US Army Corps of Engineers
Hydrologic Engineering Center

Stochastic Modeling of Extreme Floods on the American River at Folsom Dam

Appendix C - 72-Hour Precipitation-Frequency Relationship and Uncertainty Analysis for the 1860-mi^2 American River Watershed

September 2005

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MGS Engineering Consultants, Inc.
7326 Boston Harbor Road NE
Olympia, WA 98506

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US Army Corps of Engineers
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14. ABSTRACT
This report presents the results of the application of a stochastic flood model to develop flood-frequency relationships for the American River at Folsom Dam. Flood-frequency relationships are presented for flood characteristics of peak discharge, maximum 24-hour discharge, maximum 72-hour discharge, maximum reservoir release, runoff volume, and maximum reservoir level.

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Prepared by:
MGS Engineering Consultants, Inc.
7326 Boston Harbor Road, NE
Olympia, WA 98506

For:
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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72-HOUR PRECIPITATION-FREQUENCY RELATIONSHIP AND UNCERTAINTY ANALYSIS FOR THE 1860-MI^2 AMERICAN RIVER WATERSHED

July 17, 2002

OVERVIEW

A 72-hour precipitation-frequency relationship is needed for the stochastic modeling of extreme storms for the 1860-mi^2 American River watershed. An uncertainty analysis is also needed to provide uncertainty bounds for the 72-hour 1860-mi^2 precipitation-frequency relationship and to provide information on the source and magnitude of uncertainties.

Both the 72-hour 1860-mi^2 precipitation-frequency relationship and uncertainty analysis are critical elements in the stochastic modeling of floods for the American River. The magnitude of 72-hour precipitation over the watershed is a primary factor in determining the magnitude of floods on the American River. Likewise, uncertainties for the 72-hour precipitation-frequency relationship are major contributors to the magnitude of uncertainties for the flood-frequency relationships for flood peak discharge, runoff volume, and maximum reservoir level at Folsom Dam.

This report documents the procedures used in developing the 72-hour 1860-mi^2 precipitation-frequency relationship for the American River watershed and conducting the uncertainty analysis for that relationship. The report also provides estimates of areal reduction factors that may be of use for estimating 72-hour precipitation at other watersheds on the west face of the Sierra Mountains. Several sections of a previous report on examination of areal reduction factors[17] in deriving a 72-hour precipitation-frequency relationship are repeated here to provide background information and continuity with prior analyses.

BACKGROUND DATA AND SUPPORTING ANALYSES

Data sources and supporting analyses for the development of the 72-hour 1860-mi^2 precipitation-frequency relationship and uncertainty bounds include: the findings of the regional precipitation-frequency study conducted for the west face of the Sierra Mountains (Schaefer[14]); examination of issues related to areal reduction factors[17]; and the GIS storm analyses of 72-hour watershed-average precipitation for 37 of the largest storms observed over the American River watershed[15].

Precipitation records date to the late 1800's in areas within and near the American River watershed. Eleven stations have measurements of daily precipitation that begin in either 1898 or in the first decade of the 20th century. These long-term stations provide a good record of the occurrence of large storm events in the period since 1898.

One of the issues examined in the regional precipitation-frequency analysis was the selection of the period of record expected to be most representative of the precipitation characteristics in the future planning period, perhaps the next ten to thirty years. Two of the logical choices are to use either the record from the most recent past, or to use the long-term record. These choices reflect the bias-variance tradeoff and the reader is referred to the report on precipitation regional analysis[14] for a more complete discussion and analysis of stationarity of the precipitation record.

One of the conclusions reached in the regional analysis was that regional L-moment ratio statistics for the period from 1966-1998 were essentially the same as those for a 9-station index comprised of long-term stations dating to the turn-of-the-century (Figure 1). Thus, selection of either the most recent record or the long-term record would yield similar regional growth curves. Given that choice, it was recommended that the most recent period from 1966 to present be used as representative of the future planning period based on the premise that near-future climatic conditions are most likely to be similar to most-recent past climatic conditions. This choice had the added benefit of a greater number of precipitation stations and better quality of the records in the period from 1966 to present. Accordingly, derivation of the 72-hour 1860-mi^2 precipitation-frequency relationship was based largely on the systematic record from 1966 to present. This record was augmented by the addition of historical information on extreme storms in the period from 1898-1965.

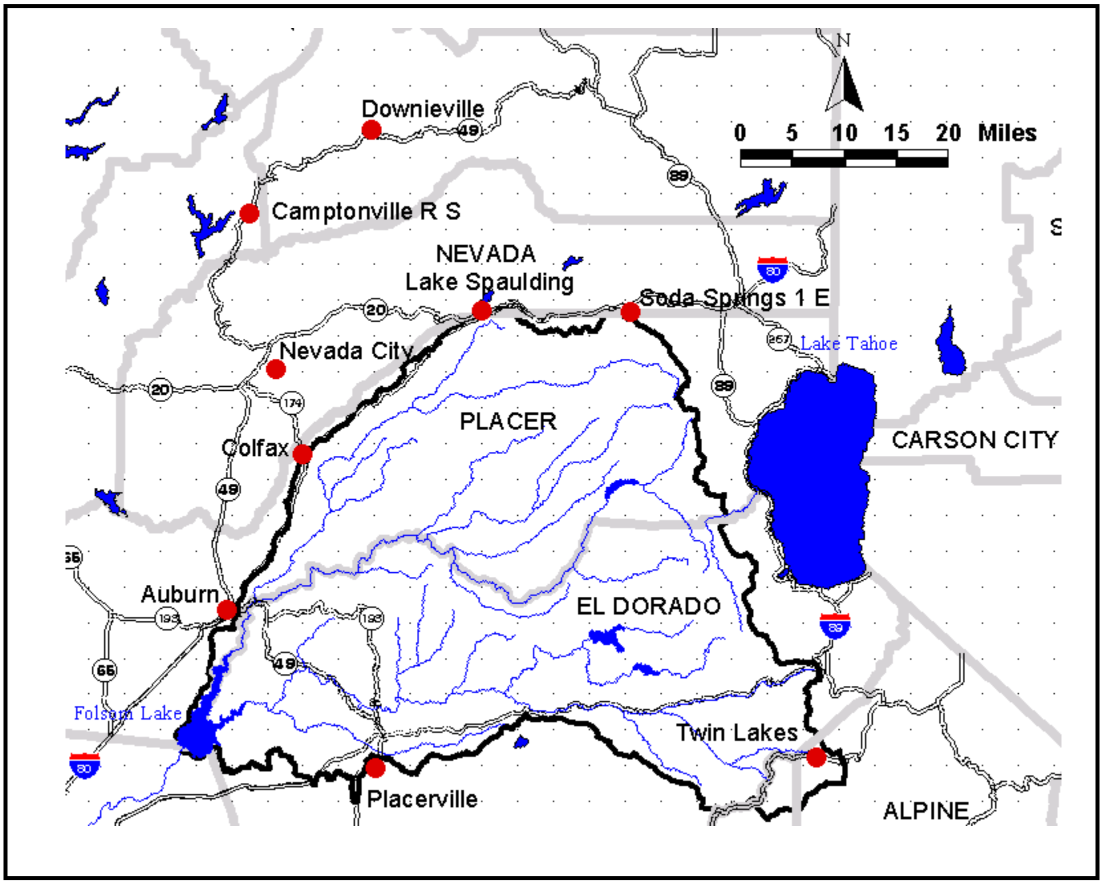

Figure 1 – Long-Term Stations Used in 9-Station Index for 72-Hour Precipitation for American River Watershed

WATERSHED-AVERAGE PRECIPITATION FOR 1860-MI^2 WATERSHED

An annual maxima series of watershed-average 1860-mi^2 precipitation is needed for conducting at-site frequency analyses. Watershed-average annual maxima were estimated by either spatial analysis of storm data or by a GIS-Modified Thiessen approach that included a Thiessen[22] type analysis augmented by information obtained from the spatial analysis of storms. These two methods are described below.

