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Local Precipitation-Frequency Studies

Development of 1-Hour/1-Square Mile Precipitation-Frequency Relationships for Two Example Nuclear Power Plant Site

2014 TECHNICAL REPORT

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Development of 1-Hour/1-Square Mile Precipitation-Frequency Relationships for Two Example Nuclear Power Plant Sites

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Abstract

To ensure that nuclear power plants are adequately protected against extreme rainfall plant design has traditionally relied on deterministic requirements to define the extent of flooding that might need to be accommodated. For purposes of probabilistic risk assessment (PRA), a more comprehensive understanding of the relationship between the frequency and amount of extreme rainfall is necessary. Such an understanding is also needed to provide further perspective on the challenges posed by precipitation corresponding to the deterministic criteria.

To explore the state of the technology and data available to support a more comprehensive probabilistic evaluation, EPRI undertook an evaluation of the precipitation-frequency relationship for two sites in the United States, one an inland site and the other an Atlantic Ocean coastal site. The study was primarily based on regional precipitation-frequency relationships that embody National Weather Service data from a large number of precipitation measurement stations in the vicinity of the plant sites.

Plants in the United States are designed to be protected against flooding that could result from local intense precipitation (LIP). For design purposes, LIP is defined based on precipitation associated with a 1-hour/1- square mile probable maximum precipitation (PMP) event. The method described in this report was applied to calculate the probability of the PMP occurring for the two example sites as well.

The approach employed in this report successfully demonstrated the feasibility of a probabilistic technique for establishing precipitation-frequency relationships for local precipitation events. The regional analyses also found that an event corresponding to the 1-hour/ 1-square mile PMP would result in an extremely large amount of precipitation and would be extremely rare.

Keywords
Exceedance probability
Flooding
Local intense precipitation
Nuclear power plants
Precipitation
Precipitation-frequency

Executive Summary

To ensure that nuclear power plants are adequately protected against extreme rainfall plant design has traditionally relied on deterministic requirements to define the extent of flooding that might need to be accommodated. For purposes of probabilistic risk assessment (PRA), a more comprehensive understanding of the relationship between the frequency and amount of extreme rainfall is necessary. Such an understanding is also needed to provide further perspective on the challenges posed by precipitation corresponding to the deterministic criteria.

Local intense precipitation (LIP) is an external flood producing event evaluated in establishing the flood design basis for plants in the United States. For design purposes, LIP is defined based on precipitation associated with a 1-hour/1-square mile probable maximum precipitation[1] (PMP) event. To explore the state of the technology and data available to support a more comprehensive probabilistic evaluation of LIP, EPRI undertook an evaluation of the 1-hour/1-square mile precipitation-frequency relationship for two sites in the United States, one an inland site and the other an Atlantic Ocean coastal site.

The study was primarily based on regional precipitation-frequency relationships that embody National Weather Service data from a large number of precipitation measurement stations in the vicinity of the plant sites. For comparison purposes the regional precipitation-frequency relationship results were complemented by maximum short-duration rainfall data for the two site study areas, world record

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[1] Definition of probable maximum precipitation (PMP) from Hydrometeorological Report 51, 1978 [1]: PMP is defined as "the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year," (American Meteorological Society 1959). In consideration of our limited knowledge of the complicated processes and interrelationships in storms, PMP values are identified as estimates. Another definition of PMP more operational in concept is "the steps followed by hydrometeorologists in arriving at the answers supplied to engineers for hydrological design purposes" (WMO 1973). This definition leads to answers deemed adequate by competent meteorologists and engineers and judged as meeting the requirements of a design criterion.

rainfalls for comparable time durations and stochastic storm transposition review. The method described in this report was also applied to calculate the probability of the PMP occurring for the two example sites.

The regional precipitation-frequency approach employed in this report successfully demonstrated the feasibility of a probabilistic technique for establishing precipitation-frequency relationships for local precipitation events.

For the two sites and associated data analyzed the study results found that an event corresponding to the 1-hour/1-square mile PMP would result in an extremely large amount of precipitation and would be extremely rare:

- The regional precipitation-frequency analyses found that the 1-hour/1-square mile rainfall PMP values are very low likelihood events with annual exceedance probabilities less than 10^{-6}.
- The 1-hour/1-square mile rainfall PMP values exceed site study area and world record rainfalls for comparable time durations.
- Review considering stochastic storm transposition led to estimates consistent with the precipitation-frequency analyses.

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Section 1: Overview

The 1-hour/1-square mile probable maximum precipitation (PMP) is used in the nuclear industry as a basic, deterministic input for assessing a design basis flood event at a nuclear power plant due to localized flooding from the occurrence of a high-intensity precipitation event. This event is termed local intense precipitation (LIP).

The 1-hour/1-square mile PMP is in the range of 16 to 19-inches [2] for much of the United States east of the Continental Divide. This postulated event is likely associated with a grouping of convective storm cells in a mesoscale convective system (MCS) commonly termed a thunderstorm. The areal coverage of the portion of the storm with extreme intensities applicable to a LIP event would be quite small, on the order of two square miles or less [Tomlinson, 11].

For use in probabilistic risk assessment (PRA), an understanding and definition of the relationship between precipitation and frequency is necessary. There is also interest in obtaining a quantitative understanding of the probability of the 1-hour/1-square mile PMP design event because it is perceived to represent an extremely rare event. For comparison, Table 1-1 lists the world record short-duration rainfalls [3]. The rareness of the LIP event can be inferred when considering that the LIP design event exceeds the world record rainfalls for comparable time durations and must also be a direct hit, the high-intensity rainfall must coincide with the site of the nuclear power plant. Given these considerations, there is interest in quantifying the precipitation-frequency characteristics for short-duration, high-intensity precipitation and in estimating the annual exceedance probability (AEP) of the 1-hour/1-square mile PMP.

Table 1-1
World Record Short-Duration Rainfalls World Record Rainfalls (In)

World Record Rainfalls (In)			
Duration	**Precipitation (in)**	**Storm Location**	**Storm Date**
42-min	12.0	Holt, Missouri	June 22, 1947
60-min	15.8	Shangdi, Nei Monggol, China	July 3, 1975
2-hrs 10-min	19.0	Rockport, West Virginia	July 18, 1889

This report presents information on the results of regional precipitation-frequency analyses that were conducted to develop precipitation-frequency relationships for an inland and a coastal site in the United States. These analyses also include an assessment of the rarity of the site-specific 1-hour/1-square mile PMP at the inland and coastal sites.

Section 2: Precipitation-Frequency Relationship Analysis

Precipitation-frequency relationships for 1-hour precipitation annual maxima for an inland and coastal site were developed using L-moment regional frequency analysis methods by Hosking and Wallis [4] and L-RAP software by Schaefer and Barker [5]. The procedures used in conducting the regional analysis and developing the precipitation-frequency relationships and uncertainty bounds are described in the following sections.

2.1 Data Sets

Precipitation annual maxima series datasets for the 1-hour and 2-hour durations were obtained from the National Weather Service (NWS) for precipitation measurement stations within several hundred miles of the two sites. The datasets were originally assembled by the NWS for use in producing NOAA Atlas 14 [6]. The period of record for those datasets ended in 2000 and the datasets were updated with all available hourly data for the years from 2001 through 2010. Quality-checking was conducted to identify and remove false annual maxima that occur due to periods of missing data, and measurement and recording errors. Only stations with 25-years or more of record were used in the regional analysis.

