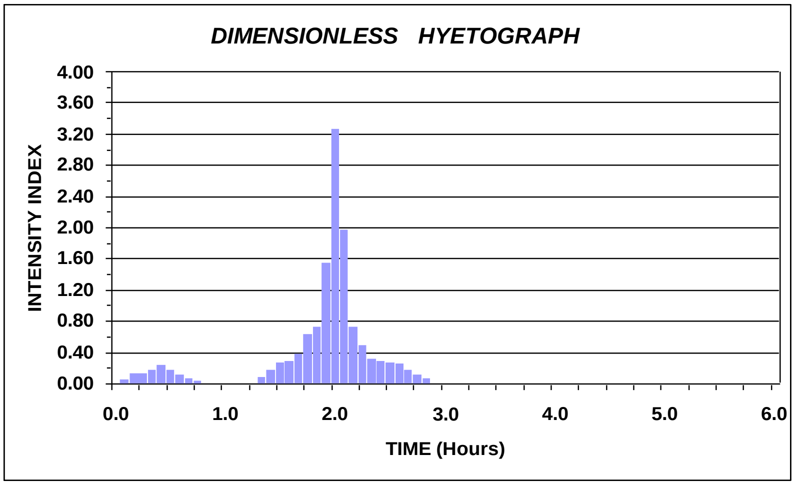

Figure 21 – Short-Duration Dimensionless Design Hyetograph for Transition Zone 147

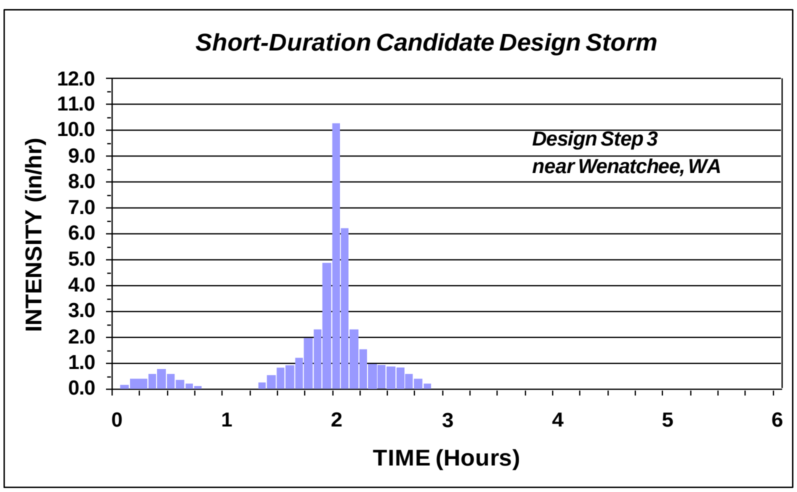

Figure 22 – Scaled Short-Duration Candidate Design Storm for Site near Wenatchee, Washington

