Procedures for Simplified Stochastic Event Flood Modeling (SSEFM) for Developing Hydrologic Hazard Curves for Semi-Quantitative Risk Analysis (SQRA)

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OVERVIEW

This document describes procedures for developing Hydrologic Hazard Curves (HHCs) that are suitable for use in scoping level and Semi-Quantitative Risk Analyses (SQRA) using Simplified Stochastic Event Flood Modeling (SSEFM) methods. The methodology provides for assembly of HHCs for each flood-frequency characteristic of interest such as: inflow flood peak; inflow runoff volume; maximum reservoir level; depth-duration of reservoir level above a specified elevation; and maximum reservoir discharge. The HHCs are in-turn used to evaluate the likelihood of Potential Failure Modes (PFMs). The SSEFM procedures utilize simplifications and approximations of the detailed Stochastic Event Flood Model (SEFM[21]) that allow estimates of probabilistic hydrologic loadings to be made with a level-of-effort commonly employed in conventional deterministic hydrologic modeling of floods. A detailed stochastic flood analysis is usually needed to develop HHCs that are suitable for final decisions within a Risk-Informed Decision-Making (RIDM) framework.

One of the benefits of using stochastic flood modeling is it offers the opportunity to gain a better understanding of the hydrologic behavior of the watershed and response of the reservoir for rare to extreme storms and floods as compared to deterministic approaches that use conservative assumptions. This is particularly important as it relates to examining seasonal flood responses to storms for typical antecedent soil moisture and watershed conditions. The analyses of data for setting representative soil moisture, watershed conditions and initial reservoir levels provides qualitative/quantitative information about realistic watershed behavior that can be very helpful in make preliminary assessments of hydrologic risk.

Figure 1, below, shows the steps in developing HHCs using the SSEFM method and descriptions of the various steps are provided in the following sections.

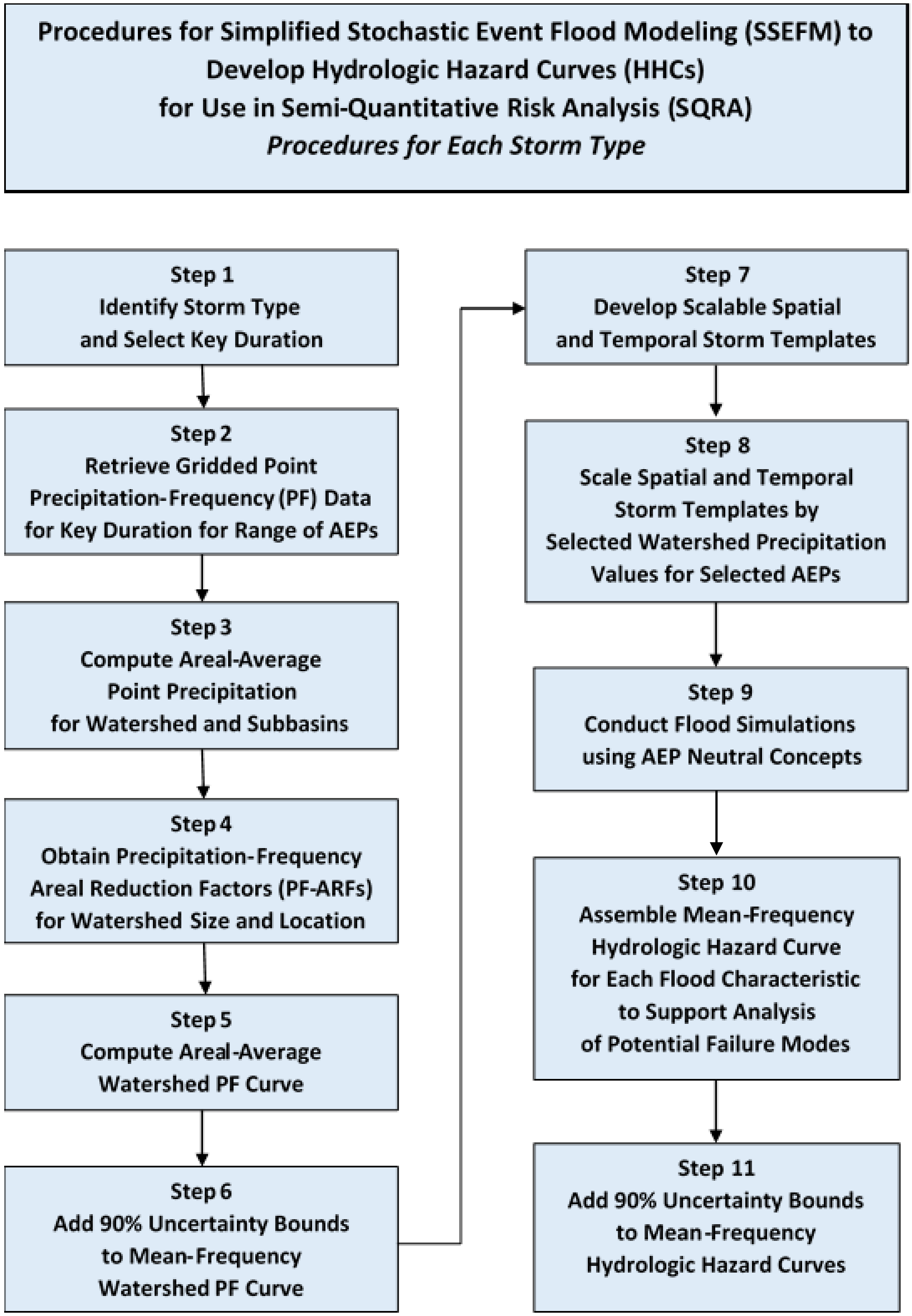


Figure 1 – Flowchart of Tasks in the Simplified SEFM Method
for Computer Simulation of Floods Produced by a Specified Storm Type

1.0 Identify Storm Types that Can Produce Significant Flooding on the Watershed

Identification of the storm type(s) that is critical in producing floods that could pose a hazard to a dam is influenced by the size and geographic location of the watershed and the flood storage volume of the reservoir. This step focuses on the storm types that can affect the watershed by identifying which of four storm types: Mid-Latitude Cyclones (MLC); Tropical Storm and Remnants (TSR); Mesoscale Storm with Embedded Convection (MEC); and Local Storm (LS) are capable of generating floods that could pose a hazard to the dam of interest. This information is important because the various storm types have different: watershed precipitation-frequency characteristics; spatial and temporal storm patterns; and seasonality which result in different flood-frequency characteristics and HHCs.

MLC (Extratropical Cyclone) storm events are synoptic scale low pressure systems that may be fed by atmospheric rivers and often include fronts. This storm type produces long-duration storm events with low to moderate precipitation intensities over very large areas occurring predominantly in the fall, winter and early spring months in the continental U.S.

TSR (Tropical Moisture) is a general category of synoptic scale long-duration storms fed by tropical moisture and includes hurricanes, tropical storms and tropical depressions and their remnants which affect coastal and near-coastal areas adjacent to the Atlantic Ocean and Gulf of Mexico. Remnant TSR atmospheric moisture can also other storm types further inland. These are warm season events that occur primarily June through early November. TSR synoptic scale storms differ from MLCs in several ways. TSRs have warm cores with smaller areal-coverage compared to MLCs which have cool/cold cores, smaller larger areal-coverage and commonly have cold fronts associated with the circulation pattern. TSRs typically have sequences of rain bands with some level of convection (thunderstorm cells) that produces temporal patterns with bursts of precipitation amongst a background level of precipitation. Precipitation-frequency gridded datasets specifically for the TSR storm type are not commonly available except where detailed SEFM studies have been conducted. Precipitation-frequency gridded datasets are currently available for areas included in the Tennessee Valley Study Area and Texas coastal areas (MetStat et al9,10). For locations where TSR precipitation-frequency information is unavailable, use the all-season, all storm type point precipitation-frequency information from NOAA Atlas 1414 for the 48-hour key duration.

MEC (Large thunderstorm or cluster of thunderstorm cells) is a general category of mesoscale storms which includes Mesoscale Convective Complexes (MCCs) and other mesoscale events with complex clusters of thunderstorm cells that are capable of producing short-duration, very high-intensity precipitation and generating flash floods. These are warm season events typically early April through October primarily affecting areas east of the continental divide. MEC storms do affect areas west of the continental divide but are smaller in scale than the eastern MECs and occur less frequently.

LS (Small thunderstorm) storm types are a general category of smaller convective events which can also produce short-duration, high-intensity precipitation and generate flash floods. The LS storm type is smaller in scale than the MEC storms and generally shorter in total duration. These are storms of interest for smaller watersheds particularly in the inter-mountain west, west of the continental divide. Local Storms typically occur in the warm season from May through September.

Note this storm typing terminology is different than used in Probable Maximum Precipitation (PMP) analyses. General storms (PMP) correspond to synoptic-scale long-duration MLC and TSR storm types that may include localized convection from frontal systems. Local Storms (PMP) generally correspond to short-duration high-intensity MEC storm types east of the continental divide and Local Storms west of the continental divide.

1.1: Select Key Duration(s)

Identify the Key Duration for the applicable storm type(s) where the key duration is representative of the time period when the majority of precipitation typically occurs for a specific storm type and is used for development of the areal-average watershed precipitation-frequency relationship. Key durations for the various storm types are listed in Table 1. The 48-hour duration is typically the key duration for the MLC storm type, with the exception that the 72-hour duration can also be used for locations on the west coast of the US where very long-duration MLCs are common, often fed by atmospheric river conditions. An Alternate Key Duration would only be used if precipitation data are not available for the primary Key Duration shown in column 2 of Table 1.

SEFM and SSEFM account for the natural variability of storm duration through the temporal storm templates which are discussed in Section 7.

Table 1 – Listing of Key Durations for Four Storm Types

STORM TYPE	KEY DURATION (Hours)	ALTERNATE KEY DURATION (Hours)
Local Storm (LS)	2	1
Mesoscale Storm with Embedded Convection (MEC)	6	6
Mid-Latitude Cyclone (MLC)	48, 72	24
Tropical Storm and Remnants (TSR)	48	24

2.0 Retrieve Precipitation-Frequency Gridded Data for Key Duration(s) for Range of AEPs

Point precipitation-frequency (PF) information is used in the development of a watershed PF relationship for each storm/flood type that can pose a hazard to the dam of interest. Point PF gridded datasets for selected Annual Exceedance Probabilities (AEPs) are primarily available from two sources. Regional PF studies have been conducted for several study areas and storm types for use in detailed stochastic flood modeling for dams throughout the U.S. (Figure 2, MGS Engineering Consultants and MetStat[9,10,12,15,17,18,19]). Gridded precipitation datasets for selected AEPs ranging from 1:2 through 10^{-7} are available from those studies. It is anticipated these datasets will be available in the future from third party websites.

Gridded datasets for point PF are also available from NOAA Atlas 14[14] for much of the U.S. for key durations and selected AEPs ranging from 1:2 through 1:1,000 AEP (NOAA, NWS Precipitation Frequency (PF) Documents, http://www.nws.noaa.gov/oh/hdsc/currentpf.htm). NOAA Atlas 14 analyses are based on all-season precipitation without regard to storm type. As such, there is greater uncertainty in estimation of very rare and extreme precipitation because of the possible distortion of statistics due to the mixed population of storm types. For states without recent PF gridded datasets, (Idaho, Alaska), the most recent PF datasets available should be used.

The use of storm typing to produce homogenous datasets for precipitation annual maxima for specific storm types is a very recent advancement (2015, MGS et al[12], appendix E) for regional PF analyses. It is particularly important for hydrologic risk assessment, where the primary interest is in extreme storms and floods. As indicated above, the majority of PF datasets currently available do not distinguish between storm types and represent a mixed population of storm types where the mixture of storm types varies with the duration being analyzed. Studies which included storm typing components have been completed for areas shown in Figure 2. Findings from NOAA Atlas 14 are to be used where regional analyses using storm typing are not available.

For the case of humid climates, the use of a key duration with NOAA Atlas 14 findings helps in obtaining a more representative watershed PF relationship using the NOAA 14 PF gridded datasets. This occurs because the various storm types typically produce significant precipitation magnitudes over a somewhat limited range of durations (Table 1). For sub-humid, semi-arid and arid climates, duration is less effective in separating out storm types and mixed populations of storm types are common. This leads to greater uncertainty in estimation of very rare and extreme storm magnitudes in these climatic settings. It is expected that future regional PF studies for use in hydrologic risk assessments will utilize storm typing, as storm typing is now accepted practice at all of the Federal dam safety agencies.

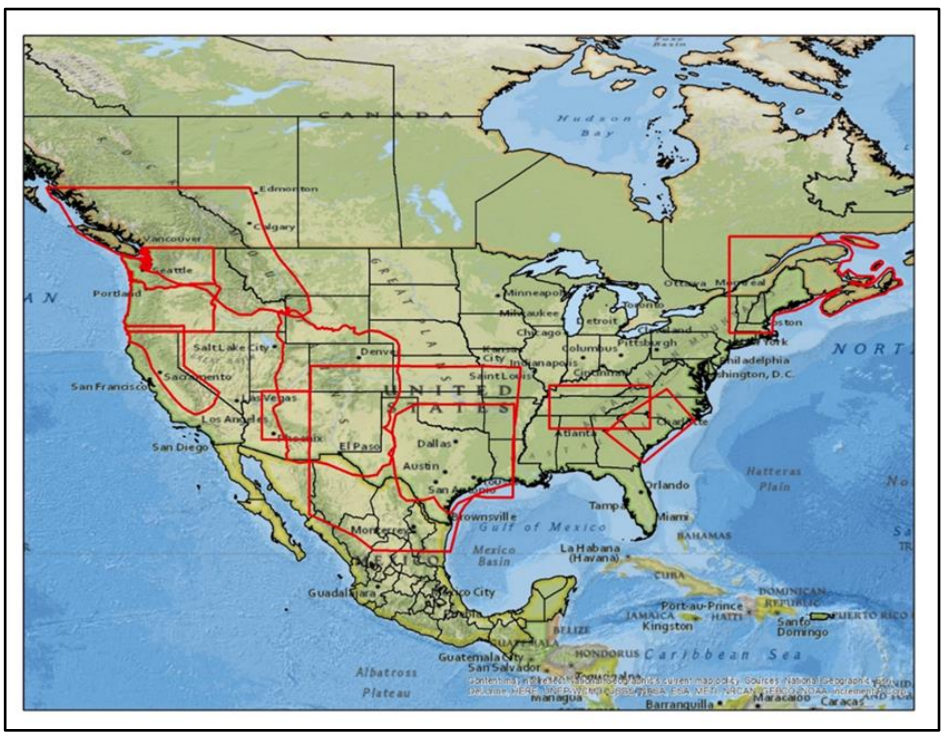


Figure 2 – Study Areas where Regional Precipitation-Frequency Studies Have Been Conducted for Dam Safety Applications Using Storm Typing Procedures

Typically, only one storm type (one key duration) is required for analysis. The existing PMF study for a project often provides information about the storm type(s) that would be applicable to the watershed being evaluated. If the existing PMF study indicates that one storm type is the controlling storm type (such as a general storm), a watershed precipitation-frequency relationship is only needed for the MLC or TSR storm type. If the existing PMF study indicates that multiple storm types should be examined, then a watershed PF relationship must be developed for each storm type and separate flood simulations and HHCs will be required for the floods produced by each storm type. This is necessary because different storm types have different spatial and temporal characteristics and there must be compatibility between the watershed PF relationship and the associated spatial and temporal storm patterns.