2.2 Use of 1-Hour and 2-Hour Annual Maxima Data Sets

The focus of this analysis is on precipitation annual maxima for the 1-hour duration. However, there are considerations in the system of measurement for 1-hour precipitation maxima that should be addressed in conducting the analysis. Specifically, precipitation data in the U.S. for durations less than daily are obtained from automated gages. The vast majority of automated gages report on 1-hour intervals on the clock-hour rather than measurements taken on a continuous basis. Thus, it is common for the greatest precipitation in a continuous 60-minute period to be split between adjacent hourly reporting periods. This results in the apparent 1-hour maxima being under-reported relative to the true precipitation maxima for a continuous 60-minute period. This discrepancy is accounted for by an observational period adjustment factor [6, 7], which for one observational period is an increase of 13% to the summary statistics for the mean and standard deviation. The measures of skewness and kurtosis for annual maxima obtained from one observational period are also biased and subject to greater sampling variability which are not accounted for by the adjustment factor. This situation is not highly significant when quantile estimates are of interest for more common events up to perhaps an AEP of 1:500. However, this is an important consideration when estimating very extreme AEPs for precipitation approaching the magnitude of the PMP.

The approach taken in this study was to use the results of the analysis of 1-hour annual maxima for estimating the 1-hour at-site mean and to use the 2-hour annual maxima for estimating the regional L-moment ratios L-cv, L-skewness and L-kurtosis. Specifically, the 1-hour precipitation data constitute a time-series of hourly precipitation values. The 2-hour annual maxima are computed by sliding a 2-hour window through the hourly time-series and identifying the greatest total precipitation in adjacent hourly reporting periods. This procedure greatly reduces the problems that occur when precipitation is split into adjacent hourly reporting periods because the greatest precipitation amount in a continuous 1-hour period is captured within the 2-hour window. This approach is appropriate because thunderstorm precipitation is typically short-lived with the greatest intensities occurring over short periods, such that the true 2-hour annual maxima are typically not much greater than the true 1-hour annual maxima. In this description, "true" applies to the situation where precipitation measurements are made on a continuous basis where true 2-hour and 1-hour maxima would correspond to actual 120-minute and 60-minute continuous measurements, respectively. For the two sites in this study, the true 2-hour at-site mean is about 20% larger than the true 1-hour at-site mean. As such, the regional L-moment statistics for 2-hour annual maxima are more accurate measures of the regional statistics relative to what would be obtained for 1-hour annual maxima measured on a continuous basis. Figures A-1 and A-2 in Appendix A show the underestimation of 1-hour precipitation-frequency that would occur if 1-hour annual maxima were used for computing regional statistics and probability distribution parameters rather than the 2-hour annual maxima.

2.3 Largest 1-Hour and 2-Hour Precipitation Events

The largest 1-hour and 2-hour annual maxima in the study areas are of natural interest for comparison with the 1-hour/1-square mile PMP values. Table 2-1 lists the two largest 1-hour and 2-hour precipitation values and associated dates of occurrence and the 1-hour/1-square mile PMP values. The historical maxima in the study areas are relatively small by comparison to the world record values (Table 1-1) and the PMP values.

Table 2-1
Comparison of Precipitation Maxima in Study Areas and Probable Maximum Precipitation

Study Area	1-Hour Precipitation		2-Hour Precipitation	
Inland Site	3.50-in	Jul 21, 1953	5.45-in	Jul 21, 1951
	3.38-in	Jun 18, 2009	5.24-in	Aug 6, 1986
	17.9-in	PMP	20.8-in	PMP
Coastal Site	3.33-in	Aug 20, 1997	6.50-in	Aug 20, 1997
	4.00-in	Aug 27, 2009	5.60-in	Aug 27, 2009
	18.4-in	PMP	21.2-in	PMP

2.4 Homogeneous Regions

Regional frequency analysis uses a large sample set of observations of the same phenomenon at multiple sites to improve magnitude-frequency estimation for all sites within a homogenous region (Hosking and Wallis [4] and Stedinger et al [12]). A homogeneous region is a collection of sites that can be described by a common magnitude-frequency relationship after the site data are rescaled by the at-site mean. As with all regional analyses, the usefulness of the precipitation-frequency relationship computed for a selected site is dependent upon similarity of the site with the regional precipitation-frequency characteristics. Care must be exercised in conducting the regional analysis to form homogeneous regions by grouping sites that are representative of the site of interest or to account for differences with the regional average characteristics due to site meteorological/climatic characteristics.

Homogeneity was assessed by subdividing the areas around each site into quadrants at distances of 100-nautical miles (nm) and 150-nm for the inland site (Figure 2-1) and 100-nm and 120-nm for the coastal site (Figure 2-2). Note that these figures include locations for all precipitation measurement stations where data were available from NOAA Atlas 14. As discussed in Section 2.1, only those stations with 25-years or more of record were used in the regional analyses.

L-moment sample statistics were computed for annual maxima data from precipitation stations within each of the eight sub-areas formed by the quadrants/radii and heterogeneity tests were conducted [4] to assess the heterogeneity of each subarea. For each site, all eight subareas were found to be acceptably homogeneous and the stations were pooled for regional analysis. This resulted in 116 stations with 5,349 station-years of record at the inland site and 35 stations and 1,635 station-years of record for the coastal site. Heterogeneity measures were then computed for the collection of all stations to confirm acceptable homogeneity and the results are shown in Tables 2-2, 2-3.

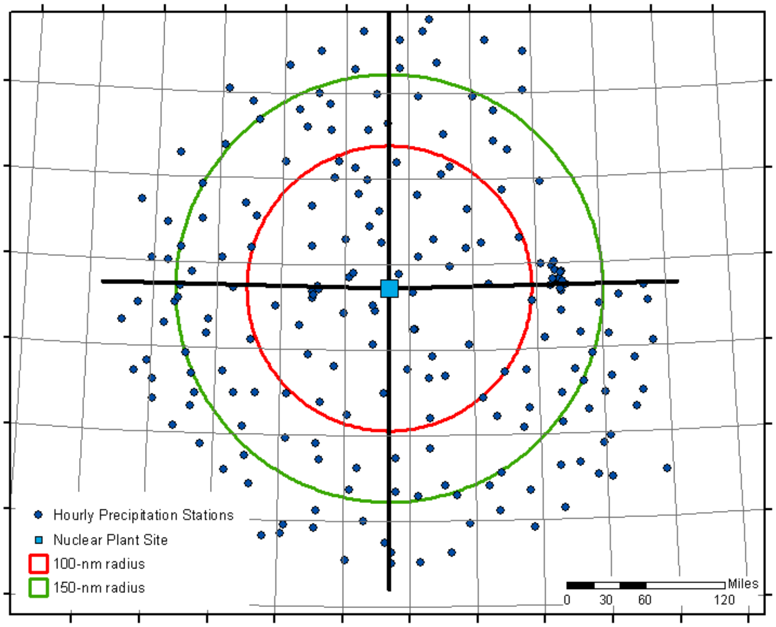

Figure 2-1
Subdivision of the Area Surrounding the Inland Site into Quadrants within Radii of 100-nm and 150-nm forming Eight Subareas