Spatial Analysis of Storms using GIS-Based Methods

Precipitation magnitudes can vary significantly over short distances in mountainous terrain. This non-linearity of the precipitation field makes it difficult to accurately interpolate precipitation between stations and to estimate areal average precipitation from any coarse network of stations. To overcome this problem, GIS-based storm analyses[16] were conducted for a selected group of large storm events. As a separate element of this project, analyses were conducted for the 37 largest storms[15] using an isopercental approach[9,16], Geographical Information System (GIS) software, and the findings from a spatial analysis of 72-hour at-site mean values using PRISM[3,10] products. These analyses were conducted to develop spatial and temporal templates for the stochastic modeling of extreme storms. Ten to sixteen stations, representing a combination of hourly and daily gages, were typically used in the GIS storm analyses and procedures were used with the isopercental approach to account for the orographic effect in interpolating precipitation between stations. This approach provided the most reliable estimates of 72-hour watershed-average precipitation.

Estimation of Watershed-Average Precipitation using GIS-Modified Thiessen Approach

The GIS-based analysis of storms was conducted for the larger storm events. Many of the smaller storms that produced annual maxima were not included in the GIS-based analysis of storms. Watershed-average precipitation for these smaller annual maxima were estimated using a GIS-Modified Thiessen approach. The GIS-Modified Thiessen approach was comprised of two steps. First, a Thiessen[22] type analysis was used for making an initial estimate of 72-hour watershed-average 1860-mi^2 precipitation. Six stations were identified with long-term, high-quality records, that provided reasonable areal representation from Folsom Lake to the headwaters on the North and South Forks of the American River (Figure 2). Thiessen weighting factors were obtained by first constructing standard Thiessen polygons. The polygons were then adjusted to have regions of influence for each station that extended over areas with similar mean annual precipitation[3,10]. This adjustment was made to partially compensate for the spatial non-linearity of precipitation in the mountainous watershed. This first step provided a Modified Thiessen estimate of the watershed-average precipitation. Table 1 lists the stations that were used in the Modified Thiessen computation along with the areal weighting factors determined for each station.

This initial estimate was then improved by incorporation of information obtained from the GIS-based analysis of storms. Specifically, a regression relationship (Figure 3) was developed between the 6-station Modified Thiessen estimate and the results of the GIS-based storm analyses for the sample set of 37-storms. The regression relationship was then used to compute an improved estimate of watershed-average 72-hour precipitation.

Assembly of 72-Hour Watershed-Average Precipitation Annual Maxima Series

Each year, noteworthy storms were identified and watershed-average 72-hour precipitation was computed for each candidate storm using the 6-station Modified Thiessen approach. An improved estimate of the annual maximum was then made using the regression relationship between the results of the Modified Thiessen and GIS approaches (Figure 3). These procedures allowed the date of the largest 72-hour precipitation event to be identified for each year, and allowed the watershed-average 72-hour precipitation amount to be estimated (Table 2, column 5).

For those storms where a GIS-based storm analysis had been conducted, the GIS estimate of watershed-average precipitation was selected as the annual maximum (Table 2, columns 6 and 7). For all other storms, the GIS-Modified Thiessen estimate was selected as the 72-hour watershed-average precipitation annual maximum (Table 2, columns 5 and 7). These procedures produced an annual maxima series of watershed-average 1860-mi^2 precipitation for the period from 1966-2002 (Table 2, column 7).

In addition, sufficient precipitation records exist back to 1898 to allow a determination of the largest 72-hour watershed-average precipitation events in the historical period from 1898 through 1965. The historical record was reviewed and a threshold of 10.0-inches was selected as being sufficiently large to allow an unambiguous identification of storms that exceeded the threshold. There are six storms in the period from 1898-1965 that exceeded the threshold of a watershed-average 10.0-inches (Table 3), and three storms exceeded the threshold during the period from 1966-2002.

The 72-hour watershed-average precipitation was estimated for all storms that exceeded the 10.0-inch threshold in the historical period from 1898-1965 in a manner similar to that described above. It is noted that a GIS-based storm analysis was conducted for all storms that exceeded the 10-inch threshold in the historical period, except for the 1909 storm. A GIS-based analysis was not conducted for the 1909 storm because there were no hourly data available, which is a prerequisite for conducting an isopercental[9,16] storm analysis.

Table 1 – Stations and Thiessen Weighting Factors
used in Computing Watershed-Average 1860-mi^2 Precipitation

STATIONS	BLUE CANYON	COLFAX	PLACERVILLE	REPRESA	SODA SPRINGS	TWIN LAKES
THIESSEN WEIGHT	0.18	0.14	0.25	0.06	0.18	0.19

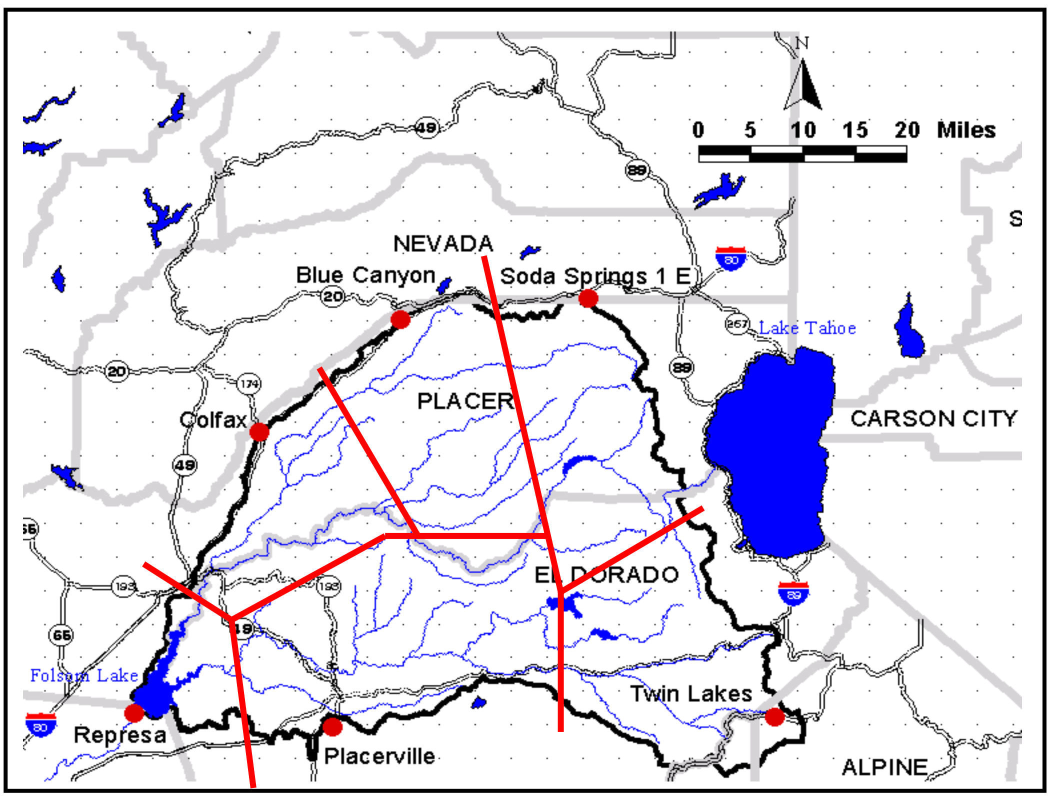

Figure 2 – Modified Thiessen Network for Estimating 72-Hour 1860-mi^2 Precipitation for American River Watershed