3.0 Compute Areal-Average Point Precipitation for the Watershed

This is an intermediate step for later use in converting gridded point PF estimates to areal average PF for a watershed. For each storm type, intersect the GIS shapefile (Figure 3) for the watershed and subbasins of interest with the gridded PF datasets obtained in Section 2.0 to determine areal-average point precipitation for the watershed and each subbasin for the key duration and a range of AEPs. Figures 4 and 5 depict examples of areal-average point PF relationships for the two data sources described in Section 2.0. If there is not an available GIS shapefile available, basin delineation shapefiles can be obtained using the USGS StreamStats tool (https://water.usgs.gov/osw/streamstats/). If GIS shapefiles or gridded PF datasets are unavailable, then a manual method is needed for averaging data from the frequency mapping over the basin for each key duration.

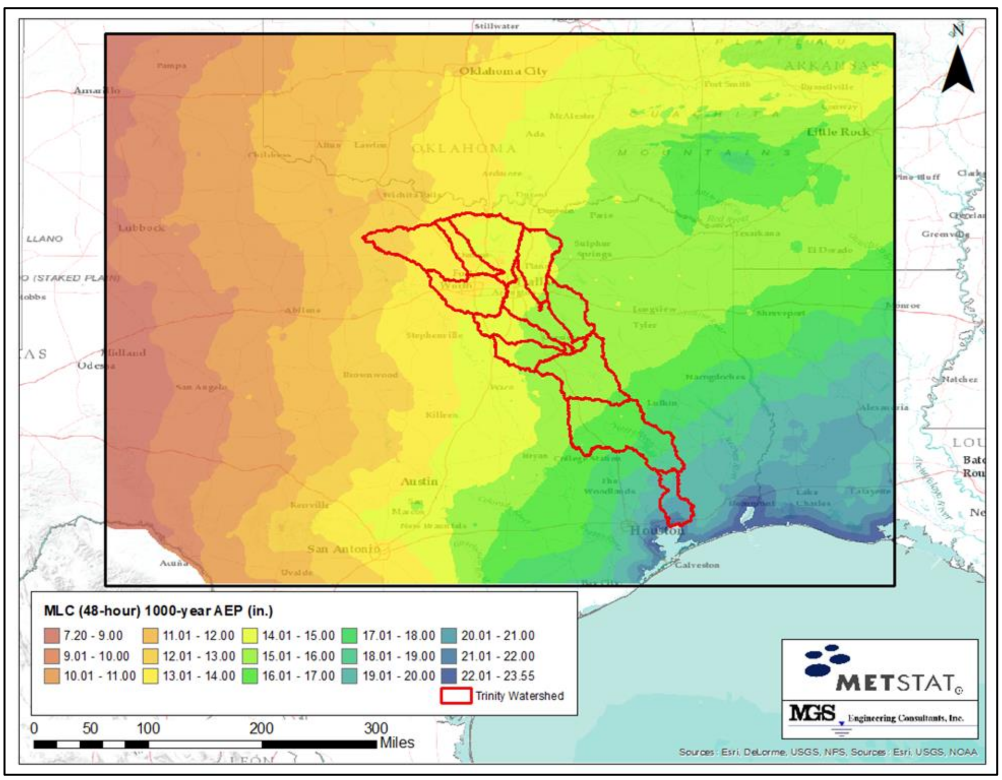


Figure 3 – Example of Intersection of a Watershed and Subbasins for a Gridded Precipitation-Field for a Selected Duration and Annual Exceedance Probability

Note that it is common practice for PMF and other watershed studies to use subbasins in describing the watershed. It is not the intent of the simplified method to require the use of subbasins to help define the spatial distribution of precipitation. It is often acceptable to use a uniform distribution of precipitation across the watershed provided it is not oversimplifying the spatial distribution of precipitation, such as in mountainous terrain. However, it should be recognized that simplifications to the spatial distribution of precipitation may affect the validity of any watershed model calibrations to historical floods and the accuracy of HHCs that are produced. The analyst may find it easier to include the subbasins even with their added complexity. Use of spatial storm patterns in SSEFM flood simulations is discussed in Section 7.

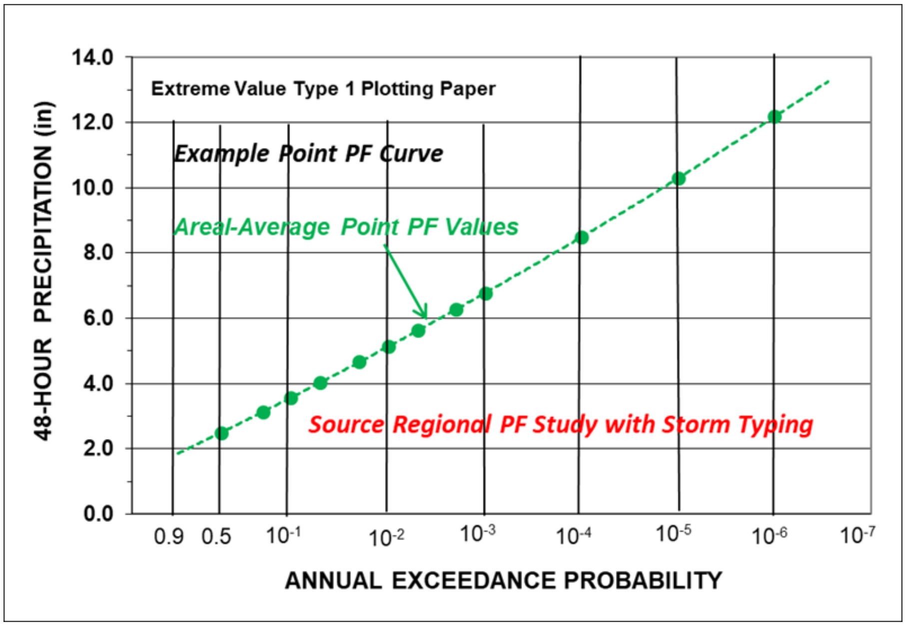


Figure 4 – Areal Average Point Precipitation-Frequency Estimates for Selected Annual Exceedance Probabilities Obtained from Regional Precipitation-Frequency Analyses Employing Storm Typing

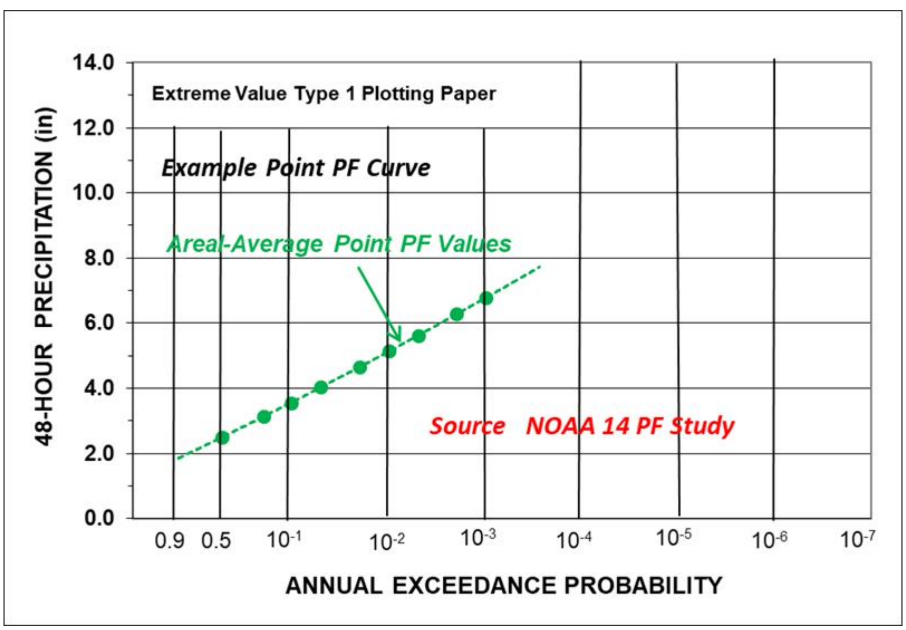


Figure 5 – Areal Average Point Precipitation-Frequency Estimates for Selected Annual Exceedance Probabilities Obtained from NOAA Atlas 14

4.0 Determine Precipitation-Frequency Areal Reduction Factors (PF-ARF) for Watershed

Precipitation-Frequency Areal Reduction Factors (PF-ARFs) are used to convert areal-average point precipitation to areal-average watershed precipitation. PF-ARFs for geographically-fixed areas (watersheds) vary with storm type, watershed size, storm rareness, and the physiography and climatology of the location of the watershed. In addition, published PF-ARF values are typically mean values for a collection of storms where the PF-ARF values for individual storms exhibit the natural variability of storm characteristics specific to the given storm type.

It should be noted that ARFs provided in Hydrometeorological Reports (HMRs) are storm-focused values obtained from analyses of historical storms without regard to a specific watershed. What is required for hydrologic risk analyses are PF-ARFs for the fixed geographic location of the watershed. The geographically-fixed PF-ARFs account for the natural variability of the shape of the storm spatial patterns relative to the shape of the watershed. In particular, the storm-focused ARFs are computed as the areal-average precipitation for a given storm area (mi^2) divided by the maximum point precipitation in the storm. Whereas, the PF-ARFS are defined as the areal-average precipitation over the watershed for a specific AEP divided by the areal-average point precipitation for the specified AEP. While these are both termed ARFs, they are distinctly different numerically.

Currently, there are three methods available for obtaining PF-ARF values. First, PF-ARF values can be found in journal articles for some location-specific and storm-type specific studies of PF-ARF values. Many of these articles/studies can be found with a Google search for a particular physiographic region. In addition, PF-ARF values are available from detailed stochastic flood analyses for specific storm types for the study areas depicted in Figure 2. Example PF-ARF values for convective storm types in the Colorado and New Mexico area (MetStat et al[9]) are shown in Figure 6, where the PF-ARF values were obtained by stochastic storm generation methods using stochastic storm transposition (resampling) of observed convective storms. PF-ARF values for the synoptic scale MLC storm type for the Tennessee Valley study area (MGS et al[12]) are shown in Figure 7, where the PF-ARF values are based on stochastic storm generation methods using anisotropic spatial correlation structures developed for MLC storms observed on the Tennessee valley watershed. It is anticipated that PF-ARF relationships produced from detailed stochastic flood studies will be available in the future from third party websites as more detailed studies are completed.

Second, research conducted by Kao et al[7] for the Nuclear Regulatory Commission (NRC) using reanalysis gridded precipitation datasets has produced preliminary PF-ARF values for fixed geographical areas for numerous physiographic regions throughout the U.S. Those findings are consistent with PF-ARF values depicted in Figure 7 where the PF-ARF values vary with watershed size, duration and AEP. Figure 8 depicts an example of PF-ARF values for synoptic scale storms for the 1:10 AEP. The results from Kao et al[7] are a convenient resource adequate for PF-ARF values for synoptic scale MLC storms for SQRA applications.

PF-ARFs suitable for SQRA for a specific watershed can also be developed from reanalysis gridded precipitation datasets for a key duration. This approach is not suitable for a detailed QRA because of uncertainties and inaccuracies inherent in reanalysis datasets owing to the difficulties in spatial mapping of precipitation and preservation of both point PF and watershed PF characteristics.