4.2.1 Example Assembly of Long-Duration Candidate Design Storm

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

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

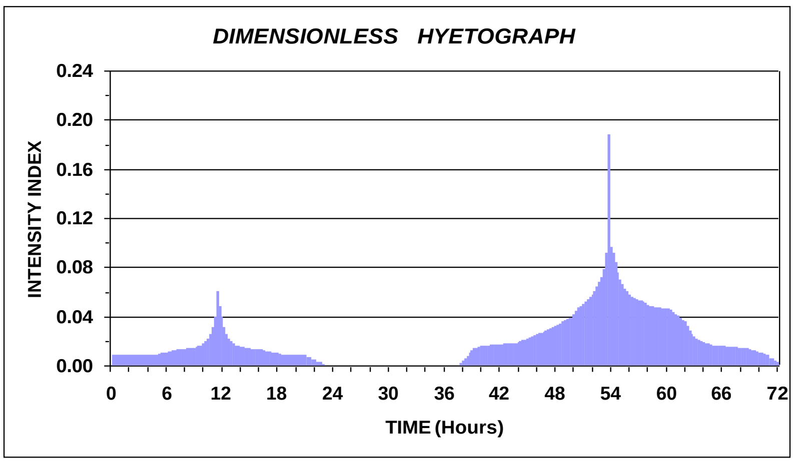

Figure 23 – Long-Duration Dimensionless Design Hyetograph for Climatic Region 32

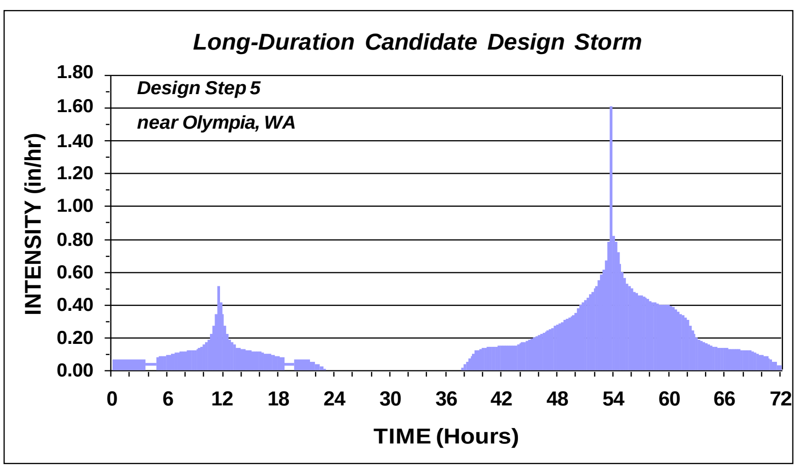

Figure 24 – Scaled Long-Duration Candidate Design Storm for Site near Olympia, Washington

4.3 ASSEMBLING CANDIDATE DESIGN STORMS FOR LARGE WATERSHEDS

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

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

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

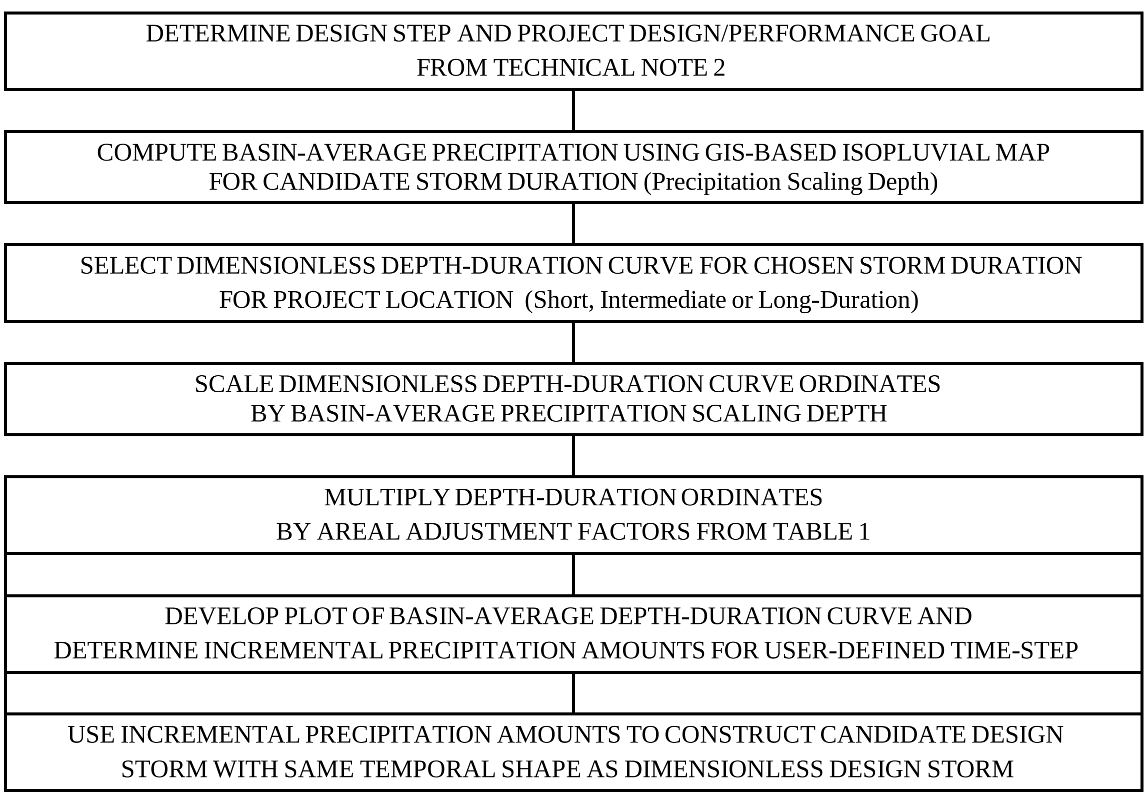

Figure 25 – Flowchart for Construction of a Candidate Design Storm for Large Watersheds

4.3.1 Example Assembly of Intermediate-Duration Candidate Design Storm

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

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

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

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

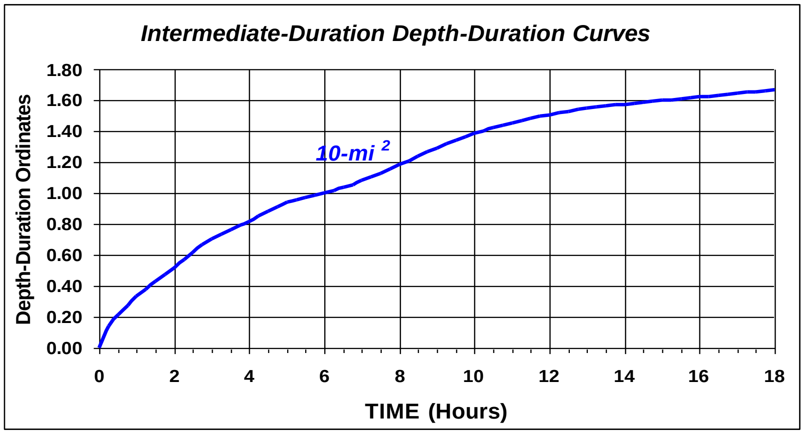

Figure 26 – Intermediate-Duration Dimensionless Depth-Duration Curve for Climatic Region 31