Table 2 – Annual Maxima Series of Watershed-Average 72-Hour Precipitation for the 1860-mi^2 American River Watershed for 1966-2002

WATER YEAR	72-HOUR STORM STORM DATE TO INCLUDE			72-HOUR WATERSHED-AVERAGE PRECIPITATION (inches)		
	MONTH	DAY	YEAR	GIS MODIFIED THIESSEN	GIS STORM ANALYSIS	ADOPTED VALUE
1966	11	18	1965	4.48		4.48
1967	1	22	1967	7.53	7.05	7.05
1968	2	21	1968	3.50		3.50
1969	1	21	1969	10.30	10.34	10.34
1970	1	16	1970	6.74	6.46	6.46
1971	12	3	1970	5.72		5.72
1972	12	24	1971	4.70		4.70
1973	1	18	1973	5.35		5.35
1974	11	12	1973	5.84	6.20	6.20
1975	2	3	1975	4.49		4.49
1976	10	27	1975	2.96		2.96
1977	1	3	1977	3.33		3.33
1978	1	16	1978	5.98		5.98
1979	1	12	1979	5.14		5.14
1980	1	13	1980	9.67	9.94	9.94
1981	1	29	1981	6.92	6.37	6.37
1982	2	15	1982	7.78	8.17	8.17
1983	12	22	1982	7.77	8.24	8.24
1984	12	26	1983	6.24	6.04	6.04
1985	2	9	1985	4.44		4.44
1986	2	18	1986	13.75	13.99	13.99
1987	2	13	1987	4.14		4.14
1988	4	21	1988	3.03		3.03
1989	11	24	1988	5.33	4.91	4.91
1990	11	27	1989	5.15	4.44	4.44
1991	3	3	1991	6.59		6.59
1992	2	16	1992	3.61		3.61
1993	12	10	1992	6.51	7.19	7.19
1994	2	19	1994	3.27		3.27
1995	3	10	1995	7.59	7.93	7.93
1996	12	13	1995	7.64	7.88	7.88
1997	1	2	1997	11.40	11.22	11.22
1998	1	12	1998	5.16		5.16
1999	2	8	1999	8.42	8.41	8.41
2000	2	14	2000	7.40		7.40
2001	2	11	2001	3.41		3.41
2002	12	3	2001	4.16		4.16

Table 3 – Storm Dates and Watershed-Average 72-Hour Precipitation that Exceeded 10.0-inches for the 1860-mi^2 American River Watershed for the Period from 1898-1965

WATER YEAR	72-HOUR STORM STORM DATE TO INCLUDE			72-HOUR WATERSHED-AVERAGE PRECIPITATION (inches)		
	MONTH	DAY	YEAR	GIS MODIFIED THIESSEN	GIS STORM ANALYSIS	ADOPTED VALUE
1909	1	14	1909	10.56		10.56
1951	11	20	1950	11.80	12.46	12.46
1956	12	23	1955	14.02	13.81	13.81
1963	10	13	1962	13.59	14.05	14.05
1963	2	1	1963	12.65	11.39	11.39
1965	12	23	1964	12.90	12.47	12.47

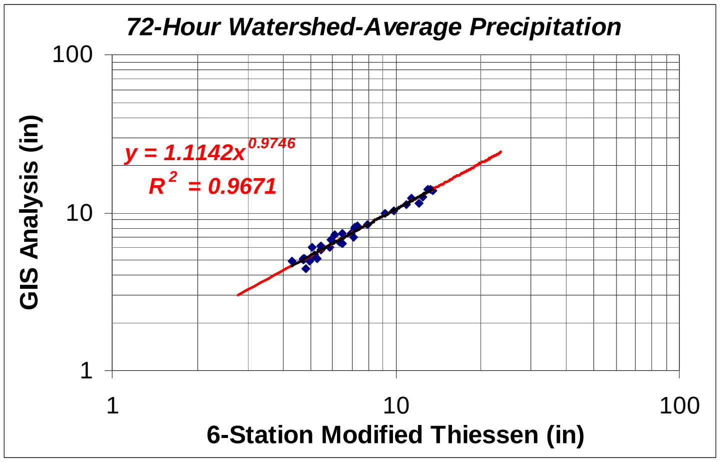

Figure 3 – Regression Relationship between the 6-Station Modified Thiessen and GIS Estimates of 72-Hour Watershed-Average Precipitation for the 1860-mi^2 American River Watershed

METHODS FOR ESTIMATING 72-HOUR 1860-MI^2 PRECIPITATION-FREQUENCY RELATIONSHIP

Three types of methods were used to estimate the 72-hour 1860-mi^2 precipitation-frequency relationship. Those methods that can leverage information from the regional precipitation-frequency analysis are preferred as they have greater reliability due to the large datasets utilized in those analyses. The three types of methods are described below and the results compared in Table 7.

Method #1 – At-Site Analyses of Systematic and Historical Data

Three at-site frequency analyses were conducted of the systematic and historical data. The Generalized Extreme Value (GEV) distribution[5,19] was used to describe the precipitation annual maxima and historical data for the 1860-mi^2 watershed (Tables 2 and 3, column 7) for each of the three at-site analyses. The GEV distribution was selected based on the results of the regional precipitation-frequency analysis[14], where the GEV distribution was found to be the best-fit distribution for describing point precipitation-frequency. Similar behavior would be expected for areal precipitation, and the suitability of the GEV for describing areal precipitation will be demonstrated in later sections.

Three separate at-site analyses were conducted to allow an assessment of the effect of alternate fitting methods on quantile estimates (Table 7). At-site methods would be expected to have wider uncertainty bounds for extreme events compared to methods that use regional information due to the higher sampling variability inherent in smaller samples.

Probability Weighted Moments Solution – The first at-site analysis method fitted the GEV distribution to the systematic data from 1966-2002 (Table 2, column 7) using a Probability Weighted Moments (PWM)[5] solution. The probability-plot of the systematic data is shown in Figure 4 along with the precipitation-frequency curve for the GEV distribution fitted by the PWM solution method.

Least-Squares Probability-Plot Solution – A Least-Squares probability-plot method[19] (LS) was also used to fit the GEV to the combined systematic and historical data (Tables 2 and 3, column 7). In that approach, a plotting position formula was used to estimate the annual exceedance probabilities of the observed precipitation. Distribution parameters were obtained from the least-squares solution and used to describe the precipitation-frequency relationship (Figure 5). Specifically, the plotting-position formula for censored data (Stedinger[19]) was used for estimating annual exceedance probabilities for the nine largest 72-hour precipitation events that exceeded the 10.0-inch threshold in the period from 1898-2002.

$$AEP = \frac{r}{n}\left(\frac{i-\theta}{r+1-2\theta}\right) \quad \rightarrow \quad AEP = \frac{9}{105}\left(\frac{i-0.44}{9.12}\right) \qquad \text{(1a)}$$

where: *AEP* is annual exceedance probability; *r* is the number of exceedances of the threshold; *n* is equal to (*s*+*h*), the number of years of record in the systematic record (*s*) plus the historical period (*h*); *i* is the rank of the precipitation events that exceed the threshold, ranked in descending order from 1 to *r*; and θ is a plotting-position weighting factor taken to be 0.44 (Gringorten[4]).

Estimation of the annual exceedance probability for each of the remaining precipitation events in the systematic record (Stedinger[19]) was computed as:

$$AEP = \frac{r}{n}+\left(1-\frac{r}{n}\right)\left(\frac{j-\theta}{s-e+1-2\theta}\right) \quad \rightarrow \quad AEP = \frac{9}{105}+\left(\frac{96}{105}\right)\left(\frac{j-0.44}{34.12}\right) \qquad \text{(1b)}$$

where: *s* is the number of years of systematic record; *e* is the number of exceedances over the threshold in the systematic record; and *j* is the rank of the precipitation events in the systematic record that are below the threshold, ranked in descending order from 1 to *s*-*e*.