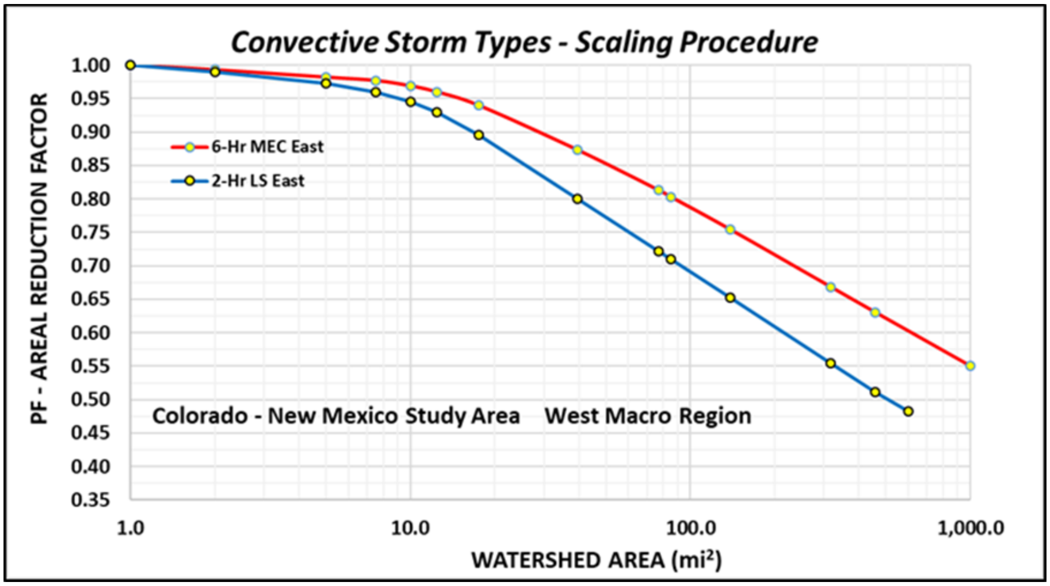


Figure 6 – Precipitation-Frequency Areal Reduction Factors (PF-ARF) for Convective Storm Types for Locations in Colorado and New Mexico

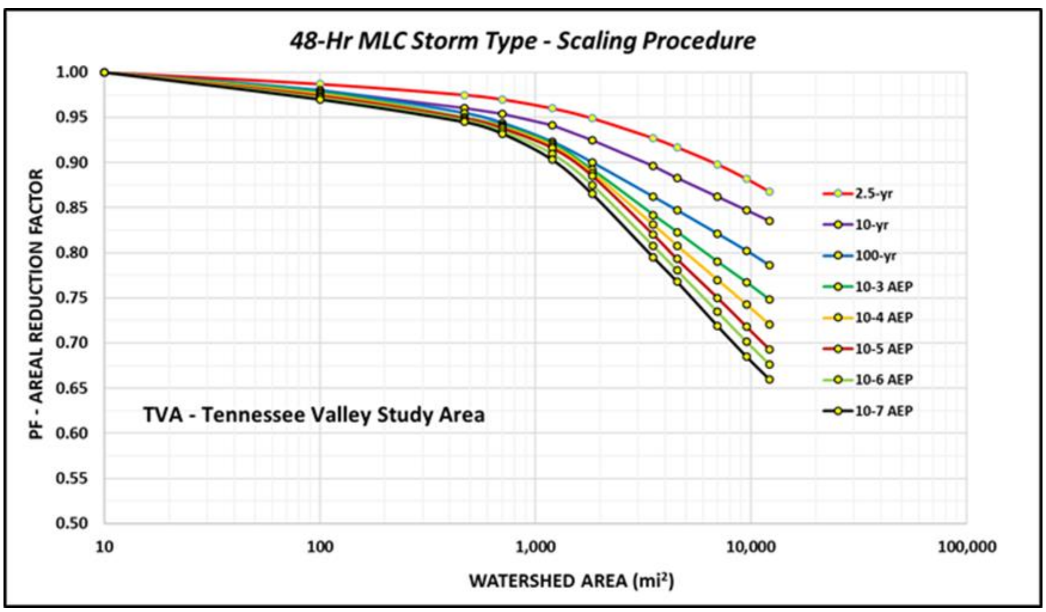


Figure 7 – Precipitation-Frequency Areal Reduction Factors (PF-ARF) for Synoptic Scale Mid-Latitude Cyclones for Locations in Tennessee Valley Study Area

Note in Figure 7 that the PF-ARF values vary with AEP. This behavior has been found in numerous studies of areal reduction factors for geographically fixed areas. A physical interpretation of this behavior can be made in terms of storm efficiency. Storm efficiencies in common storms are relatively low and can be maintained over large areas, thus less areal reduction relative to point PF. Conversely, in very rare and extreme storms, storm efficiency is relatively high over a more localized area(s), but that high level of storm efficiency cannot be maintained over large areas and thus a greater drop-off relative to point PF. This behavior is depicted in Figure 9 comparing a fixed value PF-ARF with a variable PF-ARF for an example 3,000-square mile watershed in the Tennessee Valley area.

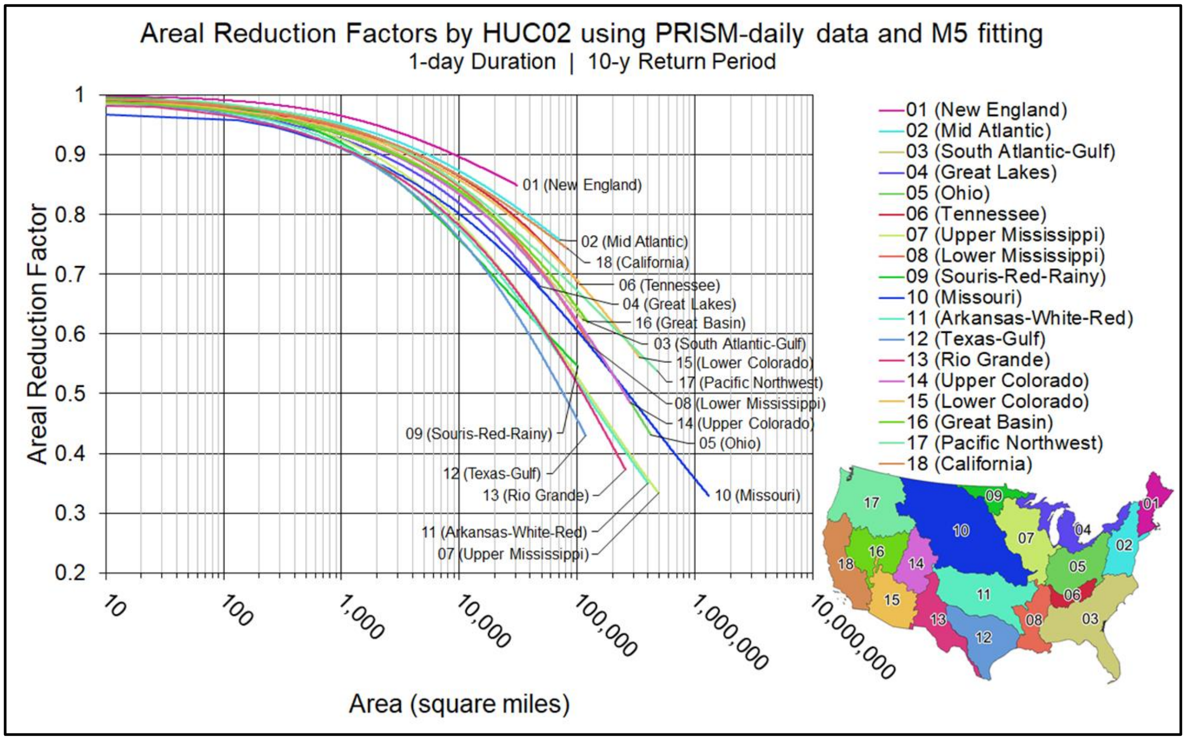


Figure 8 – Precipitation-Frequency Areal Reduction Factors (PF-ARF) for Synoptic Scale 24-Hour Duration Precipitation for Various Physiographic Regions (Kao et al[7])

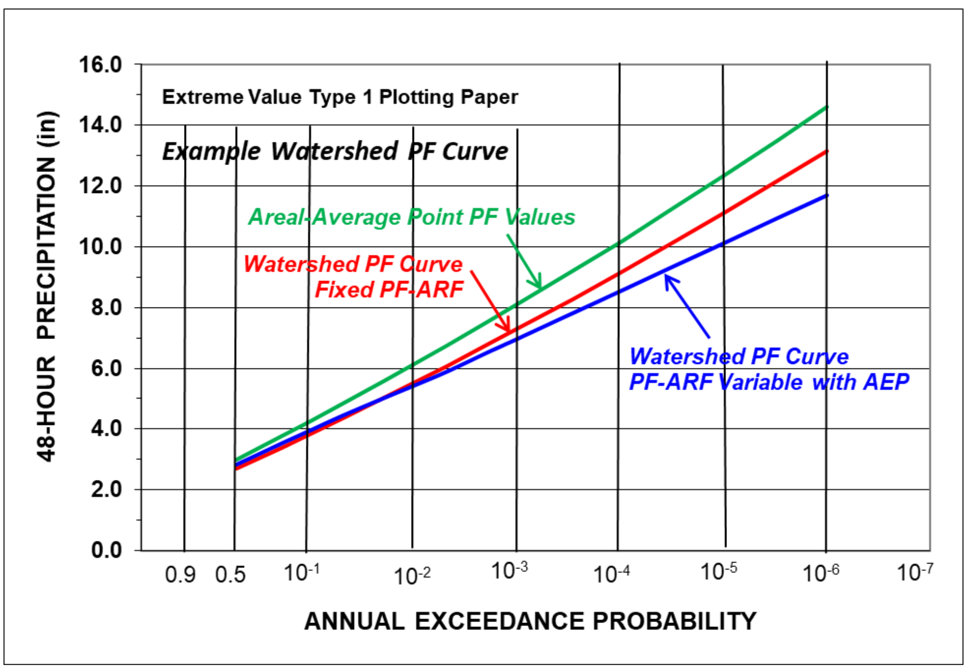


Figure 9 – Example 3,000-square mile Watershed Precipitation-Frequency Curves with a Fixed PF-ARF Value Compared with PF-ARF Values that Vary with AEP for Synoptic Scale Mid-Latitude Cyclones for a Location in Tennessee Valley Study Area

Lastly, PF-ARF values can be roughly approximated from storm-centered ARFs contained in NWS Hydrometeorological Reports and site-specific PMP studies (example Figure 10). The results of many detailed stochastic storm/flood studies have shown that storm-centered ARFs are numerically smaller in magnitude (greater areal reduction) than PF-ARFs for the reasons described earlier in this section.

Therefore, the storm-centered ARFs need to be adjusted to provide PF-ARFs for geographically fixed watersheds. Preliminary analyses indicate the PF-ARF values can be adequately approximated using the format of Equation 1 below.

$$PF\text{-}ARF = ARF_{HMR} + \alpha(1 - ARF_{HMR}) \quad (1)$$

where: ARF_{HMR} is the storm-focused ARF from a hydrometeorological report of PMP or site-specific PMP study; and α is an adjustment factor.

Equation 1 produces a watershed PF-ARF value that increases the HMR ARF value by a fraction of the "distance" between unity (ARF=1) and the HMR ARF value. An example PF-ARF computation is shown in Figure 11. Nominal adjustment factors of α=0.65 for synoptic scale MLC and TSR storm types and α=0.20 for convective storm types can be used as default values until more studies are available providing experience with α adjustment factors.

The recommended approach is to use findings from detailed PF-ARF studies for geographically fixed areas for specific locations and storm types whenever those findings are available. Alternatively for synoptic scale MLC and TSR storm types, compare the PF-ARF values described in Kao et al[7] (Figure 8) with values obtained from scaling of storm-focused ARFs from HMR and site-specific PMP studies for general storms and decide on an appropriate fixed value PF-ARF value. For convective storm events, use the scaling procedure described above.

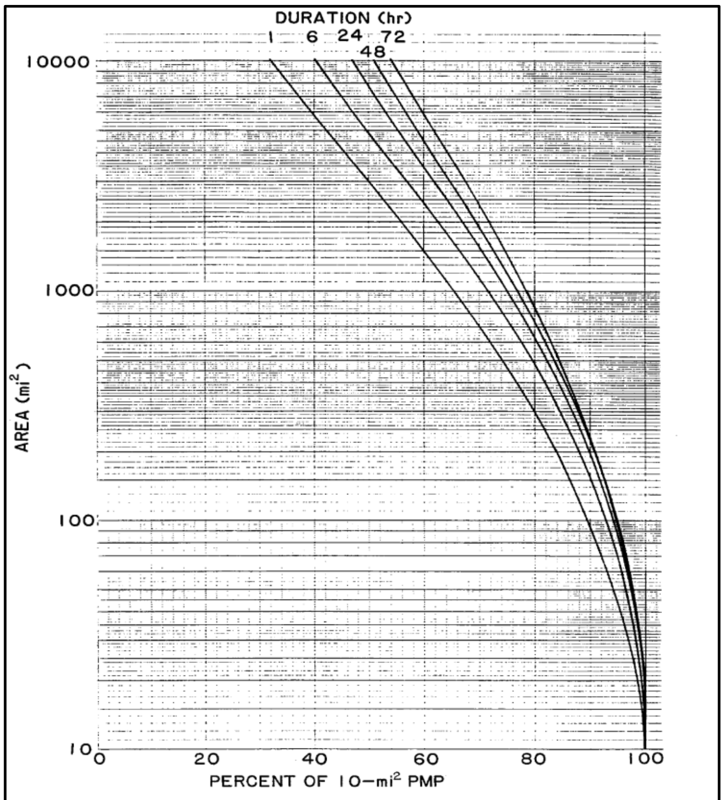


Figure 15.10.--Adopted depth-area relations for orographic subregions (Section 10.2.1).

Figure 10 – Example Storm-Centered Areal Reduction Factors for Orographic Subregions HMR 57 for Pacific Northwest, Figure 15.10, Page 198

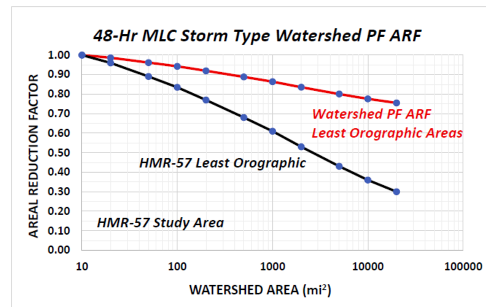
48-Hour Precipitation HMR-57
Mid-Latitude Cyclone (MLC) Storm Type

PRELIMINARY
5/15/2017

Point precipitation is considered equivalent to 10-mi² precipitation for synoptic scale storms

LEAST OROGRAPHIC — alpha=0.65

Storm Area sq miles	ARF Ratio to 10 sq miles	ARF Delta Adjustment	Watershed PF ARF
10	1.000	0.000	1.000
20	0.960	0.026	0.986
50	0.890	0.072	0.962
100	0.835	0.107	0.942
200	0.770	0.150	0.920
500	0.680	0.208	0.888
1000	0.610	0.254	0.864
2000	0.530	0.306	0.836
5000	0.430	0.371	0.801
10000	0.360	0.416	0.776
20000	0.300	0.455	0.755



OROGRAPHIC — alpha=0.65

Storm Area sq miles	ARF Ratio to 10 sq miles	ARF Delta Adjustment	Watershed PF ARF
10	1.000	0.000	1.000
20	0.995	0.003	0.998
50	0.970	0.020	0.990
100	0.940	0.039	0.979
200	0.900	0.065	0.965
500	0.820	0.117	0.937
1000	0.760	0.156	0.916
2000	0.690	0.202	0.892
5000	0.590	0.267	0.857
10000	0.510	0.319	0.829
20000	0.440	0.364	0.804

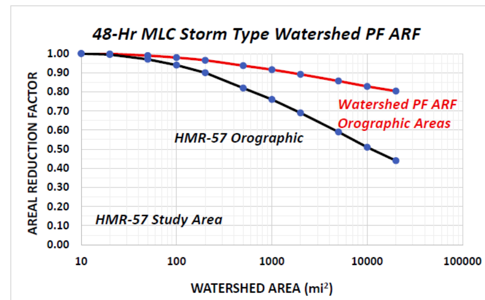


Figure 11 – Example PF-ARF Computation from HMR 57 for MLC Storm Type

5.0 Compute Precipitation Frequency (PF) Watershed Curve

The watershed PF relationship is computed for each storm type by multiplying the areal-average point precipitation values for the watershed (Section 3.0) for the key duration for the range of AEPs by the PF-ARF values from Section 4.0. The watershed PF relationship is depicted as a probability-plot as shown as the red data points and curve in Figure 12 for the case of point precipitation from detailed regional PF analyses conducted with storm typing and Figure 13 for point precipitation from NOAA Atlas 14.