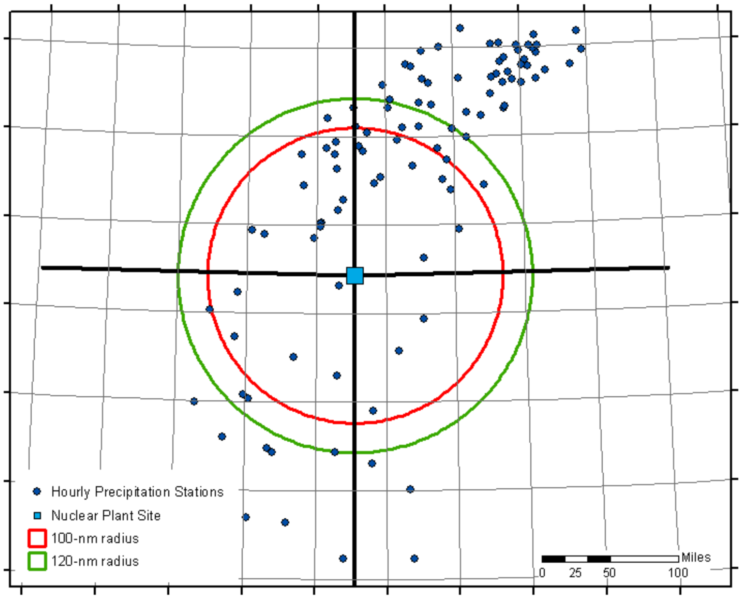

Figure 2-2
Subdivision of the Area Surrounding the Coastal Site into Quadrants within Radii of 100-nm and 120-nm forming Eight Subareas

Table 2-2
Heterogeneity Measures for 116 Stations at Inland Site

Heterogeneity Measures For Inland Site			
L-moment Ratio	**Measure**	**Computed Value**	**Conclusion**
L-cv	H1	-0.73	Use 116 Stations within 150-nm Radius for Regional Analysis
L-skewness	H2	0.03	

Table 2-3
Heterogeneity Measures for 35 Stations at Coastal Site

Heterogeneity Measures For Coastal Site			
L-moment Ratio	**Measure**	**Computed Value**	**Conclusion**
L-cv	H1	0.46	Use 35 Stations within 120-nm Radius for Regional Analysis
L-skewness	H2	0.04	

2.5 Seasonality

The seasonality of precipitation annual maxima at the two sites was analyzed by assembling datasets comprised of the dates of occurrence for annual maxima that exceeded a specified threshold. A nominal 20-year recurrence interval (RI) threshold was used for the inland site and a nominal 10-year recurrence interval threshold was used for the coastal site. These thresholds were based on the station-years of record available at the two sites, the desire to examine large storm events and also have an adequate sample size. The storm events to be included were selected non-parametrically using the Cunnane Plotting Position formula with a weighting parameter of 0.40. Thus, a station with 40-years of record would have two storms over the 20-year RI threshold and four storms over the 10-year RI threshold. The composite dataset of storm dates was assembled and duplicate storm dates were removed. This resulted in 227 unique storm dates for the inland site and 160 unique storm dates for the coastal site.

Figures 2-3 and 2-5 depict seasonality histograms for the two sites which show predominately warm season behavior that reflects the greater atmospheric moisture holding capacity in the warm season. Numerical storm dates were computed for the datasets described above using a numbering system comprised of the month and a decimal portion based on the day of the month (for example July 20 equates to 7.65). Figures 2-4 and 2-6 depict probability-plots for the numerical storm dates. A review of the probability-plots shows the seasonality to be well-behaved and well-described with a near-Normal probability distribution having low skewness.

The findings of the seasonality analyses have their application in rainfall-runoff modeling using information on the months when extreme storms would most likely occur. Subsequent analyses can then be conducted to determine the likely soil-moisture conditions that would be present if an extreme storm did occur.

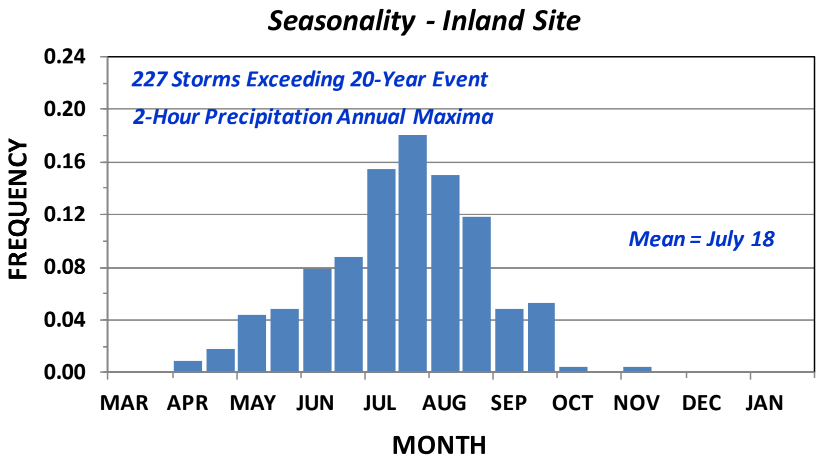

Figure 2-3
Seasonality Histogram for Storm Dates Where Precipitation Annual Maxima Exceed a 20-Year Recurrence Interval Threshold at the Inland Site

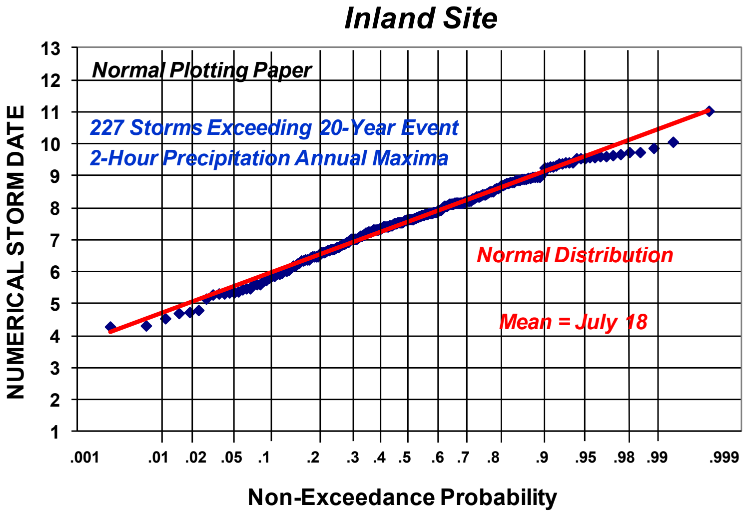

Figure 2-4
Probability-Plot of Numerical Storm Dates Where Precipitation Annual Maxima Exceed a 20-Year Recurrence Interval Threshold at the Inland Site

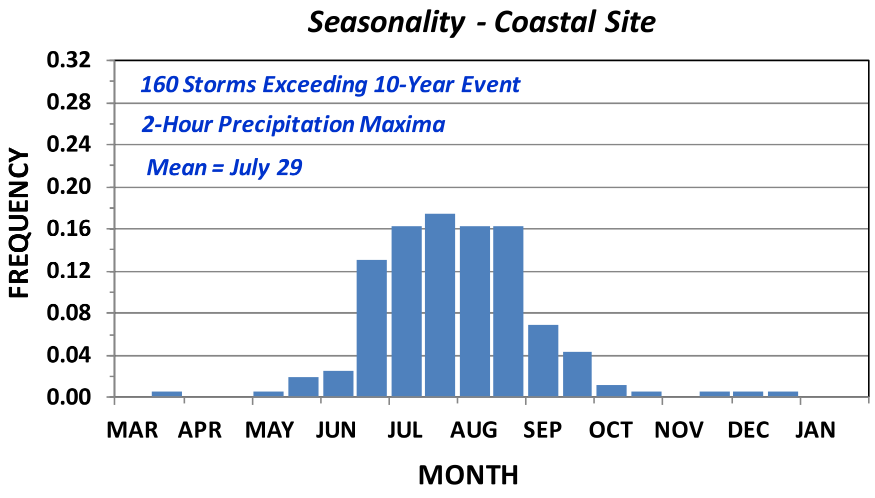

Figure 2-5
Seasonality Histogram for Storm Dates Where Precipitation Annual Maxima Exceed a 10-Year Recurrence Interval Threshold at the Coastal Site