Figure 7 depicts the probability-plot of the 72-hour 1860-mi^2 watershed-average precipitation based on Equations 4a and 4b and fitted by the least-squares (GEV) procedure.

Maximum Likelihood Solution – A Maximum Likelihood (ML) approach[6,20] was also used to fit the GEV to the combined systematic and historical data. A comparison of the precipitation-frequency curves for the least-squares and maximum likelihood solutions is shown in Figure 5 along with the probability-plot data of the systematic and historical data. It is seen that the LS and ML solutions provide similar quantile estimates for common events out through an annual exceedance probability of 0.01 (100-year recurrence interval), but diverge for more rare events. This divergence is typical of the difficulties encountered in fitting of distributions and estimation of extreme events from relatively small datasets.

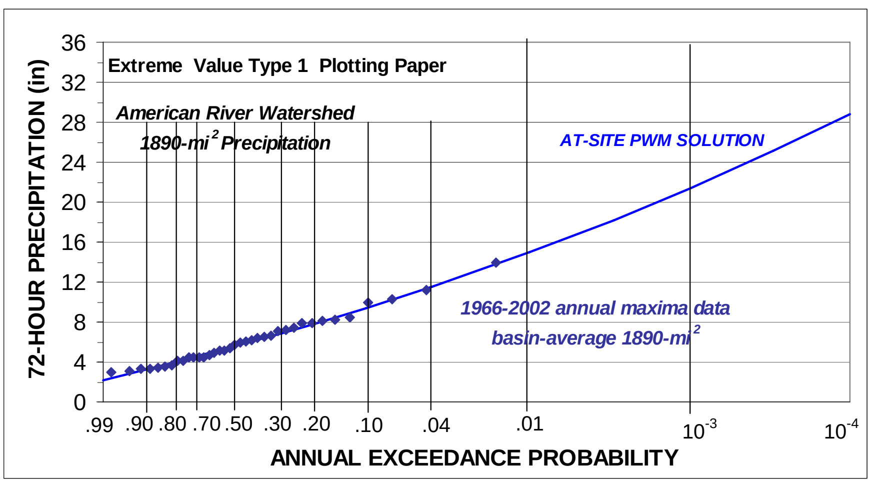

Figure 4 – At-Site Probability Weighted Moments Solution of GEV Distribution for Systematic Record from 1966-2002 for American River Watershed

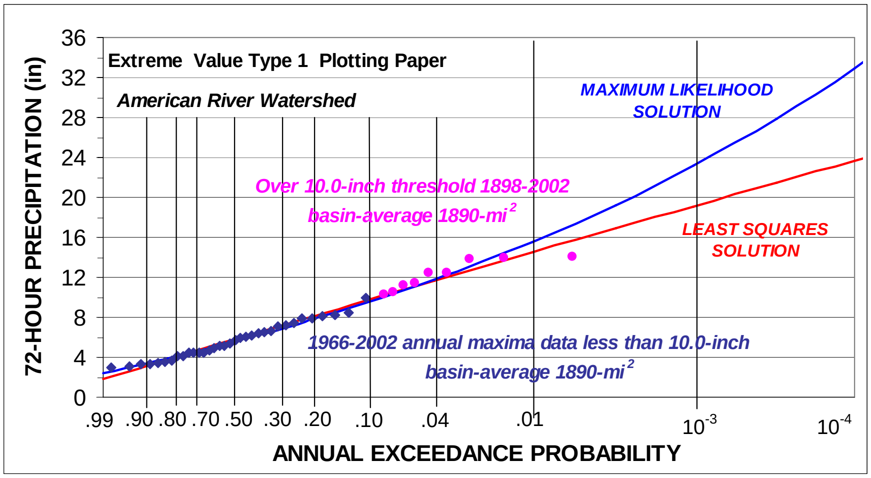

Figure 5 – At-Site Least-Squares Probability-Plot Solution and Maximum Likelihood Solution of 72-Hour Annual Maxima Systematic Data for 1966-2002 and Historical Data for 1898-1965 for GEV Distribution for 1860-mi^2 American River Watershed

Method #2 – Blue Canyon Index Station

In this approach, 72-hour precipitation at the Blue Canyon station (Figure 6) was used as an index for the magnitude of 1860-mi^2 watershed-average precipitation. A logarithmic regression was used to establish the relationship between 72-hour precipitation at the Blue Canyon station and watershed-average 1860-mi^2 precipitation obtained from the GIS-based analysis of storms (Figure 7). The 72-hour 1860-mi^2 precipitation-frequency curve (Figure 8) was derived by Monte Carlo simulation as the product of the 72-hour Blue Canyon precipitation-frequency curve and the regression relationship between Blue Canyon precipitation and the watershed-average 1860-mi^2 precipitation.

The findings of the regional precipitation-frequency analysis[14] were used to develop the 72-hour precipitation-frequency curve for the Blue Canyon station (Figure 6). In the regional precipitation analysis, the GEV distribution was found to be the best-fit distribution based on a large regional dataset of 1,943 station-years of record. The four-parameter Kappa distribution[5] was used to describe the 72-hour precipitation-frequency relationship for the Blue Canyon station. The Kappa distribution was chosen because it is capable of mimicking the three-parameter GEV distribution and precipitation-frequency relationships near to the GEV. This was done to allow alternate distributional forms to the GEV to be examined in the uncertainty analysis. Aspects of the uncertainty analysis will be discussed later in this report.

The inverse form of the Kappa distribution is:

$$q(F) = \xi + \frac{\alpha}{\kappa}\left\{1 - \left(\frac{1-F^h}{h}\right)^{\kappa}\right\} \qquad (2)$$

where: ξ, α, κ, and h are location, scale, shape, and shape parameters, respectively.

An h value of zero leads to the GEV distribution, an h value of 1 produces the Generalized Pareto[5] (GP) distribution and an h value of -1 produces the Generalized Logistic[5] (GL) distribution. Thus, positive values of h can produce frequency curves that are flatter than the GEV, and negative values of h can produce steeper frequency curves. Minor adjustments of h near a zero value (GEV) allow alternate distributional forms to be examined that are near to the GEV.

Population estimates of the at-site mean and regional L-moments for the Blue Canyon daily gage are based on the findings of the regional precipitation-frequency analysis and are listed in Table 4a. Corresponding distribution parameters and product-moments for the four-parameter Kappa distribution for the Blue Canyon station are listed in Table 4b.