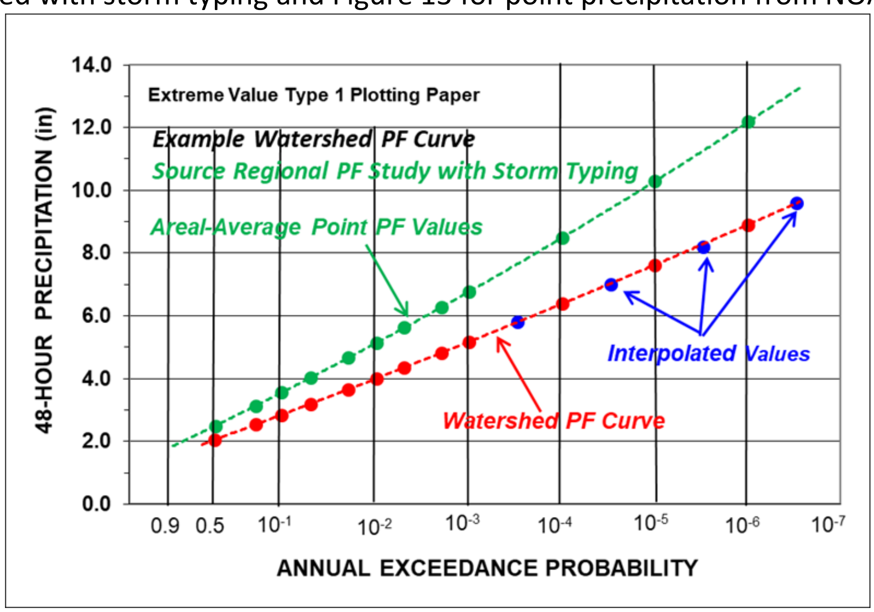


Figure 12 – Example of Watershed Precipitation-Frequency Relationship
Developed from Point Precipitation Data from Regional PF Analyses with Storm Typing

5.1 Include PMP Estimate in the Watershed PF Relationship for Use with NOAA 14 Data

Point PF estimates from NOAA Atlas 14 extend to an AEP of 1:1,000. Extrapolation beyond 1:1,000 AEP is constrained by using an AEP estimate of PMP to avoid unrealistic extrapolations. The upper portion of the watershed PF relationship is estimated using the watershed areal-average estimate of PMP based on the applicable Hydrometeorological Report or site-specific PMP Study. This is accomplished by assigning an estimated AEP to the PMP value using the AEP estimates listed in Tables 2a through 2d for the various storm types and physiographic regions. These notional values of AEP for PMP are based on experience gained from detailed regional PF studies conducted for hydrologic risk assessments. FERC staff have recommended use of conservative estimates of the AEP of the PMP to avoid underassessment of hydrologic risk. Whatever approach is adopted, the choice of the AEP of the PMP should be properly documented.

Note that site-specific PMP studies have been conducted for many dams/watersheds in the U.S. In general, the results from site-specific PMP studies are less conservative than the results contained in HMR studies conducted by the NWS. The tables below contain AEP estimates based on a mix of HMR and site-specific PMP studies which adds uncertainty to the range of AEP estimates for PMP. Figure 13 depicts the use of the estimated AEP of PMP to anchor the upper portion of the watershed PF relationship developed from point PF estimates from NOAA Atlas 14.

Plot the watershed PMP value with the estimated AEP value on the watershed PF plot developed in Section 5.0 (Figure 13). Extend a smooth curve from the 1:1,000 AEP watershed precipitation value through the PMP value (dashed red line Figure 13, below). Interpolate precipitation values for selected AEPs to fill-in the watershed PF relationship for later use in flood modeling (blue data points). Include at least one value beyond PMP to account for uncertainty in the PMP estimate and acknowledge that the existence of an upper limit to precipitation remains an open question.

Table 2a – Notional Values of Annual Exceedance Probabilities for PMP for the Mid-Latitude Cyclone (MLC) Storm Type (48-hr or 24-hr Key Duration)

PHYSIOGRAPHIC PROVINCE	ANNUAL EXCEEDANCE PROBABILITY
Coastal Areas East of Continental Divide (HMR 51)	$10^{-6.0}$
Non-Coastal Areas East of Continental Divide (HMR 51)	$10^{-6.5}$
Tennessee Valley (HMR-41 and HMR-45)	$10^{-7.0}$
Areas West of Crest of Cascade Mountains in Washington (HMR 57)	$10^{-6.0}$
Areas West of Crest of Cascade Mountains in Oregon (HMR 57)	$10^{-5.5}$
Areas West of Crest of Sierra Mountains in California (HMR 59)	$10^{-4.5}$
Intermountain Areas in Western US	$10^{-7.0}$

Table 2b – Notional Values of Annual Exceedance Probabilities for PMP for the Tropical Storm Remnant (TSR) Storm Type (48-hr or 24-hr Key Duration)

PHYSIOGRAPHIC PROVINCE	ANNUAL EXCEEDANCE PROBABILITY
Coastal Areas Near Atlantic Coast and Gulf of Mexico	$10^{-5.0}$
Inland Areas Affected by Remnants of Tropical Storms	$10^{-6.0}$

Table 2c – Notional Values of Annual Exceedance Probabilities for PMP for Mesoscale Storm with Embedded Convection (MEC) Storm Type (6-hr Key Duration)

PHYSIOGRAPHIC PROVINCE	ANNUAL EXCEEDANCE PROBABILITY
Areas East of 105th Meridian (HMR 51)	$10^{-6.5}$

Table 2d – Notional Values of Annual Exceedance Probabilities for PMP for the Local Storm (LS) Storm Type (2-hr Key Duration)

PHYSIOGRAPHIC PROVINCE	ANNUAL EXCEEDANCE PROBABILITY
Areas East of 105th Meridian (HMR 51)	$10^{-7.0}$
Areas West of Cascade and Sierra Mountains	$10^{-6.5}$
Intermountain Areas in Western US	$10^{-7.0}$

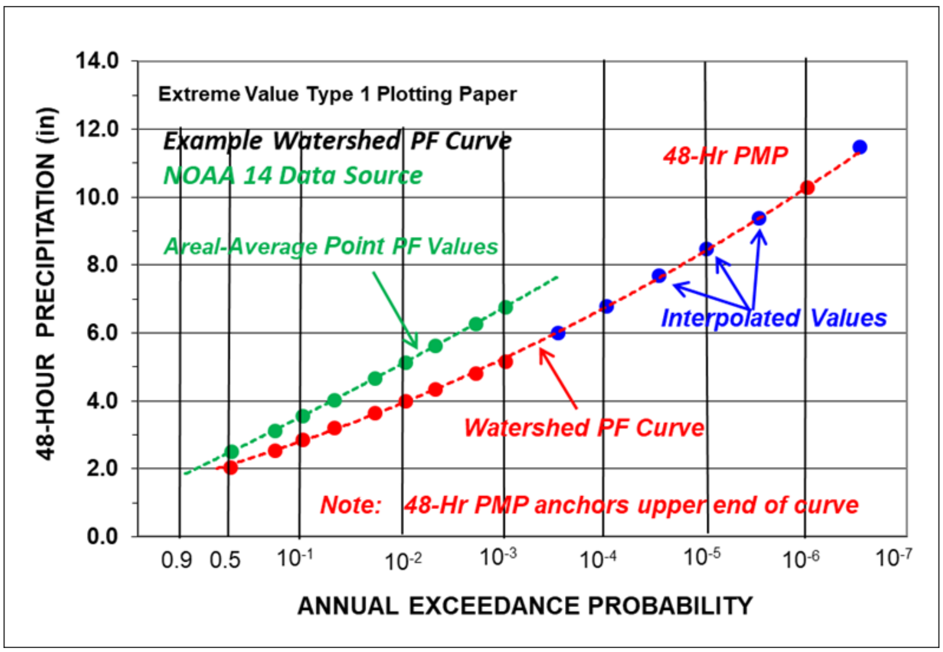


Figure 13 – Example of Watershed Precipitation-Frequency Relationship for Point Precipitation Data from NOAA Atlas 14 and Estimated Annual Exceedance Probability for PMP Value

6.0 Add 90% Uncertainty Bounds to Best-Estimate Watershed PF Relationship

It is standard practice to include uncertainty bounds for watershed PF relationships to express the magnitude of uncertainty in developing the relationship. Proper computation of uncertainty bounds is accomplished as part of a detailed regional point PF analysis and stochastic generation of the watershed PF relationship. A detailed uncertainty analysis is not possible in a simplified SEFM approach and notional values of the 5th and 95th percentiles for the 90% uncertainty bounds are provided based on generalized results from detailed uncertainty analyses for study areas shown in Figure 2. The proposed 90% uncertainty bounds are termed "notional" to emphasize they are generalized approximations to provide a sense of the magnitude of uncertainty. The 5th and 95th percentile values are formed by horizontal adjustments of the AEPs for a given precipitation magnitude. Figure 14 depicts an example of 90% uncertainty bounds for the watershed PF relationship shown in Figure 13.

Table 3 – Notional Values for Constructing 90% Uncertainty Bounds for Watershed PF Relationship

UNCERTAINTY BOUNDS: ADJUSTMENTS TO BEST-ESTIMATE WATERSHED PRECIPITATION-FREQUENCY RELATIONSHIP									
Log10 (1/AEP)	**0.40 Mean**	**1.00 10-yr**	**2.00 100-yr**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**
5th Percentile	-0.13	-0.25	-0.50	-0.75	-1.00	-1.25	-1.50	-1.75	-2.00
95th Percentile	+0.13	+0.25	+0.50	+0.75	+1.00	+1.25	+1.50	+1.75	+2.00

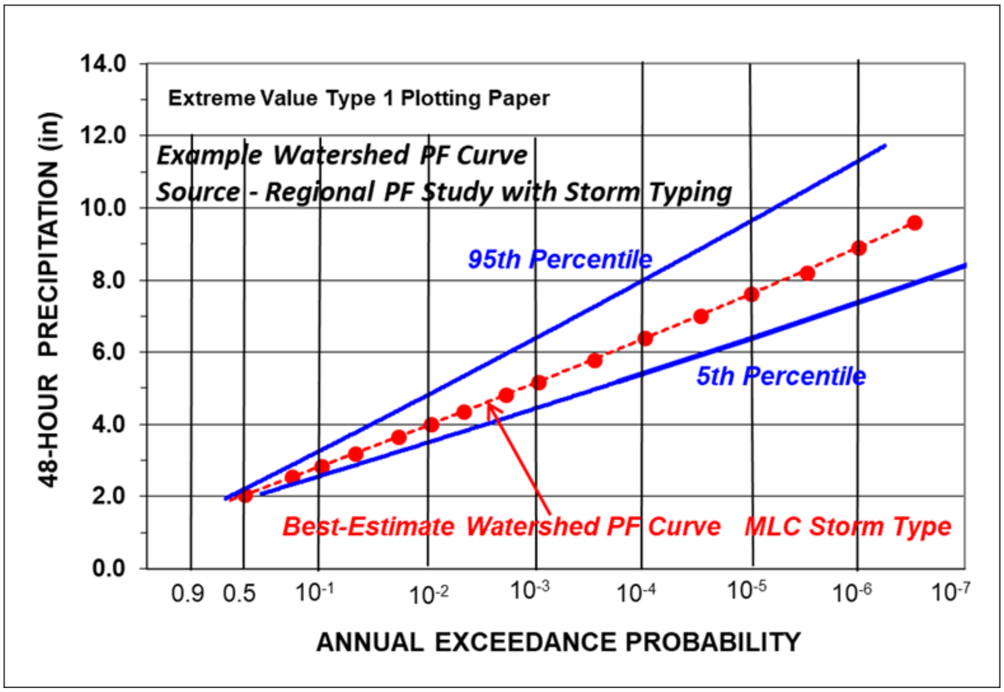


Figure 14 – Example of 90% Uncertainty Bounds
for Watershed Precipitation-Frequency Relationship (Figure 12)
Developed from Point Precipitation Data from Regional PF Analyses with Storm Typing

7.0 Obtain or Develop Scalable Spatial and Temporal Storm Templates

Scalable spatial and temporal storm templates are needed for conducting flood simulations for simplified SEFM. The spatial and temporal storm templates are stored in a dimensionless format to allow easy scaling by precipitation magnitudes taken from the watershed PF relationship for the key duration (Figures 12 and 13).

The term "*temporal pattern*" is used here to describe the incremental or mass hyetograph at a precipitation station or for a subbasin. The term "temporal template" is used to describe the collection of temporal patterns for the various subbasins in a watershed. The term "*spatial template*" is used to describe the ratio of the areal-average precipitation for a subbasin compared to the areal-average watershed precipitation, both measured for the same starting and ending times for the key duration.

A sample set of 3 to 7 spatial and temporal templates is a reasonable choice unless a greater number of storm templates are readily available. Three temporal templates may be adequate for a scoping level risk analysis whereas five or more storms would be preferred for a semi-quantitative risk analysis. It is common for one or more spatial and temporal storm patterns to be available as part of the watershed model calibration process from prior PMP/PMF studies. These spatial and temporal patterns can be used in the suite of storm templates for the simplified SEFM approach. In addition, review the literature on rare storms for areas that are climatologically and topographically similar to the watershed of interest and identify several historical storms for developing scalable storm templates. Spatial and temporal storm patterns may also be available from Federal agencies such as the US Army Corps of Engineers, US Bureau of Reclamation and National Weather Service as well as private consulting firms that specialized in storm analyses.

In general, the watershed PF relationship and the spatial pattern of precipitation are dominant factors for flood magnitude on large watersheds (say greater than 4,000 mi^2) subject to synoptic scale MLC and TSR storm types. Conversely, the watershed PF relationship and the temporal pattern of precipitation are dominant factors for flood magnitude on smaller watersheds east of the continental divide (say less than about 400 mi^2) subject to the mesoscale MEC storm type. Likewise, the watershed PF relationship and the temporal pattern of precipitation are dominant factors for flood magnitude on small watersheds in the intermountain west (say less than about 50 mi^2) subject to the local scale (LS) storm type.