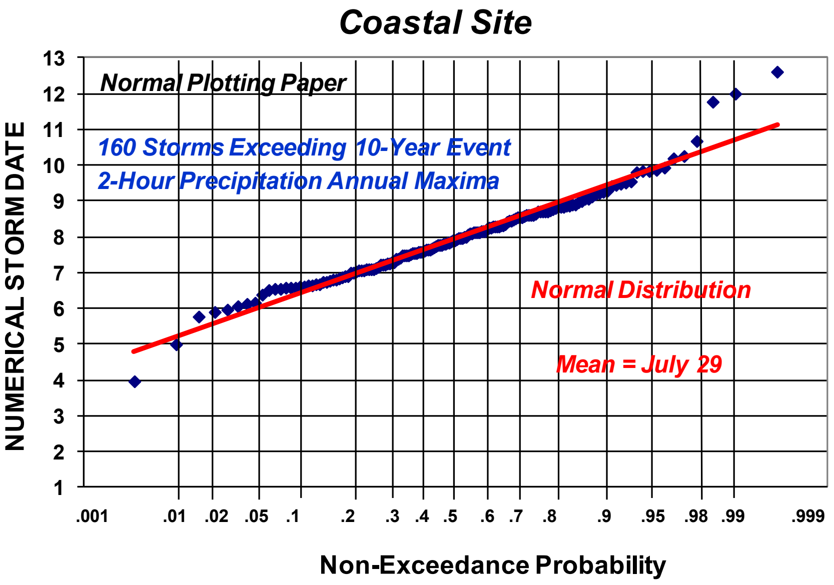

Figure 2-6
Probability-Plot of Numerical Storm Dates Where Precipitation Annual Maxima Exceed a 10-Year Recurrence Interval Threshold at the Coastal Site

2.6 Regional L-moment Statistics

Regional L-moment statistics were computed for the annual maxima data for the collection of stations at the two sites (Tables 2-4, 2-5). The similarity in regional L-moment statistics at the two sites is striking, which may be related to the similarity of thunderstorm behavior at very short durations. Estimates of the at-site means were based on an inverse-distance weighting computation of 1-hour at-site means for stations in the quadrants nearest the sites (Figures 2-1, 2-2) and included the estimate of the 1-hour at-site mean from NOAA Atlas 14

[6]. As discussed previously, the higher order regional L-moment statistics were computed from the 2-hour annual maxima for the collection of stations because they provide a more robust estimate of 1-hour annual maxima due to the limitations in the 1-hour reporting system.

Table 2-4
Estimates of Population L-moments for 116 Stations at Inland Site

Regional L-moments			
1-Hour At-Site Mean	**2-Hour Annual Maxima**		
	L-cv	**L-skewness**	**L-kurtosis**
1.410-in	0.1990	0.2160	0.1630

Table 2-5
Estimates of Population L-moments for 35 Stations at Coastal Site

Regional L-moments			
1-Hour At-Site Mean	**2-Hour Annual Maxima**		
	L-cv	**L-skewness**	**L-kurtosis**
1.445-in	0.2005	0.2050	0.1570

2.7 Identification of Regional Probability Distributions

Regional L-moments were computed for annual maxima data for the collections of stations in the quadrants shown in Figures 2-1, 2-2 for the two sites. L-moment ratio diagrams were prepared with L-skewness and L-kurtosis pairs for the collection of stations in each quadrant (Figures 2-7, 2-8). In the case of the coastal site, stations from adjacent quadrants were often combined because of the limited number of stations. A review of Figures 2-7, 2-8 shows the regional weighted-average L-skewness and L-kurtosis pairing to be very near the Generalized Extreme Value (GEV) distribution. L-moment goodness-of-fit tests were conducted [4] and the GEV distribution was identified as a suitable three-parameter probability distribution.

The four-parameter Kappa distribution was selected for describing the annual maxima data. This choice was made because the four-parameter Kappa distribution is very flexible and capable of emulating the GEV distribution and also provides the ability to emulate alternative probability distributions. This latter capability is particularly useful in an uncertainty analysis where the uncertainty in the identification/selection of a probability model is often an important contributor to the total uncertainty, particularly for very extreme events. Such an analysis is described later in this document.

The method of L-moments was used in conjunction with the at-site means and regional L-moment ratios listed in Tables 2-4, 2-5 to solve for the distribution parameters for the Kappa distribution (Tables 2-6, 2-7). The corresponding product moments for the fitted Kappa distribution are also listed in Tables 2-6 and 2-7 for comparison.

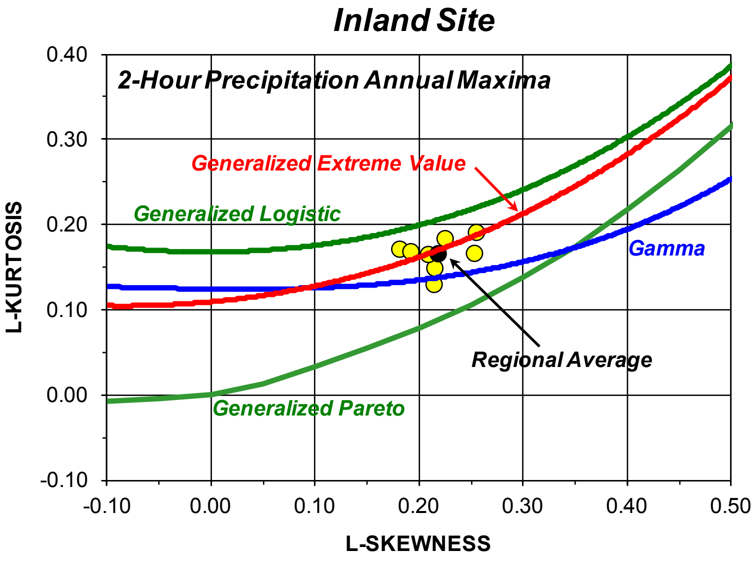

Figure 2-7
L-moment Ratio Diagram for Stations within Various Quadrants Surrounding the Inland Site

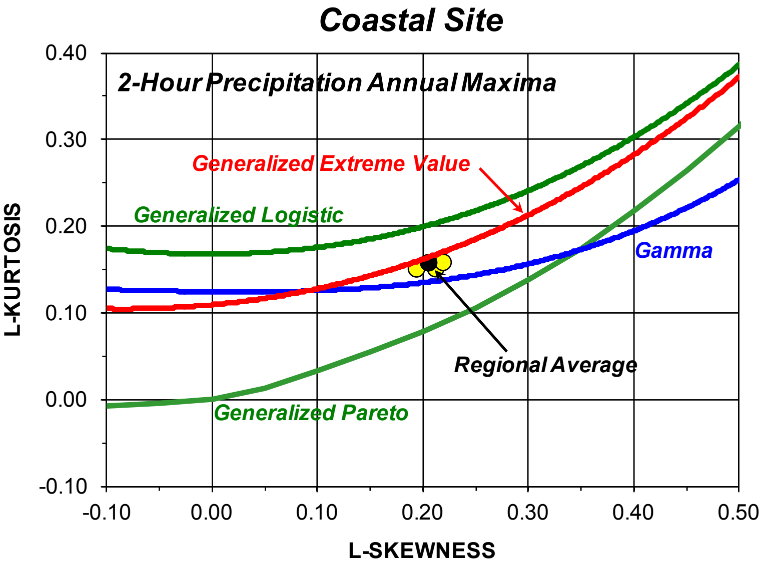

Figure 2-8
L-moment Ratio Diagram for Stations within Various Quadrants Surrounding the Coastal Site