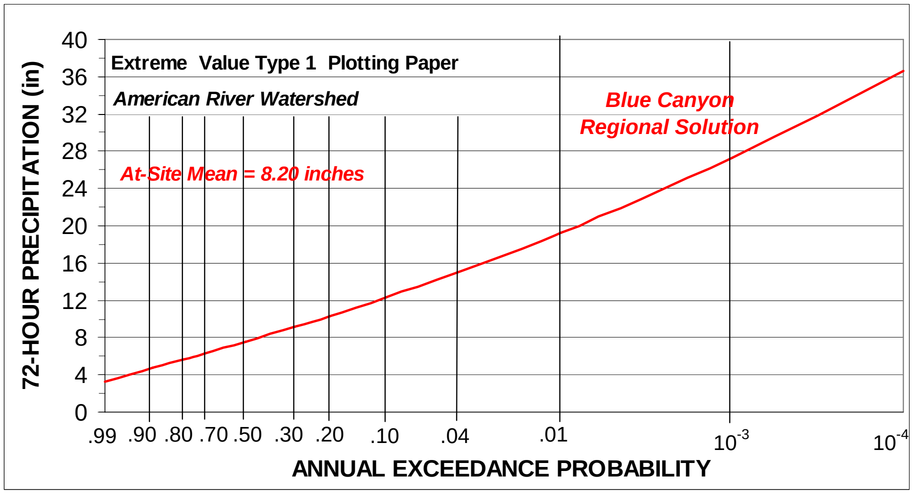

Figure 6 – 72-Hour Precipitation-Frequency Relationship for Blue Canyon Index Station

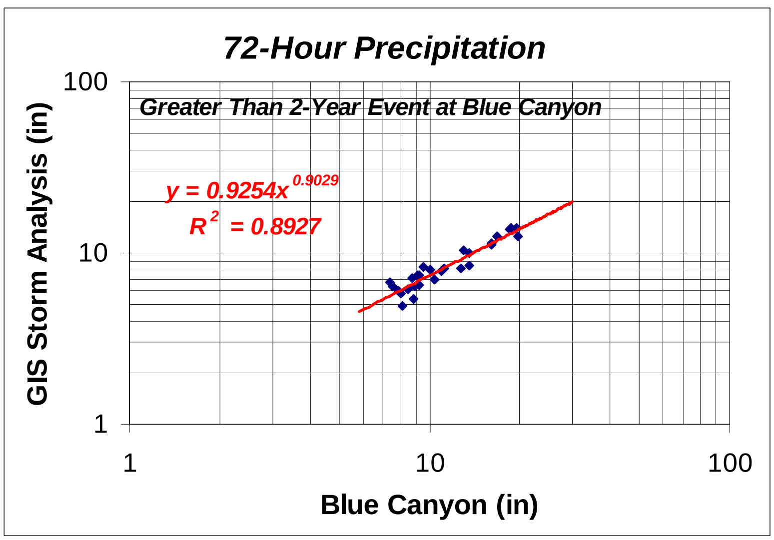

Figure 7 – Relationship Between 72-Hour Blue Canyon Precipitation and Watershed-Average 1860-mi^2 Precipitation from GIS Analysis of Historical Storms

Table 4a – Estimates of Population Moments for Blue Canyon Station

REGIONAL L-MOMENTS			
At-Site Mean	L-Cv	L-Skewness	L-Kurtosis
8.20-inches	0.2099	0.2142	0.1700

Table 4b – Distribution Parameters and Product-Moments
for Kappa Distribution for Blue Canyon Station

DISTRIBUTION PARAMETERS			
Xi (ξ)	***Alpha (α)***	***Kappa (κ)***	***h***
6.7068	2.3099	-0.0702	-0.01
PRODUCT MOMENTS			
At-Site Mean	**Coefficient Variation**	**Coefficient Skewness**	**Coefficient Kurtosis**
8.20-inches	0.401	1.62	8.46

Monte Carlo Derivation of Precipitation-Frequency Relationship

The 72-hour 1860-mi^2 precipitation-frequency curve (Figure 8) was derived by Monte Carlo simulation as the product of the 72-hour Blue Canyon precipitation-frequency curve and the regression relationship between Blue Canyon precipitation and the watershed-average 1860-mi^2 precipitation (Figure 7). The primary focus of the derivation and the uncertainty analysis was on rare storm events with Annual Exceedance Probabilities (AEPs) in the range from 10^{-2} to 10^{-5}. Given this focus, it was decided to analyze the results of the Monte Carlo simulations in a non-parametric manner. This approach avoided the need for making assumptions in selecting a probability distribution and the method for solution of distribution parameters.
The Monte Carlo simulation was conducted as follows:

1. Generate a sample of 456,000 annual maxima of 72-hour precipitation for the Blue Canyon station using the Kappa distribution and the distribution parameters listed in Table 4b, and using a Latin-hypercube[7,24] sampling approach;

2. For each annual maximum in Step 1, generate a 72-hour 1860-mi^2 precipitation value using the regression relationship depicted in Figure 7, and account for the unexplained variance from the regression solution (Equation 3);

   $$P_{ar} = EXP[-0.0776 + 0.9029(LN(P_{bc})) + 0.0983(N[0,1])] \qquad (3)$$

   where: P_{ar} is the 72-hour 1860-mi^2 precipitation for the American River watershed; P_{bc} is the 72-hour precipitation at Blue Canyon station; and *N[0,1]* is a standardized normal variate.

3. Rank the 456,000 values of 72-hour 1860-mi^2 precipitation annual maxima from Step 2 in descending order and compute exceedance probabilities for the ranked values using the Cunnane[2] plotting-position formula (Equation 4);

   $$AEP = \left(\frac{i-\theta}{n+1-2\theta}\right) \qquad (4)$$

   where: *AEP* is annual exceedance probability; *n* is the number of annual maxima, which equals 456,000; *i* is the rank of the precipitation annual maxima ranked in descending order from 1 to *n*; and θ is a plotting-position weighting factor taken to be 0.44 (Gringorten[4]).

4. Assemble 500 sample sets using the procedure above by repeating Steps 1 through 3 five-hundred times. Compute the expected value of the 72-hour 1860-mi^2 precipitation for each of the 456,000 annual exceedance probabilies as the mean of the 500 samples for a given AEP.

Figure 8 depicts the 72-hour 1860-mi^2 precipitation-frequency curve derived via the Monte Carlo simulation procedure described above. A probability-plot of the systematic and historical data is also shown in Figure 8 to allow a comparison with observed 72-hour storm events. Quantile estimates for selected annual exceedance probabilities are listed in Table 7.

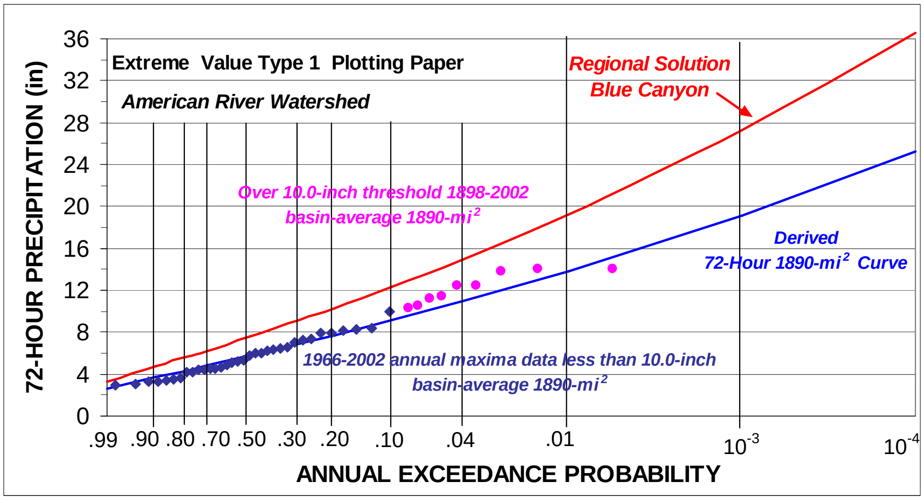

Figure 8 – 72-Hour 1860-mi^2 Precipitation-Frequency Relationship for American River Watershed Derived from Blue Canyon Index Station and Regression Relationship with GIS Storm Analyses

Method #3 – 6-Station Multivariate Autoregressive Precipitation Model

A multivariate annual autoregressive time-series precipitation model[11] was developed that utilizes the 6-stations employed in the Modified Thiessen analysis (Table 1, Figure 2). The Blue Canyon station was used as the key station and the 72-hour Blue Canyon precipitation-frequency curve was preserved in the time-series generation. All cross-correlation relationships between the 6 stations (Table 6) were preserved in the precipitation generation scheme. The multivariate annual independent autoregressive AR(0) model was used to generate 200 samples, each with 456,000 precipitation annual maxima for the watershed. For each annual maximum, the Thiessen weighting factors (Table 1) were used to make an initial estimate of the 72-hour watershed-average precipitation using the 72-hour precipitation from each station. The annual maximum was then determined by adjusting the initial Modified Thiessen estimate by the findings of the regression relationship that relates the Modified Thiessen estimate to the more accurate GIS-based estimate (Figure 3). This latter step included accounting for the unexplained variance in the regression relationship.