7.1 Constructing Scalable Spatial Templates

For small watersheds and preliminary analyses, a uniform spatial pattern may be adequate. The importance of accounting for spatial variability of a storm varies with relative scale of the storm (synoptic scale, mesoscale and local scale) compared to the size of the watershed. In general, spatial variability of the storm is of lesser importance if the size of the watershed is very small compared to the scale of the storm. The importance of depicting the spatial pattern increases as the size of the watershed increases and for unusually shaped watersheds. For the case of watersheds in mountainous terrain subject to synoptic scale storms, the orographic component of precipitation will result in significant spatial variability that should be accounted for in conducting flood simulations. For example, Figure 14 depicts the magnitude of spatial variability of 72-hour precipitation for a storm on the San Joaquin River in southern California. The relative magnitude of orographic precipitation and spatial variability of precipitation in mountainous terrain can be inferred from the spatial variability of mean annual precipitation across the watershed (PRISM, Daly[4,5]). A practical approach for a representative spatial pattern for synoptic scale MLC and TSR storms is to use the areal-average precipitation for each subbasin computed from the gridded precipitation for the 2-year or 10-year recurrence interval for the key duration.

Convective storms (thunderstorms) often have high gradients of precipitation occurring over relatively short distances. A detailed SEFM analysis would need to consider the spatial variability of convective events to achieve a higher level of accuracy required in a detailed SEFM analysis leading to a risk-informed decision. However, the need for greater spatial resolution of convective storms can be relaxed somewhat for SQRA level risk analyses.

A scalable spatial template can be created by computing a dimensionless scaling factor (ratio) for each sub-area by dividing the sub-area precipitation for the key duration by the areal-average watershed precipitation for the key duration. This can be done for subbasins or for grid-cells if using a gridded precipitation pattern. Table 4 lists the dimensionless spatial ratios for subbasins in Figure 15 which aggregate to the areal-average watershed precipitation for the key duration. This is a direct computational procedure for storms on the watershed of interest. If a spatial template is to be developed for an historical storm that occurred nearby, it must first be transposed to the watershed of interest.

In general, a convective storm spatial pattern (MEC, LS storm types) can be treated as a shape function and moved within a homogeneous climatic region from where it occurred (source) to the watershed of interest (target) for purposes of the SQRA. For synoptic scale long duration MLC and TSR storm types, the spatial pattern can generally be moved without adjustment only if both the source and target areas are devoid of orographic influence from mountainous or semi-mountainous terrain. Conversely, a meteorologist should conduct the storm transposition if either the source or target locations for the storm have significant orographic precipitation.

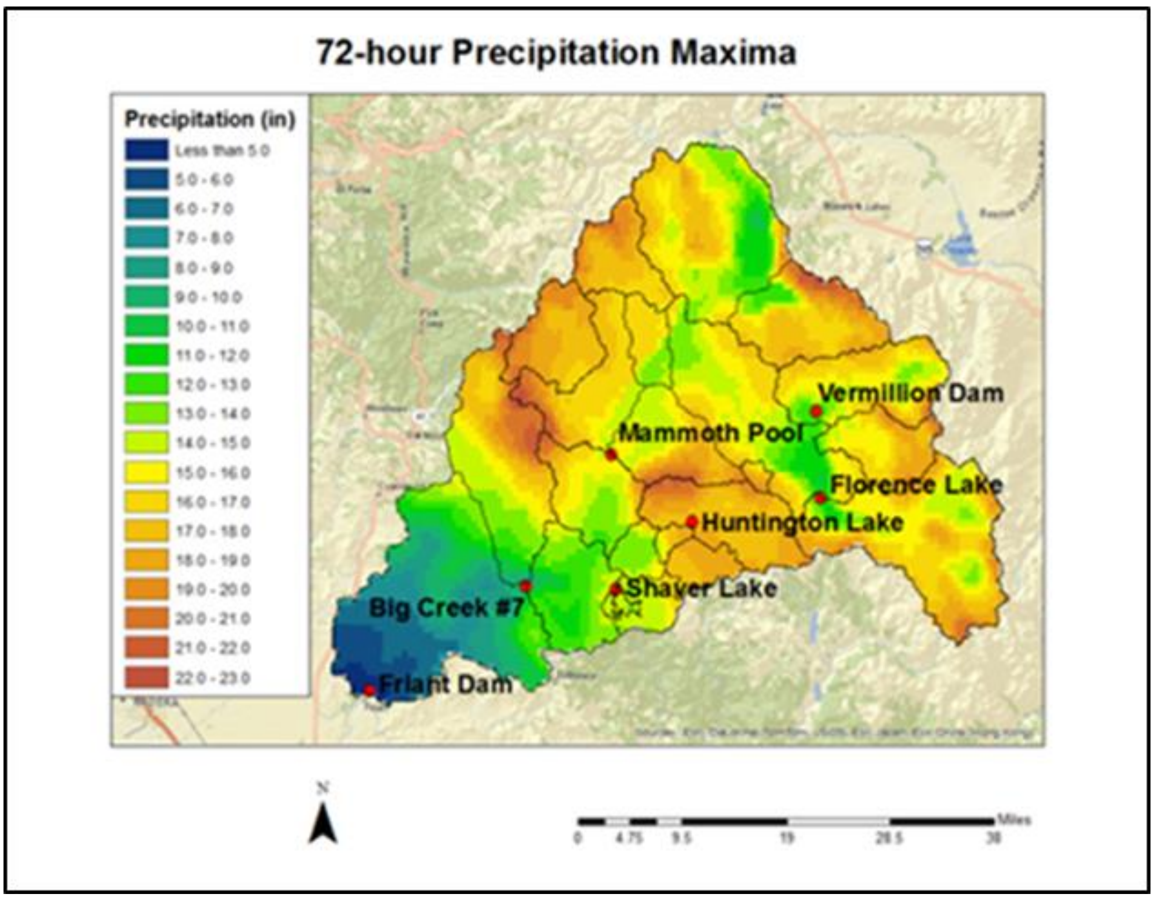


Figure 15 – Example of Spatial Variability of 72-Hour Precipitation for a Mountainous Watershed in Southern California

Table 4 – Example of Scalable Spatial Storm Template for Synoptic Scale MLC Storm Depicted in Figure 14

SUBBASIN NUMBER	SUBBASIN AREA (mi^2)	72-HOUR PRECIPITATION (in)	RATIO TO AREAL-AVERAGE WATERSHED PRECIPITATION
1	72.1	12.70	0.845
2	64.2	15.40	1.024
3	77.5	17.04	1.134
4	60.8	18.41	1.225
5	51.2	18.11	1.205
6	164.9	15.06	1.002
7	91.8	15.78	1.050
8	52.9	16.77	1.116
9	170.9	16.34	1.087
10	80.5	18.25	1.214
11	5.5	17.44	1.160
12	23.9	17.88	1.189
13	7.0	16.63	1.106
14	18.8	14.29	0.951
15	25.0	14.76	0.982
16	3.9	14.09	0.937
17	27.8	15.56	1.035
18	0.4	14.34	0.954
19	88.7	17.30	1.151
20	150.0	14.85	0.988
21	65.9	16.49	1.097
22	130.8	16.39	1.090
23	226.5	8.59	0.571
Watershed	**1661.0**	**15.03**	**1.000**

7.2 Constructing Scalable Temporal Templates

Many of the guidelines for incorporating spatial precipitation patterns in the flood simulations also apply to temporal precipitation patterns. For small watersheds and preliminary analyses, a single temporal pattern may be adequate. The importance of accounting for the variability of temporal patterns across the watershed varies with relative scale of the storm (synoptic scale, mesoscale and local scale) compared to the size of the watershed. In general, the temporal variability of the storm is of lesser importance if the size of the watershed is very small compared to the scale of the storm.

There will be variability in the actual temporal patterns across larger watersheds which vary with storm type and watershed size. This variability would be considered in a detailed stochastic flood analysis but need not be considered here to reduce the level of effort and simplify flood computations. If there are insufficient data for historical storms to assemble a suite of temporal storm templates, use an alternate synthetic approach, such as NOAA Technical Reports NWS 21[15] and NWS 27[16] or temporal information in NOAA Atlas 14.

It is recognized that using a single temporal pattern for large watersheds is often unrepresentative of actual conditions. It would be quite unusual for a storm to cover a large watershed with the same magnitude/intensity of precipitation with a temporal pattern common to all locations. However, if care is taken in areal-averaging of temporal patterns for a given storm, reasonable results can be obtained in computation of the resultant flood.

If a single temporal storm pattern is not used for a watershed, then temporal patterns will be needed for each subbasin. Each subbasin may have a different temporal pattern, or groupings of subbasins may have a common temporal pattern. Scalable dimensionless temporal storm patterns are computed by dividing each of the values in the precipitation time-series for a subbasin by the maximum precipitation observed in the historical storm for the key duration. The temporal pattern of precipitation for a subbasin is often represented by the record at a single precipitation station within/near the subbasin or by a weighted-average of temporal patterns from nearby stations.

Examples of scalable dimensionless temporal templates are listed in Table 5 and graphically depicted in Figures 16a, 16b and 16c, where the maximum 2-hour precipitation (key duration) is 3.90-inches (highlighted from 0.75-hrs to 2.50-hrs). Note that the dimensionless temporal patterns may be stored as incremental or mass precipitation patterns. Storage as dimensionless mass curves has the advantage of allowing easier cross-checking amongst a collection of temporal patterns regarding consistency of both timing and dimensionless magnitudes for a specific storm for the various subbasins.

Table 5 – Listing of an Observed Precipitation Time-Series for an Historical Local Storm and Rescaled Dimensionless Temporal Patterns

ELAPSED TIME (Hours)	OBSERVED INCREMENTAL PRECIPITATION (in)	DIMENSIONLESS INCREMENTAL TEMPORAL PATTERN	OBSERVED MASS PRECIPITATION (in)	DIMENSIONLESS MASS TEMPORAL PATTERN
0.00	0.00	0.000	0.00	0.000
0.25	0.25	0.064	0.25	0.064
0.50	0.15	0.038	0.40	0.103
0.75	0.40	0.103	0.80	0.205
1.00	1.10	0.282	1.90	0.487
1.25	0.90	0.231	2.80	0.718
1.50	0.20	0.051	3.00	0.769
1.75	0.05	0.013	3.05	0.808
2.00	0.30	0.077	3.35	0.859
2.25	0.70	0.179	4.05	1.039
2.50	0.25	0.064	4.30	1.103
2.75	0.37	0.095	4.67	1.197
3.00	0.20	0.051	4.87	1.249
3.25	0.09	0.023	4.96	1.272
3.50	0.05	0.013	5.01	1.285

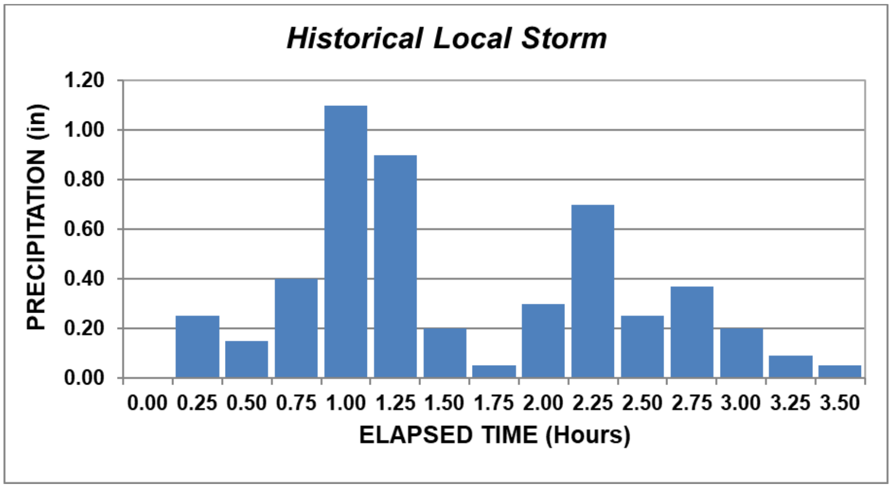


Figure 16a – Example of Observed Precipitation Time-Series for a Historical Local Storm

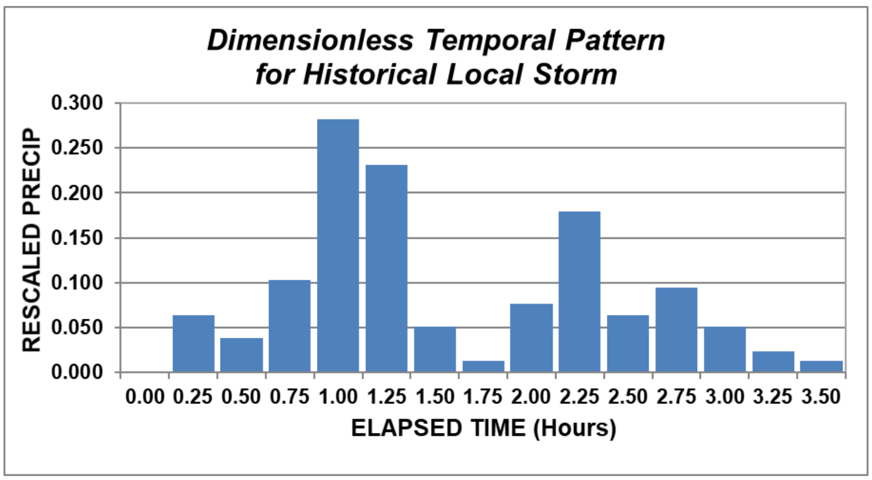


Figure 15b – Example of Dimensionless Incremental Precipitation Time-Series for a Historical Local Storm

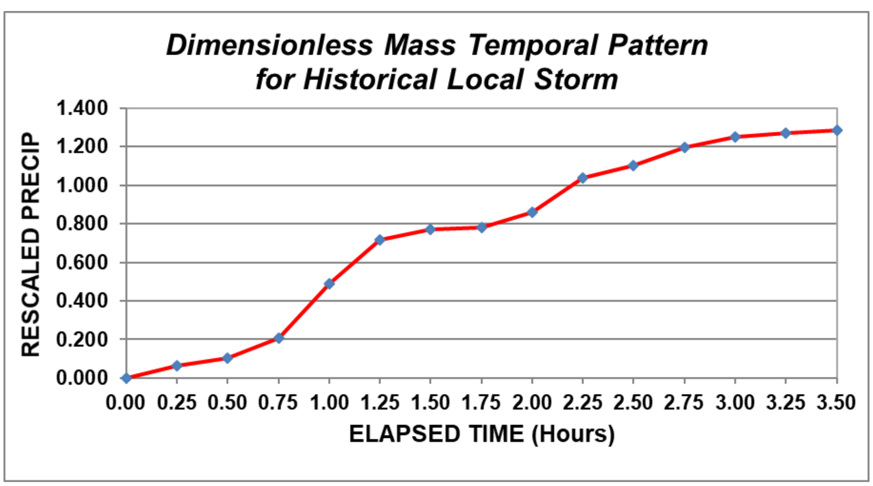


Figure 15c – Example of Dimensionless Mass Precipitation Time-Series for a Historical Local Storm

7.3 Option for Assessing Representativeness of Collection of Storm Templates

Probability-plots of depth-duration ratios for the suite of historical storm temporal templates may be used to assess the representativeness and diversity of depth-duration characteristics for the sample of historical storms for flood simulations. The use of depth-duration probability-plots is an optional step for cases where there are concerns about the sensitivity of the watershed flood response to the diversity of storm temporal patterns. Figure 17 depicts a probability-plot of depth-duration ratios for the 6-hour to 48-hou depth-duration ratio for 15 areal-average temporal patterns for a detailed stochastic flood study on the Campbell River in BC (Schaefer and Barker[21]). A review of the probability plot shows a well-behaved range of depth-duration ratios which were judged representative for stochastic flood simulations.