Table 2-6
Four-Parameter Kappa Distribution Parameters for 1-Hour Precipitation-Frequency Relationship for Inland Site

Four Parameter Kappa Distribution Parameters			
Xi (ξ)	**Alpha (α)**	**Kappa (κ)**	**H**
1.141	0.4006	-0.0449	0.1000
Regional L-moments			
At-Site Mean	**L-cv**	**L-skewness**	**L-kurtosis**
1.410-in	0.1990	0.2160	0.1630
Standard Product Moments			
At-Site Mean	**Coeff. Variation**	**Coeff. Skewness**	**Coeff. Kurtosis**
1.410-in	0.378	1.54	7.49

Table 2-7
Four-Parameter Kappa Distribution Parameters for 1-Hour Precipitation-Frequency Relationship for Coastal Site

Four Parameter Kappa Distribution Parameters			
Xi (ξ)	**Alpha (α)**	**Kappa (κ)**	**H**
1.168	0.4227	-0.0260	0.1050
Regional L-moments			
At-Site Mean	**L-cv**	**L-skewness**	**L-kurtosis**
1.445-in	0.2005	0.2050	0.1570
Standard Product Moments			
At-Site Mean	**Coeff. Variation**	**Coeff. Skewness**	**Coeff. Kurtosis**
1.445-in	0.378	1.41	6.65

2.8 Equivalent Independent Record Length (EIRL)

Equivalent independent record length (EIRL), as the name implies, represents the equivalent record length corresponding to the station-years of record of a regional data set at the different gages that are mutually independent of each other. If the storms of interest have large areal coverage relative to the density of the station network, then the EIRL will be a small fraction of the station-years of record because the closer proximity of the gages would be expected to result in greater correlation (statistical dependence) amongst the gage records. Conversely, if the areal coverage of storms is small and the density of the station network is low, then the EIRL will be a large fraction of the station-years of record. The latter case is the situation for LIP analyses.

EIRL is used in the uncertainty analysis for computing statistics for sampling distributions for the at-site mean and L-moment ratios L-cv, L-skewness and L-kurtosis. The EIRL procedure is to compute AEP estimates for each of the annual maxima at the stations using the 4-parameter Kappa distribution as fitted using the station at-site mean and regional L-moment ratios (Tables 2-4, 2-5).

The computed AEPs and corresponding dates are then sorted by date. The largest storms above a specified AEP threshold are retained, duplicate storms dates are removed and the rarest storm for a given date and its location is retained. This produces a dataset of unique storm dates which are physically independent because they were produced by different atmospheric/ meteorological conditions. A least-squares formulation [10] is then used to solve for the EIRL [5].

The 5,349 station-years of record at the inland site were found to equate to 4,200-years of independent record. For the coastal site, the 1,635 station-years of record were found to equate to 1,400-years of independent record. For both sites the EIRL is a relatively high proportion of the corresponding total station-years of record. This is due to the relatively small size of convective storm cells that produce 1-hour and 2-hour precipitation annual maxima and the low density network of precipitation stations. The station density for the inland site study area is about 800-mi^2 per station and the station density for the coastal site study area is about 1,700-mi^2 per station. This independent behavior is easily seen in the records by minimal matching of storm dates for annual maxima at the collection of stations.

The 4,200-years EIRL equates to 91 independent stations for the inland study area and the 1,400-years EIRL equates to 30 independent stations for the coastal study area based on the average record length at the collection stations. For the inland study area this results in 90 independent estimates of L-moment statistics and regional L-cv, L-skewness and L-kurtosis computed as weighted averages using station record length for weighting.

A graphical representation of EIRL is depicted in Figures 2-9, 2-10 where the expected number of exceedances are plotted for a range of regional sample sizes based on a standard non-parametric plotting position formula. The observed numbers of exceedances for a given AEP at the inland and coastal sites are seen to follow the pattern expected for a large independent sample size.

Although the chronological record spans the 63-year period from 1948 to 2010, there are an estimated 4,200 independent storm events produced by convective storm cells in the study area for the inland site and an estimated 1,400 independent storm events near the coastal site. This large number of independent observations creates a very large dataset of observations of convective precipitation, which provides for the robustness of the regional L-moment solutions.

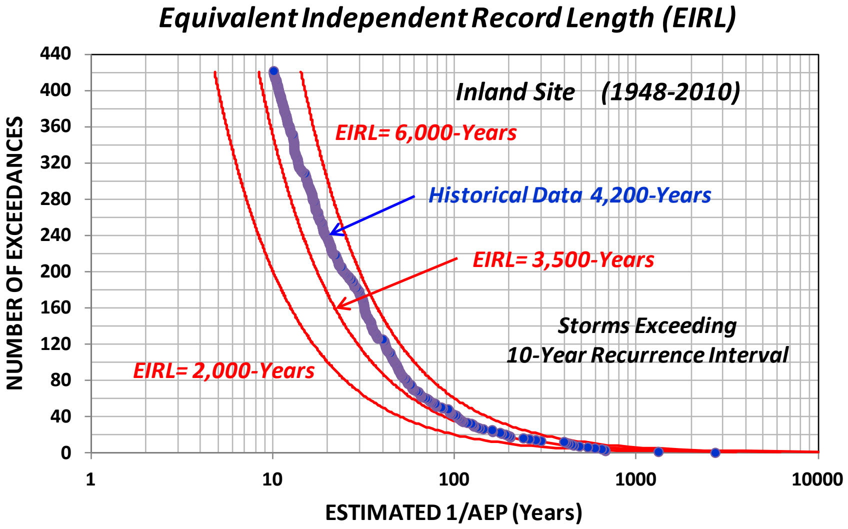

Figure 2-9
Graphical Depiction of Equivalent Independent Record Length for Inland Site

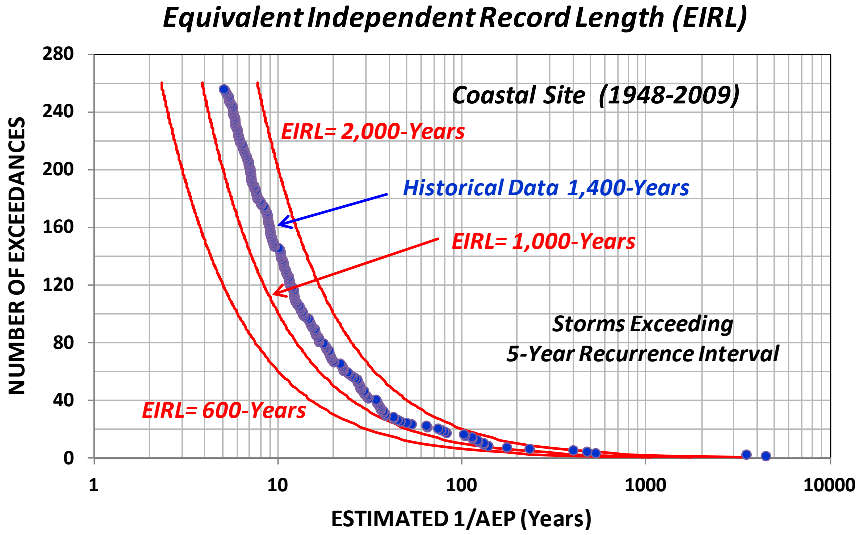

Figure 2-10
Graphical Depiction of Equivalent Independent Record Length for Coastal Site