Expected values of the quantile estimates for selected annual exceedance probabilities are listed in Table 7 and the 72-hour 1860-mi^2 precipitation-frequency relationship produced by the AR(0) model is depicted in Figure 9. Close agreement is seen with the relationship derived by the Blue Canyon Index Station method.

Table 6 – Logarithmic Cross-Correlation Coefficients
for Concurrent 72-Hour Precipitation for 54 Storms in the Period from 1898-2002

GAGES	BLUE CANYON	COLFAX	PLACERVILLE	REPRESSA	SODA SPRINGS	TWIN LAKES
BLUE CANYON	1.000					
COLFAX	0.873	1.000				
PLACERVILLE	0.824	0.796	1.000			
REPRESSA	0.687	0.754	0.696	1.000		
SODA SPRINGS	0.912	0.800	0.758	0.597	1.000	
TWIN LAKES	0.768	0.713	0.703	0.530	0.795	1.000

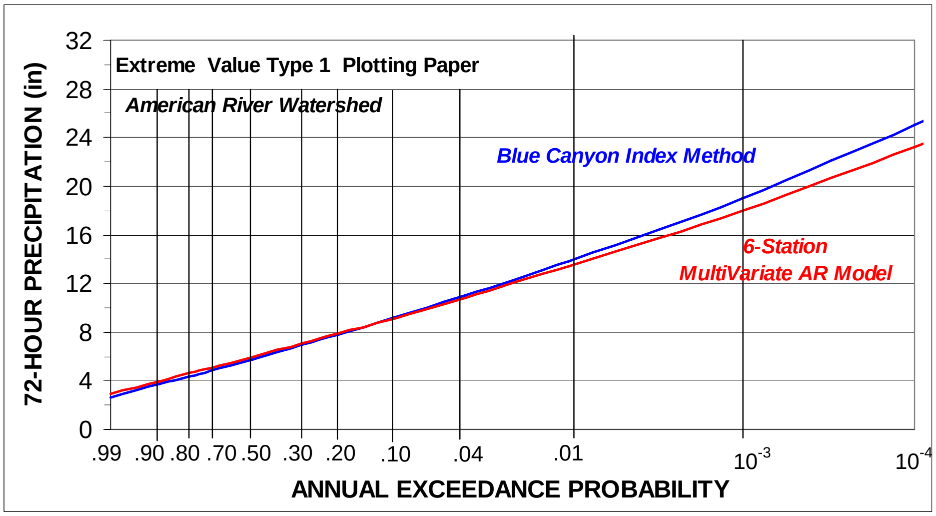

Figure 9 – 72-Hour 1860-mi^2 Precipitation-Frequency Relationship for American River Watershed Developed from 6-Station Multivariate Autoregressive Precipitation Model and Comparison with Relationship Derived from Blue Canyon Index Station Method

Table 7– Comparison of Quantile Estimates by Various Methods for 72-Hour 1860-mi^2 Precipitation for American River Watershed

72-HOUR WATERSHED-AVERAGE 1860-MI^2 PRECIPITATION				
METHOD	**ANNUAL EXCEEDANCE PROBABILITY**			
	10^{-2}	**10^{-3}**	**10^{-4}**	**10^{-5}**
Method #1 – At-Site Method At-Site PWM Solution of Systematic Record	14.9-in	21.3-in	28.8-in	37.7-in
Method #1 – At-Site Method At-Site Least Squares Solution of Systematic and Historical Record	14.5-in	19.1-in	23.6-in	28.1-in
Method #1 – At-Site Method At-Site Maximum Likelihood Solution of Systematic and Historical Record	15.5-in	23.2-in	32.9-in	45.4-in
Method #2 – Use of Regional Information Blue Canyon Index Station and Regression with GIS based Storm Analyses	13.8-in	19.0-in	25.0-in	31.9-in
Method #3 – Use of Regional Information Multivariate Autoregressive Precipitation Spatial Model AR(0)	13.4-in	18.0-in	23.2-in	29.1-in

COMPUTATION OF UNCERTAINTY BOUNDS

Greater reliability can be expected from those methods that utilize regional information. This occurs because of the use of large datasets in the regional analyses and the resultant reduction in uncertainties attributable to sample variability. Therefore, Methods #2 and #3, which utilize regional information, would be expected to have greater reliability and smaller uncertainty bounds relative to estimates from the at-site methods discussed under Method #1. A review of Table 7 shows that Methods #2 and #3 have similar quantile estimates, and there is greater variability amongst the at-site methods.

Method #2, which makes use of an index station, and storm analyses that are related to precipitation at the index station, is the more direct approach and less fraught with statistical assumptions and parameter estimations for computation of uncertainty bounds. Therefore, Method #2 was chosen for describing the precipitation-frequency relationship for the American River watershed and for computation of uncertainty bounds.

Uncertainty Associated with Climatic Stationarity

Uncertainty about the stationarity of storm characteristics and the possibility of different future climatic conditions has been identified by the National Research Council[8] as a contributor to the uncertainty of the precipitation-frequency relationship for the American River watershed. While uncertainty due to climatic stationarity is an issue, it was not addressed in the uncertainty analysis in this report. As discussed in prior sections, the derived 72-hour precipitation-frequency relationship represents the best estimate of storm characteristics for the next ten to thirty year planning period. Concerns about possible changes, or shifts, in the climatic state will be addressed during watershed hydrological modeling. Specifically, the effect of possible alternative climatic states, as expressed by alternative precipitation-frequency relationships, will be examined in the watershed modeling phase as part of the stochastic modeling of extreme storms and floods.

Proposed Approach to Development of Uncertainty Bounds

Uncertainty in the 72-hour 1860-mi^2 precipitation-frequency relationship arises from several sources. The total uncertainty includes contributions of uncertainty from the at-site mean and L-moment ratios L-Cv and L-skewness for the Blue Canyon index station; from selection of the underlying probability distribution; from slope and intercept parameters of the regression relationship; and from the unexplained variance in the regression relationship. Each of these parameters/elements was included in the uncertainty analysis and construction of uncertainty bounds.

Blue Canyon Index Station

The Generalized Extreme Value (GEV) distribution was identified through L-moment goodness-of-fit tests in the regional precipitation analysis[14] as the best three-parameter distribution. The four-parameter Kappa distribution with a shape parameter of h = - 0.01, which is essentially equivalent to a three-parameter GEV, was used to describe the precipitation-frequency curve for the Blue Canyon Index Station. This choice was made to allow an analysis of uncertainty with regard to selection of the probability model. The Kappa distribution is capable of modeling distributions with characteristics similar to that of the GEV. Estimated population L-moments, product-moments, and Kappa distribution parameters for the Blue Canyon index station are listed in Tables 4a,b.

<u>Blue Canyon, At-Site Mean</u> – The at-site mean at the Blue Canyon daily gage is 8.20-inches based on the record from 1966-2002. Uncertainties about the at-site mean were modeled with a Normal distribution having a mean of zero and a standard deviation of 0.54-inches (Table 8). The standard deviation was computed based on a record length of 37-years and using a value of 0.401 for the

coefficient of variation (Table 4b). For comparison, the at-site mean at the Blue Canyon daily gage for the period from 1906-2002 is 8.26-inches. Although the standard error of estimation of the at-site mean would be smaller for the period from 1906-2002 due to the larger sample size, it was decided that use of the statistics for the period from 1966-2002 would be consistent with the prior decision to use findings from the most recent period for describing the precipitation-frequency characteristics.