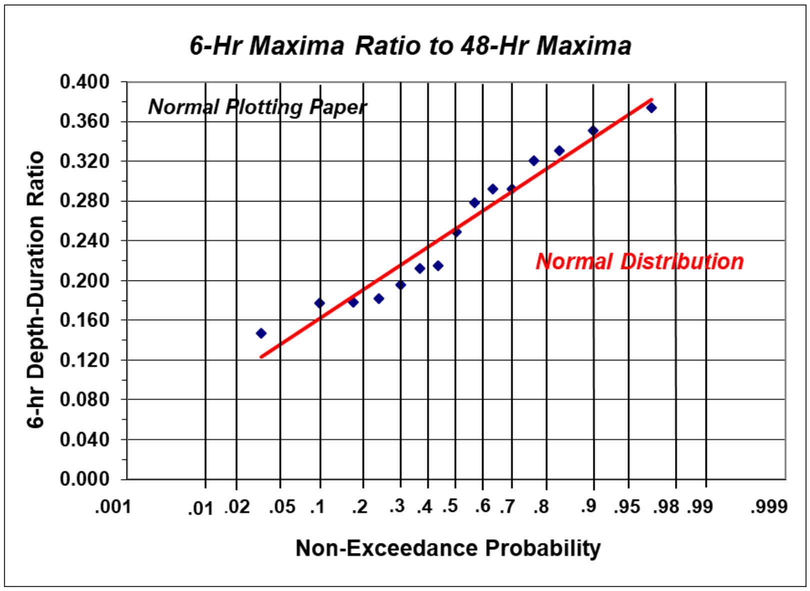


Figure 17 – Example of the Range of Depth-Duration Ratios for a Collection of 15 Temporal Storm Templates for the Synoptic Scale MLC Storm Type Campbell River, BC

8.0 Scale Spatial and Temporal Storm Templates by Watershed Precipitation Magnitudes

Precipitation events for flood simulations are produced by scaling the collection of dimensionless spatial and temporal storm templates by precipitation magnitudes for selected AEPs obtained from the watershed PF relationship (Figures 12 and 13). An example of scaling for the dimensionless temporal template shown in Figure 16b is depicted in Figure 18 where the temporal template has been scaled to a maximum 2-hour precipitation of 6.00-inches. This can be compared to Figure 16a where the observed storm had a 2-hour volume of 3.90-inches.

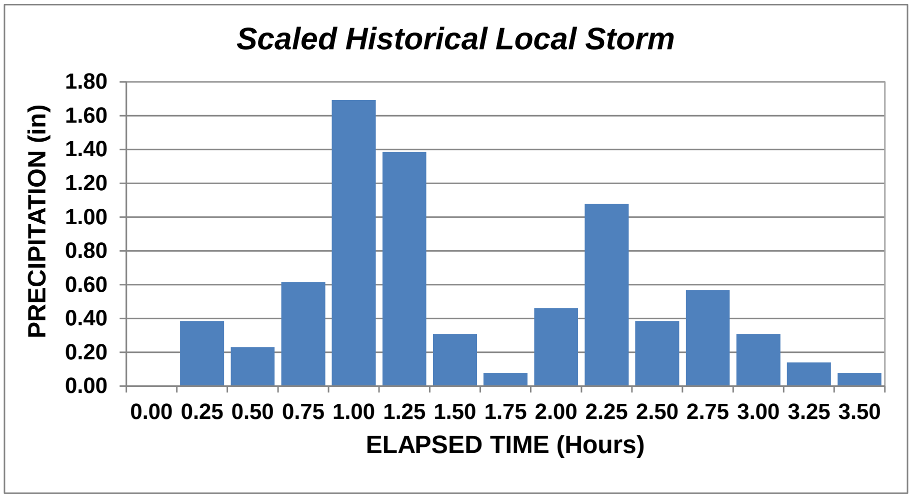


Figure 18 – Example of Observed Precipitation Time-Series for a Historical Local Storm Shown in Figure 16b Scaled to a 2-hour Maximum of 6.00-inches

9.0 Conduct Hydrologic Modeling Using an AEP Neutral Approach

Hydrologic modeling is conducted for each group of scaled spatial and temporal storm templates for watershed precipitation magnitudes for the selected AEPs used to define the watershed PF relationship (Figures 12 and 13). *AEP Neutral* concepts (Nathan and Bowles[13]) are used in flood simulations where typical values of hydrometeorological conditions are used for storm seasonality, antecedent soil moisture, initial reservoir level, snowpack, freezing level, etc. The goal is the AEP for the computed flood outputs will have the same AEP as the watershed precipitation values used to generate the flood outputs. Typical values of hydrometeorological conditions will generally yield reasonable flood-frequency estimates in humid climates where “typical” may be interpreted as mean or median values whichever is more prone to flood generation. AEP Neutral concepts are more difficult to apply in semi-arid and arid climates where large floods are often produced by antecedent conditions that are somewhat more flood-prone than median or mean antecedent conditions.

The AEP Neutral concept, as the name implies, is conceptual and some level of uncertainty exists in practice about whether the goal of matching the AEP of watershed precipitation and flood outputs is actually achieved. Care should be exercised in selection of typical antecedent conditions based on experience with flood characteristics for the watershed of interest. Use of a snowmelt algorithm that is based on energy principles is preferred for simulation of snowmelt and rain-on-snow floods.

The set of flood simulations described above will produce *n* estimates of a given flood output such as inflow flood peak discharge and maximum reservoir level for each watershed precipitation AEP which is the same number (*n*) as the number of storm templates. Use the average of the *n* values for each flood output to compute the mean estimate of the flood output for each AEP (such as the mean of the maximum reservoir levels for a given AEP). Construct a hydrologic hazard curve for each flood characteristic of interest by constructing a probability-plot for each flood output using the mean values obtained from hydrologic modeling similar to that shown in Figure 19.

9.1 Option for Consolidating Subbasins to Simplify Watershed Model

In many cases, the dam/watershed being evaluated will have a previously calibrated watershed model with available historical storm and flood data used for calibration. The analyst has the option to retain the existing subbasin configuration or to consolidate some subbasins to simplify the watershed model for applying AEP Neutral rainfall-runoff modeling. The simplification option might be chosen for watersheds with a large number of subbasins and complex climatic and soils/land-use. The analyst will need to determine whether recalibration of the simplified watershed model is warranted given the changes made to the subbasin configuration and the greater uncertainty associated with an uncalibrated or partially calibrated watershed model.

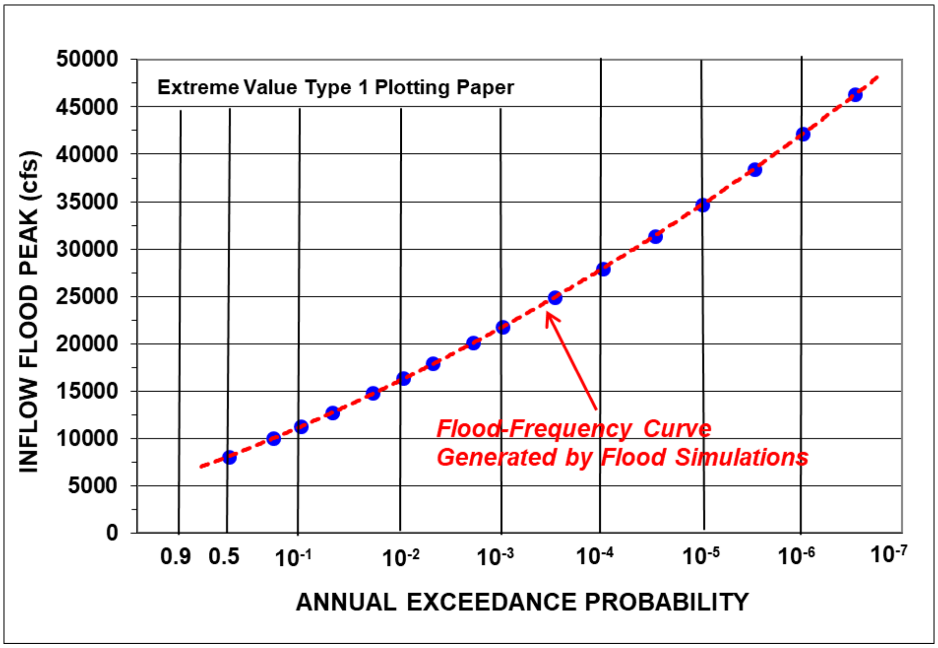


Figure 19 – Example of a Hydrologic Hazard Curve for Inflow Flood Peak Developed from Flood Simulations Conducted for a Range of Precipitation AEPs

10.0 Assemble Hydrologic Hazard Curve (HHC) for Each Flood Output of Interest

Hydrologic hazard curves will be needed to support risk analysis for the various flood-related potential failure modes being evaluated for a given dam. An HHC is assembled by computing a mean value for the set of storm templates (typically 3-7 spatial and temporal storm templates) for each watershed precipitation AEP. The collection of mean values for the flood output of interest are then used to construct the HHC probability-plot as shown by the blue data values in Figures 19 and 20b.

Figures 20a and 20b depict an example of a watershed PF relationship and resultant HHC for maximum reservoir level, where there are corresponding data values for selected AEPs of watershed PF and maximum reservoir level on each probability-plot.

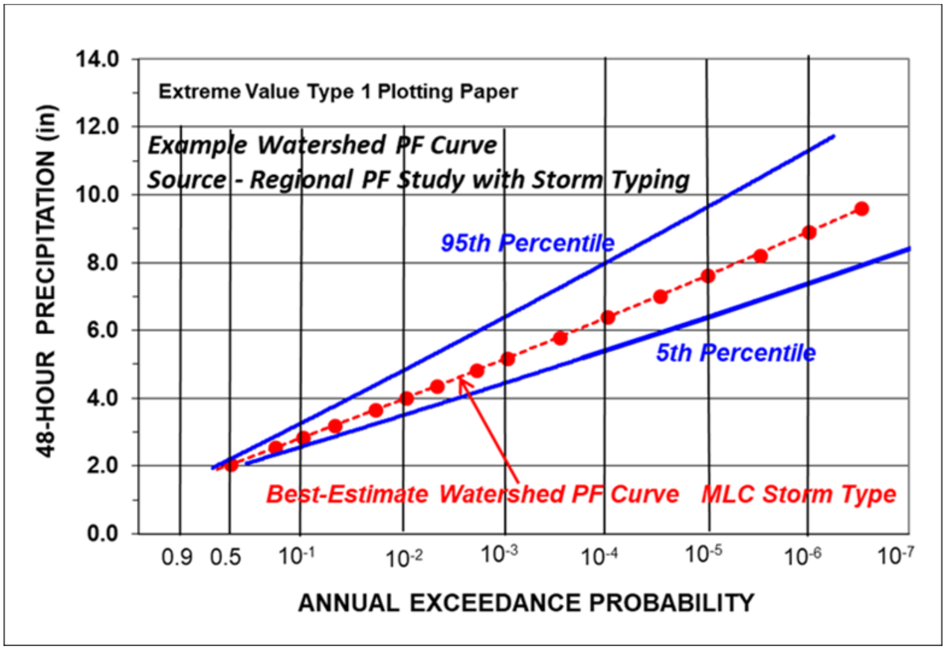


Figure 20a – Example of Watershed Precipitation-Frequency Relationship where the Best-Estimate Curve was used to Generate the Hydrologic Hazard Curve Shown in Figure 19b

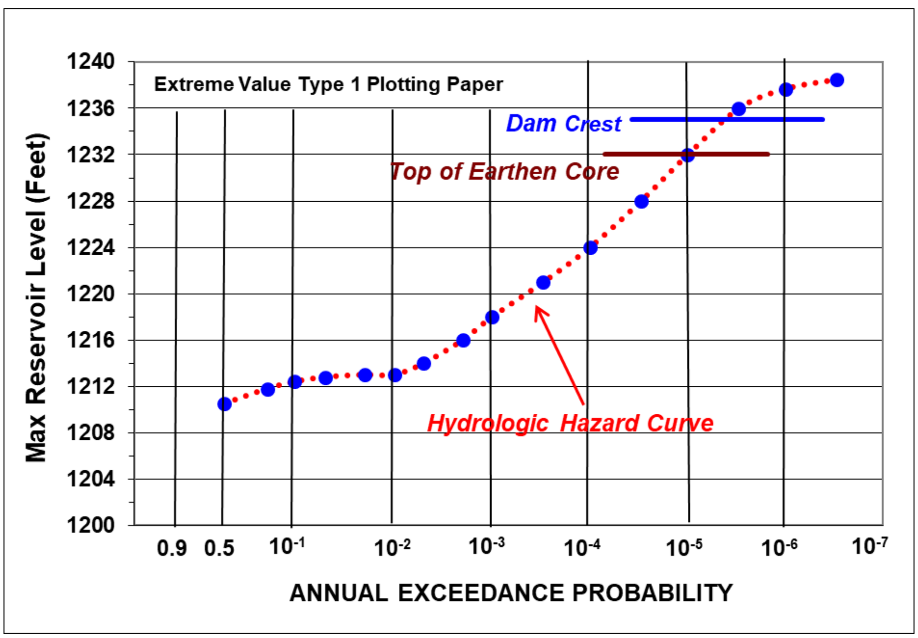


Figure 20b – Example of Hydrologic Hazard Curve for Maximum Reservoir Level Developed Using Simplified Procedures for Hydrologic Modeling

11.0 Add Notional Values of Uncertainty Bounds for Hydrologic Hazard Curves

Experience with the findings of detailed stochastic flood modeling indicates that sizable aleatoric and epistemic uncertainties exist in all elements of the flood simulations. Uncertainties are inherent in the watershed PF relationship, spatial and temporal storm templates, likelihoods of the various hydrometeorological inputs and representative parameters for the various hydrologic and hydraulic processes. Likewise, sizable uncertainties exist due to imperfect understanding of the hydrologic processes and imperfections in the watershed models. It is difficult to quantify the magnitude of uncertainties in this simplified approach, but they would exceed the magnitudes computed in detailed studies.