2.9 Assessment of Uncertainties for Precipitation-Frequency Relationships

An uncertainty analysis was conducted to develop the mean frequency curve and uncertainty bounds for 1-hour precipitation annual maxima at the two sites. The sampling distributions for the aleatoric uncertainty in the at-site means and L-moment ratios L-cv and L-skewness are well represented by a Normal distribution [4]. The statistics for the uncertainty distributions are listed in Tables 2-8, 2-10 based on the sample statistics for the regional data sets of 116 stations at the inland site and 35 stations at the coastal site as adjusted by their respective values of EIRL.

Uncertainty in the identification of the regional probability distribution was modeled by considering the regional probability distribution to be a 3-parameter distribution represented by a form of the 4-parameter Kappa distribution with a fixed value of the 2nd shape parameter (*h*). Epistemic uncertainty in the identification of the regional probability distribution was modeled by allowing the 2nd shape parameter (*h*) of the Kappa distribution to vary around the regional *h* value (Table 2-6, 2-7). Specifically, L-kurtosis is functionally related to L-skewness for the Kappa distribution in a manner very similar to the GEV curve in Figure 2.7. A Normally distributed residual was added to the L-kurtosis value to obtain a variance for L-kurtosis matching that observed in the regional sample of L-kurtosis values. This procedure preserves the correlation between L-kurtosis and L-skewness for the Kappa distribution and provides for variability in the shape parameter *h* when distribution parameters are computed for the Kappa distribution.

For each site, Latin-hypercube sampling was used to select 1,000 sample sets of at-site means and values of L-cv and L-skewness from the sampling distributions. Corresponding values of L-kurtosis were then selected based on the relationship between L-kurtosis and L-skewness for the Kappa distribution [4] and included a Normally-distributed residual (Tables 2-8, 2-9). The Kappa distribution was then fitted by the method of L-moments for each of the 1,000 sample sets to create 1,000 plausible 1-hour precipitation-frequency relationships. Uncertainty bounds were then computed using non-parametric ranking of the 1,000 quantiles estimates for a given AEP.

The resultant mean-frequency curves and uncertainty bounds for the two sites are shown in Figures 2-11, 2-12. The relative narrowness of the uncertainty bounds is attributable to the large values of EIRL, which reflect very large sample sets of independent observations of thunderstorm precipitation. In particular, the smaller width of the uncertainty bounds for the inland site relative to the coastal site is due to having a three times longer independent record (EIRL) for the inland site.

Table 2-8
Uncertainty Characteristics for Assessing Effect of Uncertainties for Computed Precipitation-Frequency Relationships for the Inland Site

<table>
<tr><th colspan="6">Uncertainty Characteristics</th></tr>
<tr><th>Component</th><th>Probability Model</th><th>Mean</th><th>Standard Deviation</th><th colspan="2"></th></tr>
<tr><td>At-Site Mean</td><td>Normal</td><td>1.4100</td><td>0.0330</td><td colspan="2" rowspan="3"></td></tr>
<tr><td>L-cv</td><td>Normal</td><td>0.1990</td><td>0.0023</td></tr>
<tr><td>L-skewness</td><td>Normal</td><td>0.2160</td><td>0.0079</td></tr>
<tr><th>Component</th><th colspan="3">Probability Model</th><th colspan="2">Residuals</th></tr>
<tr><td rowspan="2">L-kurtosis</td><td colspan="3" rowspan="2">L-kurtosis functionally related to L-skewness for Kappa distribution</td><th>Prob Model</th><th>Std Dev</th></tr>
<tr><td>Normal</td><td>0.0056</td></tr>
</table>

Table 2-9
Uncertainty Characteristics for Assessing Effect of Uncertainties for Computed Precipitation-Frequency Relationships for the Coastal Site

<table>
<tr><th colspan="6">Uncertainty Characteristics</th></tr>
<tr><th>Component</th><th>Probability Model</th><th>Mean</th><th>Standard Deviation</th><th colspan="2"></th></tr>
<tr><td>At-Site Mean</td><td>Normal</td><td>1.4450</td><td>0.0300</td><td colspan="2" rowspan="3"></td></tr>
<tr><td>L-cv</td><td>Normal</td><td>0.2005</td><td>0.0042</td></tr>
<tr><td>L-skewness</td><td>Normal</td><td>0.2050</td><td>0.0135</td></tr>
<tr><th>Component</th><th colspan="3">Probability Model</th><th colspan="2">Residuals</th></tr>
<tr><td rowspan="2">L-kurtosis</td><td colspan="3" rowspan="2">L-kurtosis functionally related to L-skewness for Kappa distribution</td><th>Prob Model</th><th>Std Dev</th></tr>
<tr><td>Normal</td><td>0.0120</td></tr>
</table>

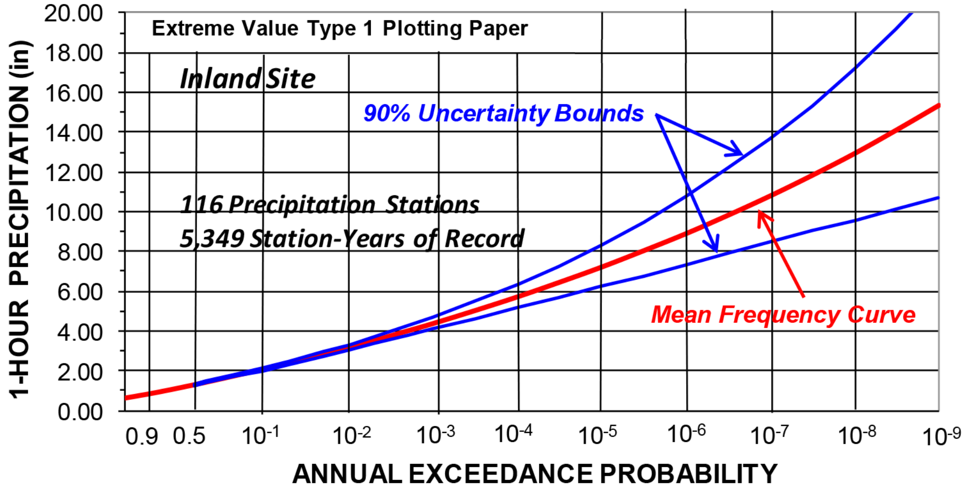

Figure 2-11
Precipitation-Frequency Relationship and 90% Uncertainty Bounds for 1-Hour Precipitation Maxima for the Inland Site