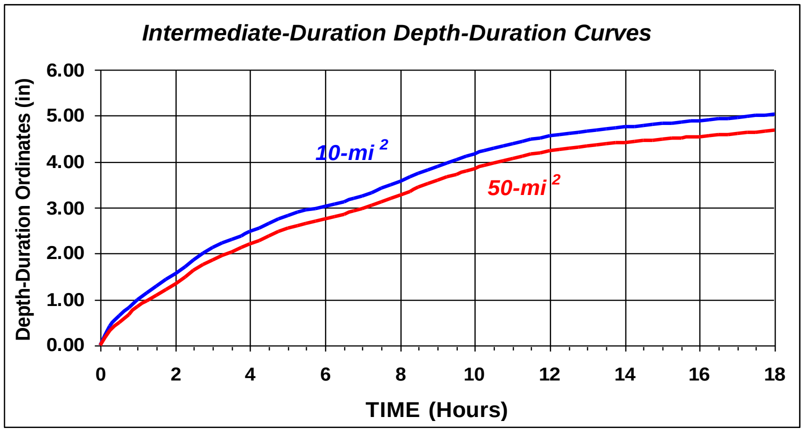

Figure 27 – Scaled Intermediate-Duration Depth-Duration Curves for Climatic Region 31 for Site near Seattle

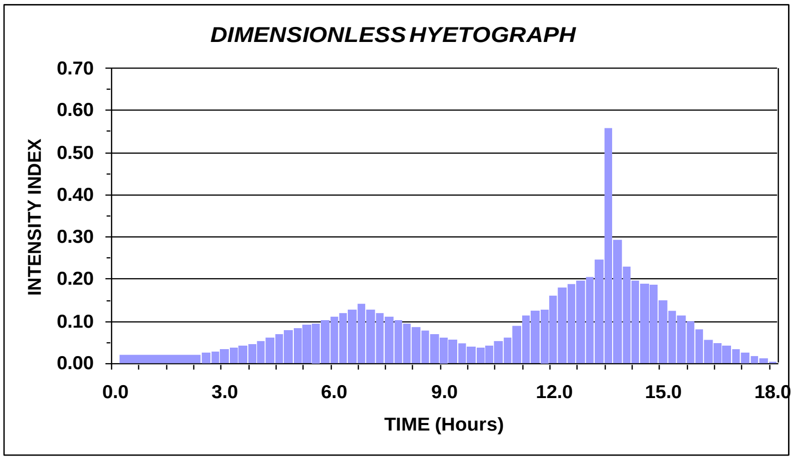

Figure 28 - Intermediate-Duration Dimensionless Design Hyetograph for Climatic Region 31

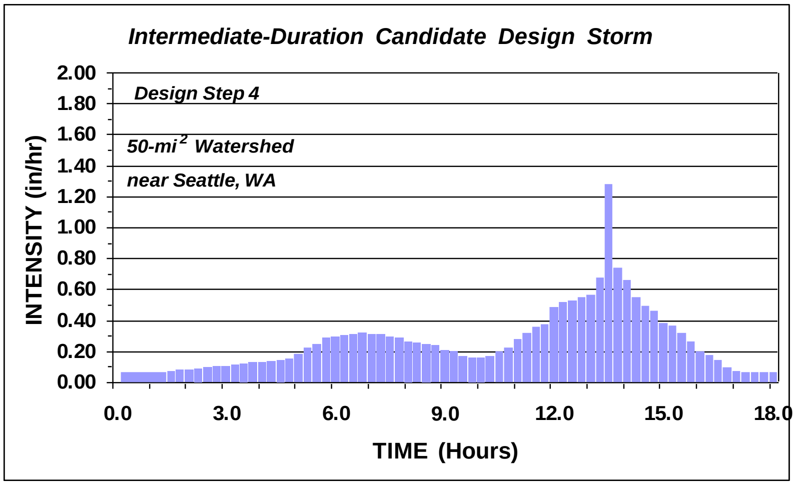

Figure 29 – Intermediate-Duration Candidate Design Storm for a 50-mi^2 Watershed near Seattle, Washington, in Climatic Region 31

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APPENDIX A
CATALOG OF HISTORICAL STORMS

OVERVIEW

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

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

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

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

Scalable historical storms are available through the Dam Safety Office.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX B
DIMENSIONLESS DEPTH-DURATION CURVES

OVERVIEW

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

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

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

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

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

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

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