It is important to recognize the existence of uncertainties for all HHCs developed using this simplified procedure to avoid undue focus and reliance on the "accuracy" of the best-estimate HHC (mean-frequency HHC). Notional values of the 90% uncertainty bounds for hydrologic hazard curves can be estimated using the notional 90% uncertainty bounds for the watershed PF relationship, such as shown in (Figures 20a). Specifically, flood simulations can be conducted for the 95th and 5th percentile watershed PF relationships using AEP Neutral concepts similar to that described in Sections 10 and 11.

The resultant HHC showing best-estimate and 90% uncertainty bounds would be similar to that shown in Figure 21.

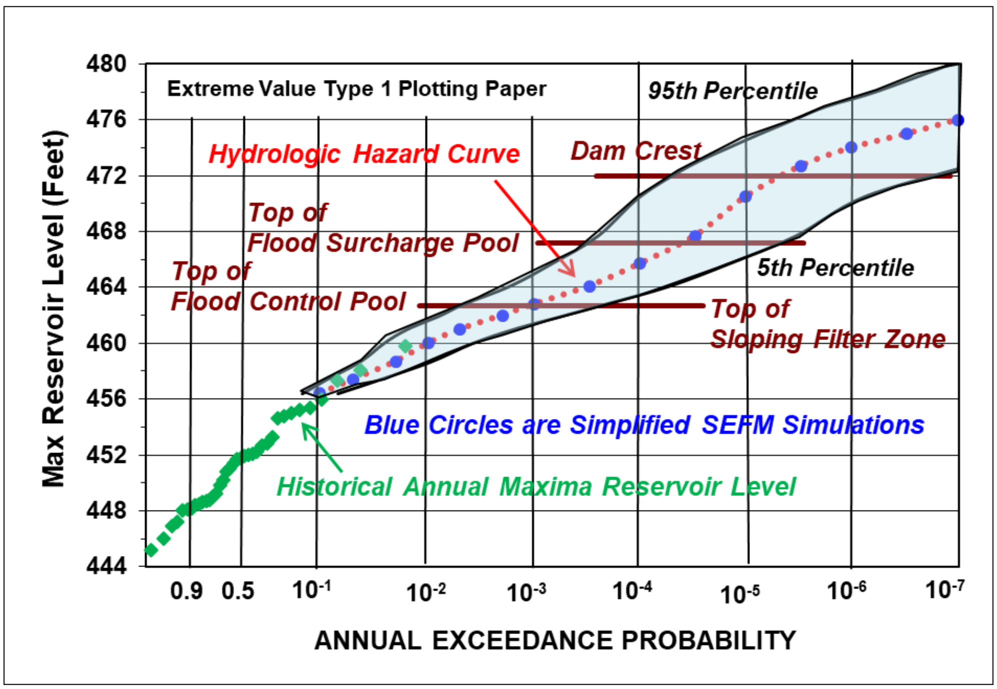


Figure 21 – Example of Hydrologic Hazard Curve for Maximum Reservoir Level Showing Best-Estimate and 90% Uncertainty Bounds

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Appendix A: Additional Information for PF-ARF Values Obtained from Hydrometeorological Reports for PMP

This appendix contains examples of PF-ARF values computed using Equation 1 for various storm types using storm-centered ARF values from NWS Hydrometeorological Reports.

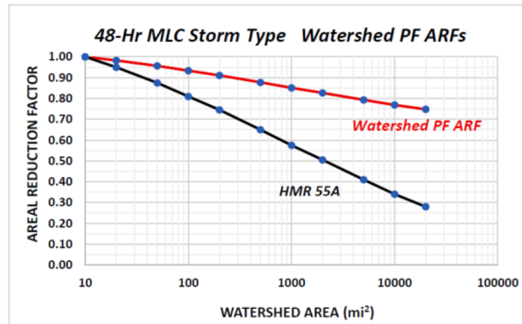
48-Hour Precipitation for Non-Orographic Areas HMR-55A: B,C,D
Mid-Latitude Cyclone (MLC) Storm Type

PRELIMINARY 5/15/2017

Point precipitation is considered equivalent to 10-mi² precipitation for synoptic scale storms

INTERPOLATED VALUES | alpha=0.65

Storm Area sq miles	ARF Ratio to 10 sq miles	ARF Delta Adjustment	Watershed PF ARF
10	1.000	0.000	1.000
20	0.950	0.033	0.983
50	0.875	0.081	0.956
100	0.810	0.124	0.934
200	0.745	0.166	0.911
500	0.650	0.228	0.878
1000	0.575	0.276	0.851
2000	0.505	0.322	0.827
5000	0.410	0.384	0.794
10000	0.340	0.429	0.769
20000	0.280	0.468	0.748



Watershed Precipitation-Frequency ARF = HMR ARF + Delta

Figure 22 – Geographically-Fixed PF-ARF Modified from Storm-Focused ARF for HMR 55a – MLC Storm Type

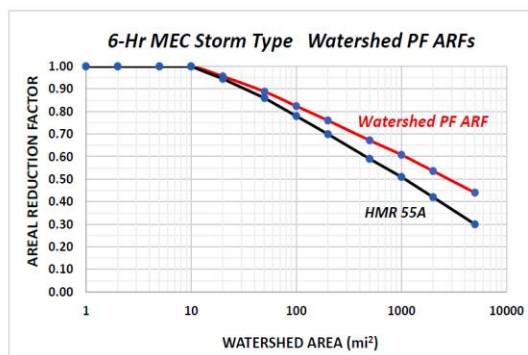
6-Hour Precipitation for Non-Orographic Areas HMR-55: B,C,D
Mesoscale Storm with Embedded Convection (MEC) Storm Type

PRELIMINARY 5/15/2017

Point precipitation is considered equivalent to 1-mi² precipitation for convective storms

INTERPOLATED VALUES | alpha=0.20

Storm Area sq miles	ARF Ratio to 1 sq miles	ARF Delta Adjustment	Watershed PF ARF
1	1.000	0.000	1.000
2	1.000	0.000	1.000
5	1.000	0.000	1.000
10	1.000	0.000	1.000
20	0.945	0.011	0.956
50	0.860	0.028	0.888
100	0.780	0.044	0.824
200	0.700	0.060	0.760
500	0.590	0.082	0.672
1000	0.510	0.098	0.608
2000	0.420	0.116	0.536
5000	0.300	0.140	0.440



Watershed Precipitation-Frequency ARF = HMR ARF + Delta

Figure 23 – Geographically-Fixed PF-ARF Modified from Storm-Focused ARF for HMR 55a – MEC Storm Type

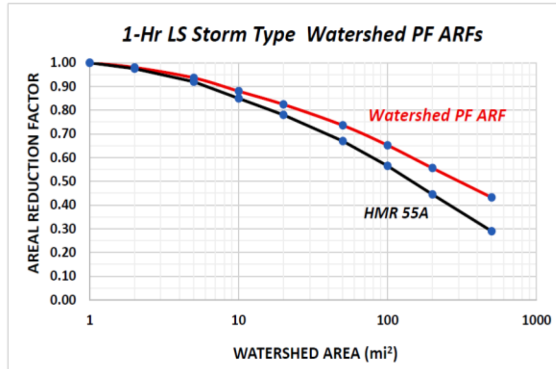
1-Hour Precipitation HMR-55A
Local Storm (LS) Storm Type

PRELIMINARY
5/15/2017

Point precipitation is considered equivalent
to 1-mi^2 precipitation for convective storms

INTERPOLATED VALUES

Storm Area sq miles	ARF Ratio to 1 sq miles	alpha=0.20 ARF Delta Adjustment	Watershed PF ARF
1	1.000	0.000	1.000
2	0.975	0.005	0.980
5	0.920	0.016	0.936
10	0.850	0.030	0.880
20	0.780	0.044	0.824
50	0.670	0.066	0.736
100	0.565	0.087	0.652
200	0.445	0.111	0.556
500	0.290	0.142	0.432
1000			



Watershed Precipitation-Frequency ARF = HMR ARF + Delta

Figure 24 – Geographically-Fixed PF-ARF Modified from Storm-Focused ARF for HMR 55a – LS Storm Type

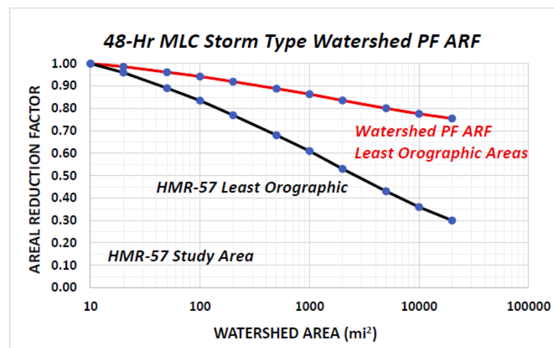
48-Hour Precipitation HMR-57
Mid-Latitude Cyclone (MLC) Storm Type

PRELIMINARY
5/15/2017

Point precipitation is considered equivalent
to 10-mi^2 precipitation for synoptic scale storms

LEAST OROGRAPHIC

Storm Area sq miles	ARF Ratio to 10 sq miles	alpha=0.65 ARF Delta Adjustment	Watershed PF ARF
10	1.000	0.000	1.000
20	0.960	0.026	0.986
50	0.890	0.072	0.962
100	0.835	0.107	0.942
200	0.770	0.150	0.920
500	0.680	0.208	0.888
1000	0.610	0.254	0.864
2000	0.530	0.306	0.836
5000	0.430	0.371	0.801
10000	0.360	0.416	0.776
20000	0.300	0.455	0.755



OROGRAPHIC

Storm Area sq miles	ARF Ratio to 10 sq miles	alpha=0.65 ARF Delta Adjustment	Watershed PF ARF
10	1.000	0.000	1.000
20	0.995	0.003	0.998
50	0.970	0.020	0.990
100	0.940	0.039	0.979
200	0.900	0.065	0.965
500	0.820	0.117	0.937
1000	0.760	0.156	0.916
2000	0.690	0.202	0.892
5000	0.590	0.267	0.857
10000	0.510	0.319	0.829
20000	0.440	0.364	0.804

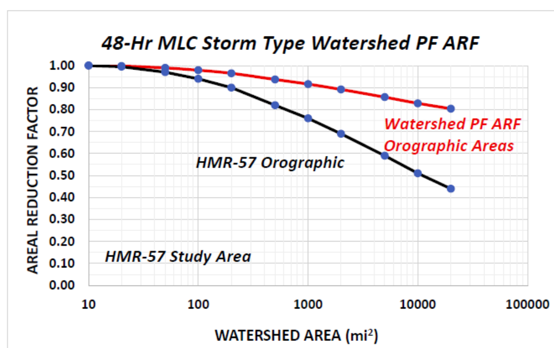


Figure 25 – Geographically-Fixed PF-ARF Modified from Storm-Focused ARF for HMR 57 – MLC Storm Type

1-Hour Precipitation HMR-57
Local Storm (LS) Storm Type

PRELIMINARY
5/15/2017

Point precipitation is considered equivalent
to 1-mi² precipitation for convective storms

INTERPOLATED VALUES

Storm Area sq miles	1-Hr PMP (in)	ARF Ratio to 1 sq miles	alpha=0.20 ARF Delta Adjustment	Watershed PF ARF
1		1.000	0.000	1.000
2		0.975	0.005	0.980
5		0.915	0.017	0.932
10		0.830	0.034	0.864
20		0.740	0.052	0.792
50		0.605	0.079	0.684
100		0.490	0.102	0.592
200		0.360	0.128	0.488
500		0.180	0.164	0.344
1000				

Watershed Precipitation-Frequency ARF = HMR ARF + Delta

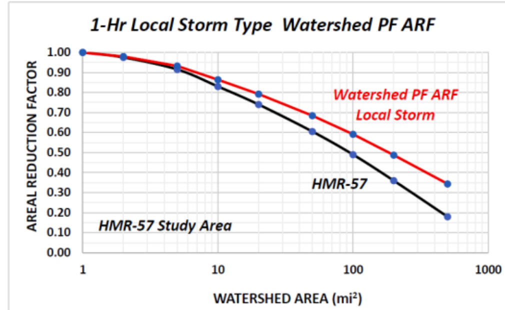


Figure 26 – Geographically-Fixed PF-ARF Modified from Storm-Focused ARF for HMR 57 – LS Storm Type

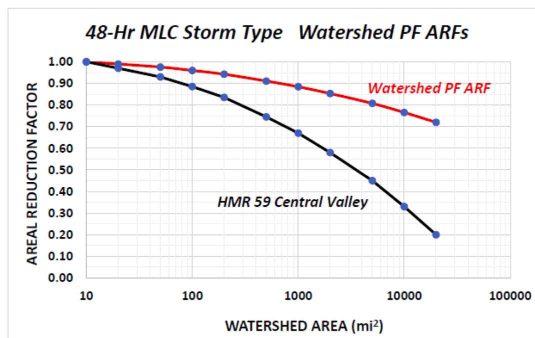
48-Hour Precipitation HMR-59
Mid-Latitude Cyclone (MLC) Storm Type