Table 8 – Sampling Distribution for Blue Canyon At-Site Mean

MEAN	STANDARD DEVIATION	COEFFICIENT SKEWNESS	PROBABILITY DISTRIBUTION
8.20-inches	0.54-inches	0.00	Normal

Blue Canyon, L-Cv – The estimated value of L-Cv is 0.2099 based on a regional analysis of 62 stations with 1,943 station-years of record that were active during the 1966-1998 period. An analysis of the Equivalent Independent Record Length (EIRL)[12,13] for the 1,943 station-years of record indicates an effective record length of 260-years (Appendix B). Uncertainties about the estimated value of L-Cv were modeled with a Normal distribution having a mean of zero and standard deviation of 0.0087 (Table 9). The Normal distribution is an appropriate choice because the sampling distribution of L-moment ratios is Normally distributed for large samples and nearly Normally distributed for small to moderate size samples (Hosking and Wallis[5]).

A standard deviation of 0.0087 equates to the standard error of estimation for L-Cv based on an EIRL of 260-years, and the sample variance for L-Cv that was exhibited in the sample-set of 62 stations. Similar results were obtained for the sampling error of L-Cv based on sampling from the Kappa distribution with the distribution parameters listed in Table 4b for a sample set of 260 annual maxima.

Table 9 – Sampling Distribution for Blue Canyon L-Cv

MEAN	STANDARD DEVIATION	COEFFICIENT SKEWNESS	PROBABILITY DISTRIBUTION
0.2099	0.0087	0.00	Normal

Blue Canyon, L-Skewness – The estimated value of L-Skewness is 0.2142 based on a regional analysis of 73 stations with 4095 station-years of record that were active during the 1900-1998 period. An analysis of the Equivalent Independent Record Length (EIRL) for the stations active in the 1900-1998 period indicates an effective record length of 650-years (Appendix B). The standard deviation for the expected value of L-skewness is 0.0196 based on an EIRL of 650-years, and the sample variance for L-Skewness that was exhibited in the sample-set of 73 stations. Similar results were obtained were obtained for the sampling error of L-Skewness based on sampling from the Kappa distribution with the distribution parameters listed in Table 4b for a sample set of 650 annual maxima.

In addition, sample values of L-skewness are correlated with sample values of L-Cv. A correlation analysis of sample L-Skewness and L-Cv values for the 1900-1998 period produced a linear correlation coefficient of 0.70. Solution of regression parameters for the expected mean values and sampling variances of L-Cv and L-Skewness yielded regression parameters with intercept of –0.1176 and slope of 1.571 (Table 10). Similar regression parameters were found by simulation of sample sets drawn from the Kappa distribution with L-moments and regional distribution parameters listed in Tables 4a,b.

The regression relationship used for simulation of L-Skewness values is shown in Equation 5 and includes a residual term to account for the unexplained variance in the regression solution.

$$L\,skewness = -0.1176 + 1.571(LCv) + 0.0140(N[0,1])] \qquad (5)$$

where: *N[0,1]* is a standardized normal variate.

Figure 10 depicts a simulated sample set of 500 pairs of L-Cv and L-Skewness values to demonstrate the general character of uncertainties for values of L-Cv and L-Skewness.

Table 10 – Regression Parameters for Sampling of Blue Canyon L-Skewness as Correlated with L-Cv

REGRESSION PARAMETERS			RESIDUAL PARAMETERS	
INTERCEPT	SLOPE	CORRELATION COEFFICIENT	UNEXPLAINED VARIANCE	PROBABILITY DISTRIBUTION
-0.1176	1.571	0.701	$(0.0140)^2$	Normal

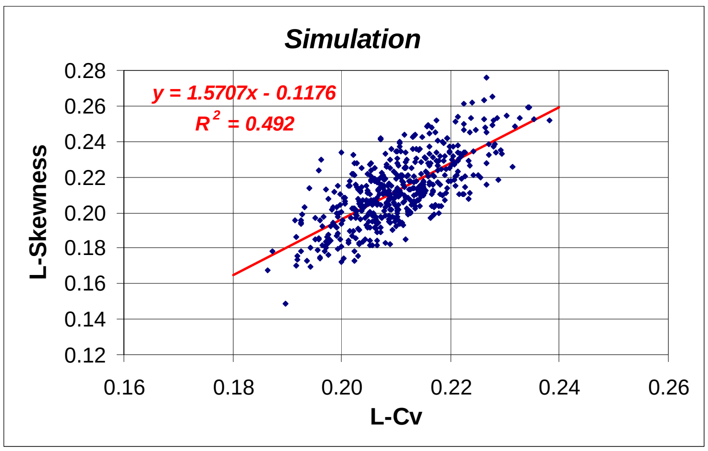

Figure 10 – Example Simulation of 500 pairs of L-Cv and L-Skewness Values

Blue Canyon, shape parameter *h* of the Kappa distribution – Uncertainties in the selection of the probability model were addressed by allowing variability in the shape parameter *h* of the Kappa distribution. Uncertainties about the mean value of –0.01 were modeled with a three-parameter Gamma distribution having a mean of zero, standard deviation of 0.18, and a coefficient of skewness of –1 (Table 11). The selection of the three-parameter Gamma distribution[5] for the sampling distribution of the *h* parameter was based on Monte Carlo simulation of sample sets drawn from the Kappa distribution with L-moments and regional distribution parameters listed in Tables 4a,b.

To illustrate uncertainties in the selection of the probability distribution, three 72-hour precipitation-frequency curves are shown in Figure 11 for the Blue Canyon station that show the effect of the change in the shape parameter *h*. The three curves have an at-site mean of 8.20-inches, L-Cv of 0.2099, L-Skewness of 0.2142, and are fitted to the Kappa distribution for *h* values of –0.18, 0.00 (GEV), and +0.18, respectively. It is seen that the primary effect of uncertainties in identification and selection of the probability model is for AEPs more rare than the 100-year recurrence interval.

Table 11 – Sampling Distribution of Shape Parameter *h* of Kappa Distribution for Blue Canyon Station

MEAN	STANDARD DEVIATION	COEFFICIENT SKEWNESS	PROBABILITY DISTRIBUTION
-0.01	0.18	-1.0	3-parameter Gamma

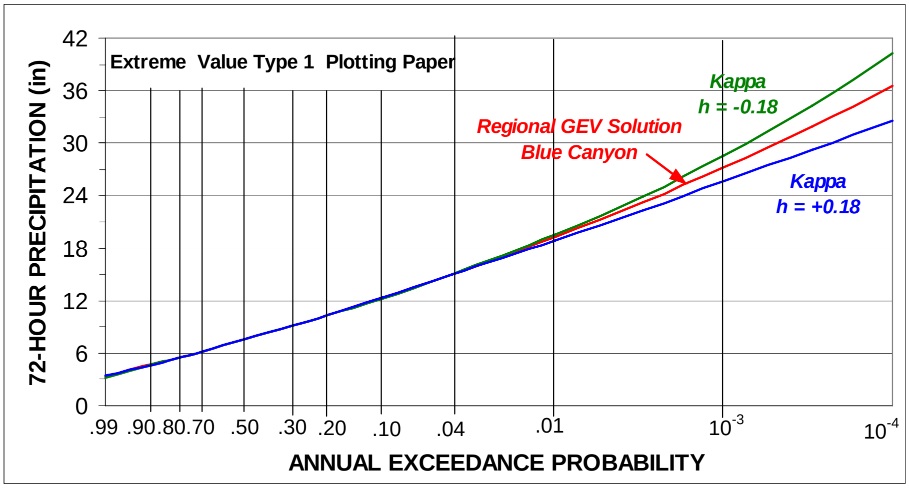

Figure 11 – Comparison of 72-Hour Precipitation-Frequency Curves for Blue Canyon Station Due to Change in Shape Parameter *h* for Four-Parameter Kappa Distribution