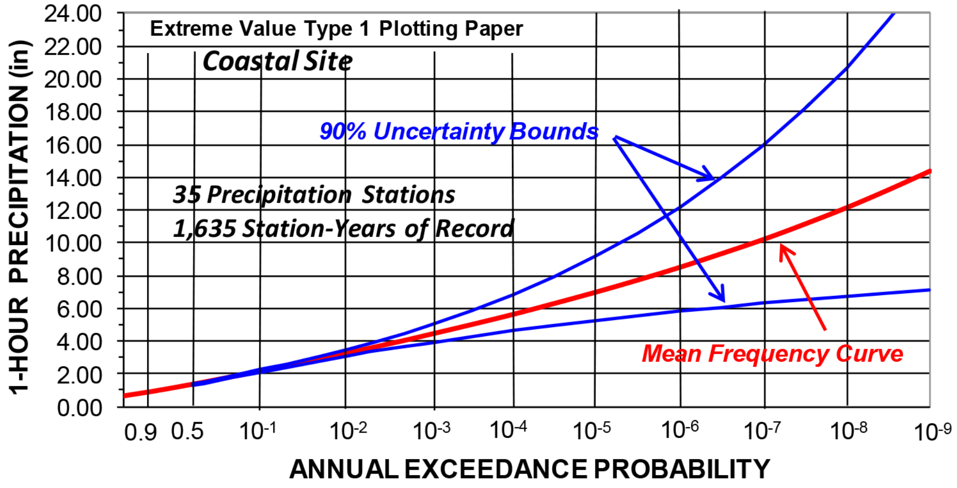

Figure 2-12
Precipitation-Frequency Relationship and 90% Uncertainty Bounds for 1-Hour Precipitation Maxima for the Coastal Site

Section 3: Stochastic Storm Transposition

Stochastic storm transposition [8] provides an alternative method for estimating the AEP of extreme precipitation events for comparison with the findings of regional precipitation-frequency analysis. The basic concept employed in the stochastic storm transposition (SST) approach as applied to localized thunderstorms is that the annual exceedance probability (AEP) for a rare precipitation magnitude at a given location can be computed based on three components. The first component is the probability distribution for thunderstorm precipitation for a specified duration occurring anywhere within a region. The probability distribution provides the exceedance probability that a specified precipitation magnitude for a localized thunderstorm will be equaled or exceeded in a given year somewhere in the region. The second component is the expected number of storm events exceeding a specified precipitation magnitude in the study region in any year. The third component is the probability that the storm occurs over the site of interest for any single storm. In this approach, the third component represents the probability of a "direct hit" which accounts for the spatial randomness of the storm within the specified study region. This generally equates to the average storm area size representative of the maximum precipitation intensity divided by the area of the study region.

The area on the ground primarily affected by thunderstorm precipitation from a mesoscale convective system (MCS) would generally be in the range of roughly 100-mi^2 to perhaps 800-mi^2. However, the areal coverage for the maximum precipitation intensity in a very extreme MCS for locations in the eastern United States would be less than two square miles [11].

Application of SST to a specific location in the United States east of the 105th meridian [9] for a LIP event would have the probability of a direct hit being about 10^{-6} (2-mi^2 storm areal coverage divided by 2x10^6-mi^2 in the eastern U.S.). This probability would be multiplied by the AEP of a selected extreme precipitation occurring anywhere in the eastern United States. Considering that no storms have occurred in the past 130-years that approached PMP values [2], the AEP for the 1-hour/1-square mile PMP occurring anywhere in the eastern U.S. in a given year is likely rarer than 1:500. Multiplication of the AEP of occurrence and the probability of a direct hit results in the AEP for a direct hit by PMP at a specific location being on the order of 10^{-9} [9]. Detailed analyses would be required to provide a more definitive estimate, but the end result is that an AEP for a direct hit by PMP would be expected to be the order of 10^{-9}.

While an AEP of 10^{-9} for 1-hour/1-square mile PMP occurrence at a specified site is an extremely small AEP, it can readily be comprehended by recognizing the very small areal coverage of the high-intensity portion of a thunderstorm and the very low frequency of occurrence of near-PMP and PMP precipitation in the eastern United States.

Section 4: 1-Hour Precipitation Comparison

The 1-hour/1-square mile values of probable maximum precipitation (PMP) were obtained from HMR-52 [3] and are 17.9-inches for the inland site and 18.4-inches for the coastal site (Table 2-1). The PMP values are shown in Figures 4-1 and 4-2 for comparison to the 1-hour precipitation-frequency relationships. The information in Table 4-1 compares the results of studies described in this report with the PMP for the two sites and shows that the PMP values are extremely large and rare.

It should be noted that the 1-hour precipitation-frequency curves have been extended to an annual exceedance probability of 10^{-9}. This is not an expression of over-confidence in a statistical approach at this extreme annual exceedance probability, but rather to allow comparison with the 1-hour/1-square mile PMP and to assess the behavior of the mean frequency curve and uncertainty bounds.

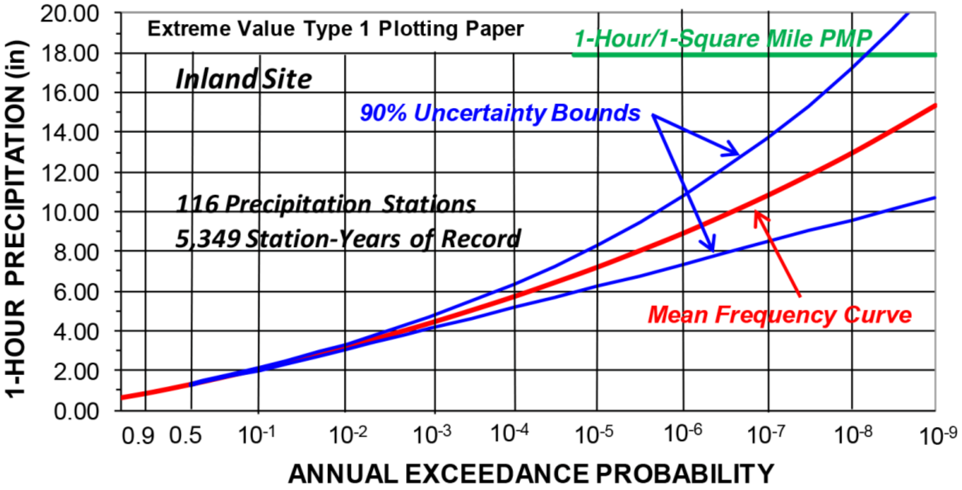

Figure 4-1
PMP and Precipitation-Frequency Relationship and 90% Uncertainty Bounds for 1-Hour Precipitation Maxima for the Inland Site

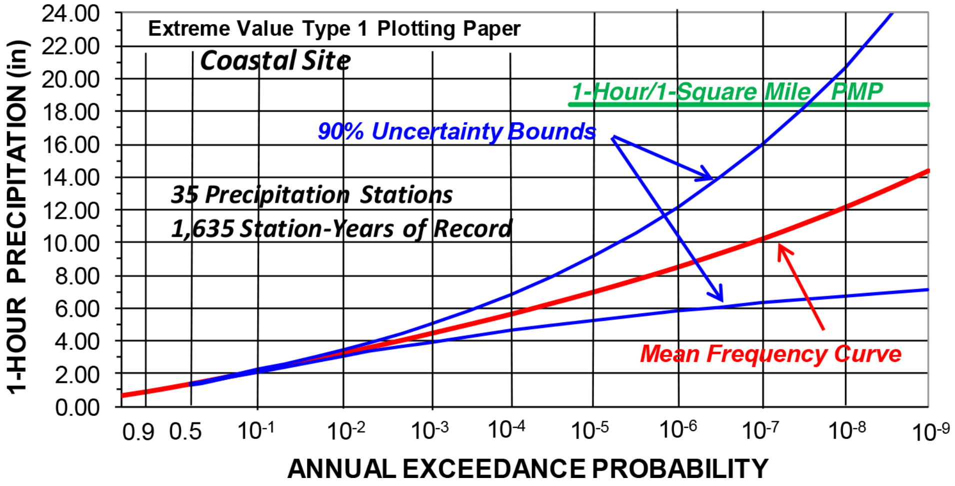

Figure 4-2
PMP and Precipitation-Frequency Relationship and 90% Uncertainty Bounds for 1-Hour Precipitation Maxima for the Coastal Site