PRELIMINARY
5/15/2017

Point precipitation is considered equivalent
to 10-mi² precipitation for synoptic scale storms

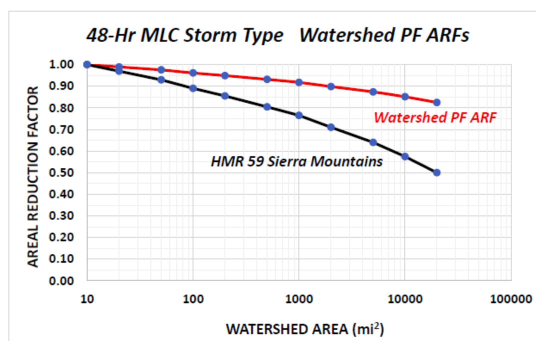
CENTRAL VALLEY

Storm Area sq miles	ARF Ratio to 10 sq miles	alpha=0.65 ARF Delta Adjustment	Watershed PF ARF
10	1.000	0.000	1.000
20	0.970	0.020	0.990
50	0.930	0.046	0.976
100	0.885	0.075	0.960
200	0.835	0.107	0.942
500	0.745	0.166	0.911
1000	0.670	0.215	0.885
2000	0.580	0.273	0.853
5000	0.450	0.358	0.808
10000	0.330	0.436	0.766
20000	0.200	0.520	0.720



SIERRAS

Storm Area sq miles	ARF Ratio to 10 sq miles	alpha=0.65 ARF Delta Adjustment	Watershed PF ARF
10	1.000	0.000	1.000
20	0.970	0.020	0.990
50	0.930	0.046	0.976
100	0.890	0.072	0.962
200	0.855	0.094	0.949
500	0.805	0.127	0.932
1000	0.765	0.153	0.918
2000	0.710	0.189	0.899
5000	0.640	0.234	0.874
10000	0.575	0.276	0.851
20000	0.500	0.325	0.825



Watershed Precipitation-Frequency ARF = HMR ARF + Delta

Figure 27 – Geographically-Fixed PF-ARF Modified from Storm-Focused ARF for HMR 59 – MLC Storm Type

1-Hour Precipitation HMR-59
Local Storm (LS) Storm Type

PRELIMINARY
5/15/2017

Point precipitation is considered equivalent to 1-mi[2] precipitation for convective storms

6-hr/1-hr Ratio = 1.2

INTERPOLATED VALUES		alpha=0.20	
Storm Area sq miles	ARF Ratio to 1 sq miles	ARF Delta Adjustment	Watershed PF ARF
1	1.000	0.000	1.000
2	0.975	0.005	0.980
5	0.940	0.012	0.952
10	0.900	0.020	0.920
20	0.795	0.041	0.836
50	0.625	0.075	0.700
100	0.500	0.100	0.600
200	0.365	0.127	0.492
300	0.285	0.143	0.428
500	0.180	0.164	0.344

Watershed Precipitation-Frequency ARF = HMR ARF + Delta

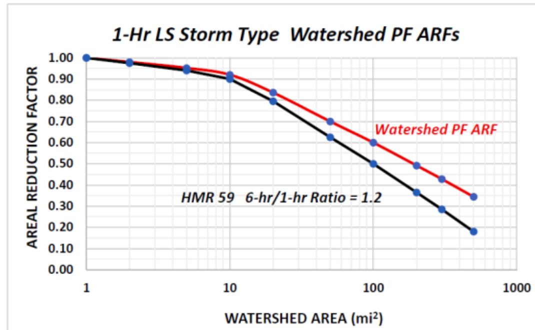


Figure 28 – Geographically-Fixed PF-ARF Modified from Storm-Focused ARF for HMR 59 – LS Storm Type

Areal Reduction Factors for Eastern US (HMR 51-52)

HMR 51 and HMR 52 do not have curves that directly provide the HMR ARFs. However, they are easily developed using Figures 18-47 in HMR-51 and Figures 23-31 in HMR-52.
The procedure is as follows:

- The determination of storm type provides the key duration.
- The figures in HMR 51 provide precipitation estimates for the 48-hour and 6-hour durations and storm area sizes for every location in the Eastern US as follows:
  - 48-hour duration – 10, 200, 1,000, 5,000, 10,000, and 20,000 sq. mi.
  - 6-hour duration – 1, 10, 200, 1,000, and 5,000 sq. mile; 1 sq. mile in HMR-52
- The figures in HMR 52 provide precipitation estimates for the 1-hour duration and area sizes for 1, 10, 100, 200, and 1000 sq. mi. for every location in the Eastern US.
- Use these figures to establish the precipitation values for each particular duration and area size for the location of the watershed centroid, using digital files (preferred), or just the paper figures.
- Plot the precipitation values on plotting paper with an equal logarithmic distribution of the storm area size on the x-axis for the key duration(s).
- Interpolate the intermediate precipitation values from the curve as follows:
  - 48 hours – 20, 50, 100, 500, and 2,000 sq. mi.
  - 6 hours – 2, 5, 20, 50, 100, 500, and 2,000 sq. mi.
  - 1 hour – 2, 5, 20, 50, and 500 sq. mi.
- Compute the HMR ARFs as a ratio of the precipitation values for the selected storm-area size (numerator) divided by the precipitation for the indexing storm area size;
  Indexing storm areas are 10 sq. miles for 48-hour duration, and 1 sq. mile for 6-hour and 1-hour durations.
- Plot the HMR ARFs vs Watershed Area.
- Apply Equation 1 to the HMR-ARF values to convert from storm-focused ARFs to geographically-fixed PF-ARFs, where watershed area now replaces storm area on the x-axis

An example for an MEC storm at 34°N 81°W in South Carolina is shown in Figure 29, below:

6-Hour PMP for 34N 81W in South Carolina
Mesoscale Storm with Embedded Convection (MEC) Storm Type

HMR-51 VALUES

Storm Area sq miles	6-Hr PMP (in)		
1	30.6	HMR-52	Figure 23
10	30.6	HMR-51	Figure 18
200	22.4	HMR-51	Figure 23
1000	16.5	HMR-51	Figure 28
5000	9.6	HMR-51	Figure 33

Point precipitation is considered equivalent to 1-mi² precipitation for convective storms

INTERPOLATED VALUES

Storm Area sq miles	6-Hr PMP (in)	ARF Ratio to 1 sq miles
1	30.6	1.000
2	30.6	1.000
5	30.6	1.000
10	30.6	1.000
20	29.0	0.948
50	26.4	0.863
100	24.5	0.801
200	22.4	0.732
500	19.0	0.621
1000	16.5	0.539
2000	13.5	0.441
5000	9.6	0.314

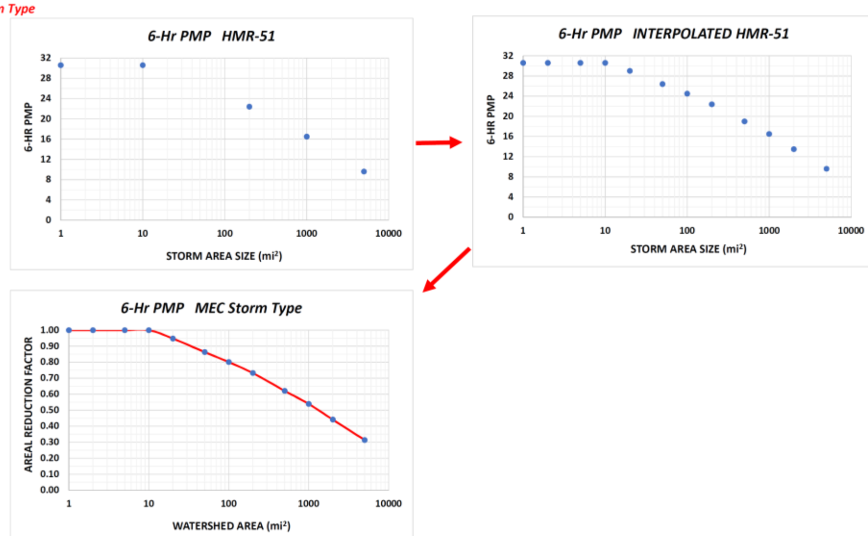


Figure 29 – Example ARF from HMR 51 and 52

The modified HMR 51-52 ARFs are shown below in Figures 29 –31.

48-Hour PMP for 36N 82W in North Carolina - Tennessee Border
Mid-Latitude Cyclone (MLC) Storm Type

PRELIMINARY 5/15/2017

HMR-51 VALUES

Storm Area sq miles	48-hr PMP (in)		
10	42.8	HMR-51	Figure 21
200	32.7	HMR-51	Figure 26
1000	26.5	HMR-51	Figure 31
5000	20.0	HMR-51	Figure 36
10000	16.9	HMR-51	Figure 41

Point precipitation is considered equivalent to 10-mi² precipitation for synoptic scale storms

INTERPOLATED VALUES

Storm Area sq miles	48-hr PMP (in)	HMR ARF Ratio to 10 sq miles		alpha=0.65 ARF Delta Adjustment	Watershed PF ARF
10	42.8	1.000		0.000	1.000
20	41.0	0.958		0.027	0.985
50	37.9	0.886		0.074	0.960
100	35.4	0.827		0.112	0.939
200	32.7	0.764		0.153	0.917
500	29.2	0.682		0.207	0.889
1000	26.5	0.619		0.248	0.867
2000	23.7	0.554		0.290	0.844
5000	20.0	0.467		0.346	0.814
10000	16.9	0.395		0.393	0.788
20000	14.0	0.327	extrapolated	0.437	0.764

Watershed Precipitation-Frequency ARF = HMR ARF + Delta

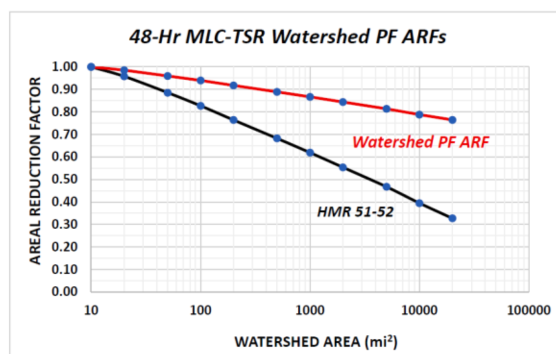


Figure 30 – Modified ARF for HMR 51-52 – MLC/TSR Storm Type

6-Hour Precipitation for 36N 82W in North Carolina - Tennessee Border
Mesoscale Storm with Embedded Convection (MEC) Storm Type

PRELIMINARY
5/15/2017

HMR-51 VALUES

Storm Area sq miles	6-Hr PMP (in)		
1	29.4	HMR-52	Figure 23
10	29.4	HMR-51	Figure 18
200	21.1	HMR-51	Figure 23
1000	15.6	HMR-51	Figure 28
5000	9.2	HMR-51	Figure 33

Point precipitation is considered equivalent
to 1-mi² precipitation for convective storms

INTERPOLATED VALUES

Storm Area sq miles	6-Hr PMP (in)	ARF Ratio to 1 sq miles	alpha=0.20 ARF Delta Adjustment	Watershed PF ARF
1	29.4	1.000	0.000	1.000
2	29.4	1.000	0.000	1.000
5	29.4	1.000	0.000	1.000
10	29.4	1.000	0.000	1.000
20	27.9	0.949	0.010	0.959
50	25.4	0.864	0.027	0.891
100	23.3	0.793	0.041	0.834
200	21.1	0.718	0.056	0.774
500	18.1	0.616	0.077	0.693
1000	15.6	0.531	0.094	0.624
2000	13.0	0.442	0.112	0.554
5000	9.2	0.313		

Watershed Precipitation-Frequency ARF = HMR ARF + Delta

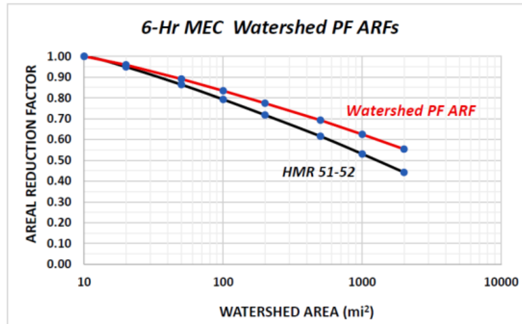


Figure 31 – Modified ARF for HMR 51-52 – MEC Storm Type

1-Hour Precipitation for 36N 82W in North Carolina - Tennessee Border
Local Storm (LS) Storm Type

PRELIMINARY
5/15/2017

HMR-52 VALUES

Storm Area sq miles	1-Hr PMP (in)		
1	18.8	HMR-52	Figure 24
10	15.4	HMR-52	Figure 29
100	10.9	HMR-52	Figure 30
200	9.0	HMR-52	Figure 31
1000	5.1	HMR-52	Figure 32

Point precipitation is considered equivalent
to 1-mi² precipitation for convective storms

INTERPOLATED VALUES

Storm Area sq miles	1-Hr PMP (in)	ARF Ratio to 1 sq miles	ARF Ratio Smoothed	alpha=0.20 ARF Delta Adjustment	Watershed PF ARF
1	18.8	1.000	1.000	0.000	1.000
2	17.9	0.952	0.953	0.010	0.962
5	16.5	0.878	0.880	0.024	0.902
10	15.4	0.819	0.817	0.036	0.855
20	14.1	0.750	0.749	0.050	0.800
50	12.4	0.660	0.660	0.068	0.728
100	10.9	0.580	0.578	0.084	0.664
200	9.0	0.479	0.490	0.104	0.583
500	6.9	0.367	0.370	0.127	0.494
1000	5.1	0.269	0.267	0.146	0.415

Watershed Precipitation-Frequency ARF = HMR ARF + Delta

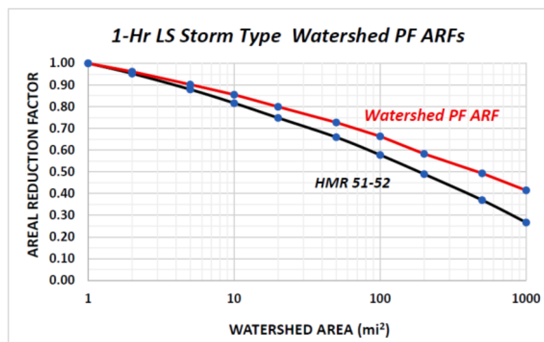


Figure 32 – Modified ARF for HMR 51-52 – LS Storm Type