Table 4-1
Comparison of PMP and Study Results

Description	**Inland Site**	**Coastal Site**
PMP	17.9 Inches	18.4 Inches
World Record Short (One Hour or Less) -Duration Rainfalls	12.0 – 15.8 Inches	
Study Area 1-Hour Maximum Rainfall	3.50 Inches	4.00 Inches
Study Area 2-Hour Maximum Rainfall	5.45 Inches	6.50 Inches
PMP Annual Exceedance Probability Using the Mean Precipitation-Frequency Relationship	$< 10^{-9}$	$< 10^{-9}$
PMP Annual Exceedance Probability Using the Upper Bound Precipitation-Frequency Relationship	$< 10^{-8}$	$< 10^{-7}$
PMP Annual Exceedance Probability from Stochastic Storm Transposition Review	On the order of 10^{-9}	

Section 5: References

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Appendix A: Comparison of Regional Frequency Curves for 1-Hour and 2-Hour Annual Maxima

Section 2.2 provides a discussion of the preference for use of 2-hour annual maxima over 1-hour annual maxima for estimation of the regional L-moment ratios L-cv, L-skewness and L-kurtosis, identification of the regional probability distribution, and solving for the distribution parameters of the regional probability distribution for the 1-hour precipitation-frequency relationship. This preference is based on the bias and increased sampling variability in estimation of the higher order moments that arises for 1-hour annual maxima due to use of a fixed clock-hour ending reporting system rather than a continuous measurement and reporting system.

Table A-1 contains a comparison of regional L-moments for 1-hour and 2-hour annual maxima for the 116 stations in the study area for the inland site. Figure A-1 depicts a comparison of regional solutions for the fitted 4-parameter Kappa distribution using regional L-moment ratios based on the 1-hour and 2-hour annual maxima for the inland site.

Table A-1
Comparison of Regional L-moment Ratios for 1-Hour and 2-Hour Durations for 116 Stations at the Inland Site

1-Hour Regional L-moments			
At-Site Mean	**L-cv**	**L-skewness**	**L-kurtosis**
1.410-in	0.1915	0.1955	0.1520
2-Hour Regional L-moments			
At-Site Mean	**L-cv**	**L-skewness**	**L-kurtosis**
1.735-in	0.1990	0.2160	0.1630

Similarly, Table A-2 contains a comparison of regional L-moments for 1-hour and 2-hour annual maxima for the 35 stations in the study area for the coastal site. Figure A-2 depicts a comparison of precipitation-frequency relationships based on regional L-moment ratios for the 1-hour and 2-hour annual maxima for the coastal site.

Table A-2
Comparison of Regional L-moment Ratios for 1-Hour and 2-Hour Durations for 35 Stations at the Coastal Site

1-Hour Regional L-moments			
At-Site Mean	**L-cv**	**L-skewness**	**L-kurtosis**
1.445-in	0.2015	0.1825	0.1380
2-Hour Regional L-moments			
At-Site Mean	**L-cv**	**L-skewness**	**L-kurtosis**
1.745-in	0.2005	0.2050	0.1570

For both sites, note the similarity of regional L-cv values but notable differences in the regional L-skewness and L-kurtosis values for the 1-hour and 2-hour durations. In both cases, the 1-hour precipitation-frequency curves are biased downward due to systematic biases imparted from the fixed clock-hour ending measurement and reporting system. As discussed previously, this is not much of a concern for AEPs more common than 1:500 but becomes an important issue for very extreme AEPs approaching the magnitude of PMP.

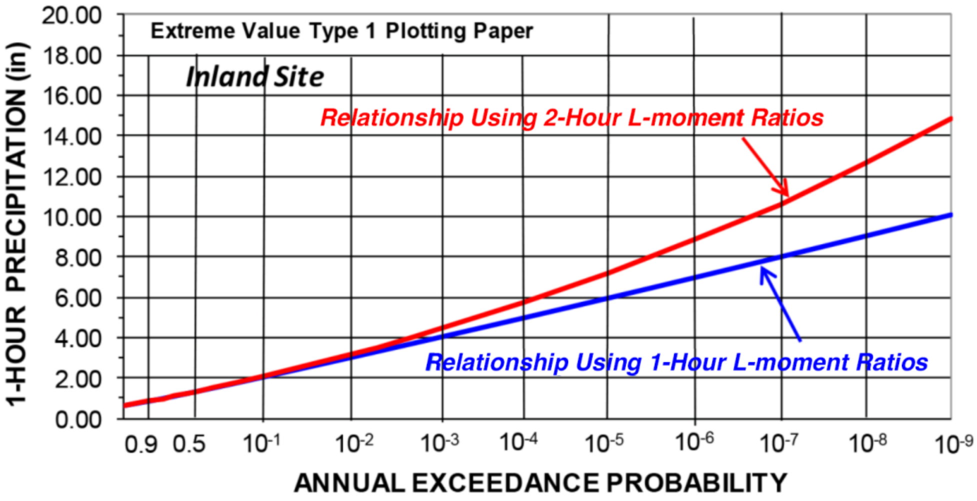

Figure A-1
Comparison of 1-Hour Precipitation-Frequency Relationships for Inland Site Using L-moment Ratios for 1-Hour and 2-Hour Precipitation Annual Maxima

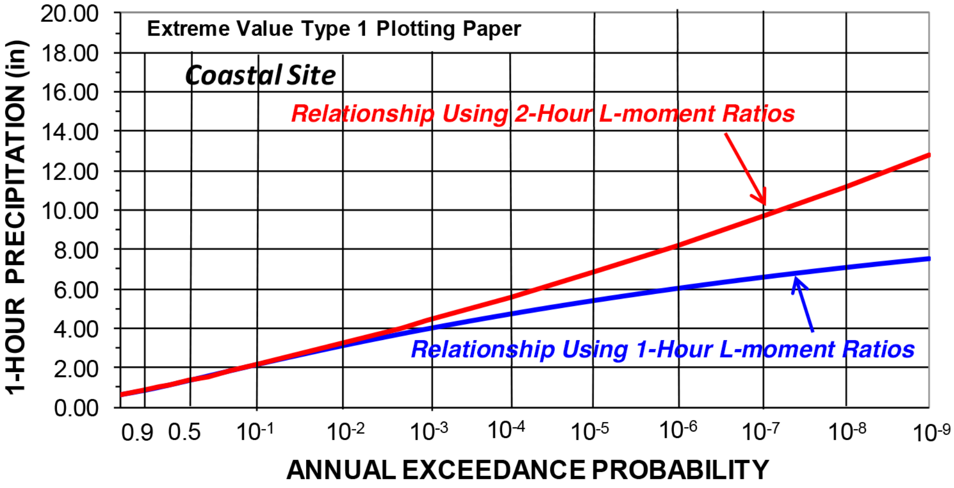

Figure A-2
Comparison of 1-Hour Precipitation-Frequency Relationships for Coastal Site Using L-moment Ratios for 1-Hour and 2-Hour Precipitation Annual Maxima

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