Regression Relationship for 72-Hour Precipitation at Blue Canyon and 72-Hour Precipitation for the American River Watershed

The logarithmic regression between 72-hour precipitation at Blue Canyon and 72-hour 1860-mi^2 precipitation for the American River Watershed (Figure 7) shows a very high level of correlation. The logarithmic regression parameter solutions were: intercept of -0.0776; slope of 0.9029; and correlation coefficient of 0.9448 for a sample set of 28 storms (Table 12a). The sample of 28 storms (Table 12b) represented storms that exceeded the 2-year recurrence interval at the Blue Canyon Station. The 2-year threshold was utilized based on experience in Australia[18] and UK[1] from studies of areal reduction factors, where different behavior was observed for storms less than, and greater than, the 2-year recurrence interval. Minor differences in the slope parameter were also seen in the storm data for the American River watershed for common storm events having a recurrence interval less than 2-years. In addition, since the focus of this study was on large (rare) storm events, this approach assured that the regression solution was based on larger magnitude storms rather than be influenced by small magnitude storms.

Uncertainties for the regression relationship were modeled by conducting separate Monte Carlo simulations based on the expected values of the intercept, slope and correlation coefficient for a sample set of 28 storms. The simulations included a residual term to account for the unexplained variance in the regression relationship. Specifically, each Monte Carlo simulation of 28 storms produced a sample set of intercept, slope, correlation coefficient, and variance of the response variable (72-hour 1860-mi^2 precipitation), that was used in the uncertainty analysis.

Table 12a – Regression Parameters for Relationship Between 72-Hour Precipitation at Blue Canyon Station and GIS Analysis of 28 Storms

REGRESSION PARAMETERS – NATURAL LOG SPACE		
INTERCEPT	SLOPE	CORRELATION COEFFICIENT
-0.0776	0.9029	0.946

Table 12b – Sampling Distribution of 72-Hour Precipitation at Blue Canyon Station for Sampling of 28 Storms

PARAMETERS - NATURAL LOG SPACE			
MEAN	STANDARD DEVIATION	COEFFICIENT SKEWNESS	PROBABILITY DISTRIBUTION
2.4218	0.3140	0.0	Normal
PARAMETERS - REAL SPACE			
MEAN	STANDARD DEVIATION	COEFFICIENT SKEWNESS	PROBABILITY DISTRIBUTION
11.84-inches	3.81-inches	1.00	2-parameter Log-Normal

Simulation Procedure
The Monte Carlo simulation procedure for calculating uncertainty bounds was similar to the procedure described earlier for derivation of the expected values of quantiles of the 72-hour 1860-mi^2 precipitation-frequency relationship. As before, outputs of 72-hour 1860-mi^2 precipitation annual maxima from the Monte Carlo simulation were analyzed in a non-parametric manner rather than by fitting a selected probability distribution to the simulation data. This was done to simplify the analysis and eliminated the need to identify/select a probability model that fits both common and very extreme events, and eliminated the need to select a fitting method for solution of the distribution parameters.

The Monte Carlo simulation was conducted as follows.

Generate 500 Sample-Sets of the 72-hour 1860-mi^2 annual maxima

Five hundred sample-sets of 72-hour 1860-mi^2 precipitation were generated, each having a record length of 456,000 annual maxima. The choice of 456,000 annual maxima was for convenience of computing selected AEPs, such as 10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5}, using a plotting position formula (Equation 4) with $\theta = 0.44$. Latin hyper-cube sampling procedures[7,24] were used for sampling of all parameters used in the Monte Carlo simulation.

For each sample-set:

<u>Blue Canyon Index Station Component</u>

1. Select a value of the at-site mean for the Blue Canyon station (Table 8).
2. Select a value of L-Cv for the Blue Canyon station (Table 9).
3. Select a value of L-Skewness based on the regression relationship with L-Cv (Equation 5, Table 10).
4. Select a value of the shape parameter (h) for the Kappa distribution for Blue Canyon (Table 11).
5. Solve for the Kappa distribution parameters using parameter values from Steps 1-4.
6. Generate 456,000 annual maxima for the Blue Canyon station using the Kappa distribution and the distribution parameters from Step 5, and using a latin-hypercube sampling[7,24] approach to set the annual exceedance probability for each annual maximum generated.

Regression between Blue Canyon Station and Watershed-Average Precipitation

7. Generate a sample set of 28 storms for the watershed. This sample set is comprised of 28 precipitation values (72-hour) for the Blue Canyon station, generated using the parameters from Table 12b; and 28 watershed-average precipitation values representing the storms from the GIS-based storm analyses (72-hour 1860-mi^2 precipitation), that were generated using Equation 3. Compute the logarithmic regression parameters, correlation coefficient and unexplained variance for the paired sample dataset of 28 storms.

8. Use the regression parameters computed in Step 7, and in a manner similar to Equation 3 that accounts for the unexplained variance, generate a 72-hour 1860-mi^2 precipitation annual maximum for each of the 456,000 annual maxima at Blue Canyon computed in Step 6.

9. Rank all of the 456,000 annual maxima 72-hour 1860-mi^2 precipitation values from Step 8 in descending order, and use the plotting position formula (Equation 4) to establish the annual exceedance probability of each annual maximum.

Analyze the Sample-Set of 500 Samples and Compute Uncertainty Bounds

At this point in the simulation procedure, 500 sample-sets of 72-hour 1860-mi^2 precipitation have been generated. Each sample-set contains 456,000 annual maxima representing one possible representation of the true precipitation-frequency curve for the watershed. Uncertainty bounds were computed for selected annual exceedance probabilities of 72-hour 1860-mi^2 precipitation, such as 10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5}, by conducting a frequency analysis of the 500 estimates for a given AEP.

10. Compute standard sample statistics for the 500 precipitation values for a given annual, exceedance probability. Rank the 500 values in descending and use a plotting-position formula (Equation 4) to estimate the 5%, 10%, 90%, and 95% exceedance values for the uncertainty bounds.

The mean curve and 90% uncertainty bounds for the 72-hour 1860-mi^2 precipitation-frequency relationship are listed in Table 13 and depicted in Figure 12. Figure 13 shows a comparison of the mean curve of expected values of 72-hour 1860-mi^2 precipitation with the systematic data (1966-2002) and historical data (1898-1965) for the American River watershed.

Table 13 –Results of Uncertainty Analyses for 72-Hour 1860-mi^2 Precipitation

ANNUAL EXCEEDANCE PROBABILITY	UNCERTAINTY BOUNDS - 72-HOUR 1860-MI^2 PRECIPITATION						
	95% Exceedance	90% Exceedance	Mean Value	10% Exceedance	5% Exceedance	Standard Deviation	Coefficient Skewness
10^{-2}	12.1-in	12.4-in	13.8-in	15.1-in	15.6-in	1.04-in	0.3
10^{-3}	15.8-in	16.3-in	19.0-in	21.8-in	22.7-in	2.12-in	0.5
10^{-4}	19.3-in	20.2-in	25.0-in	30.4-in	32.4-in	4.07-in	0.8
10^{-5}	22.7-in	24.0-in	32.0-in	41.7-in	45.3-in	7.25-in	1.1

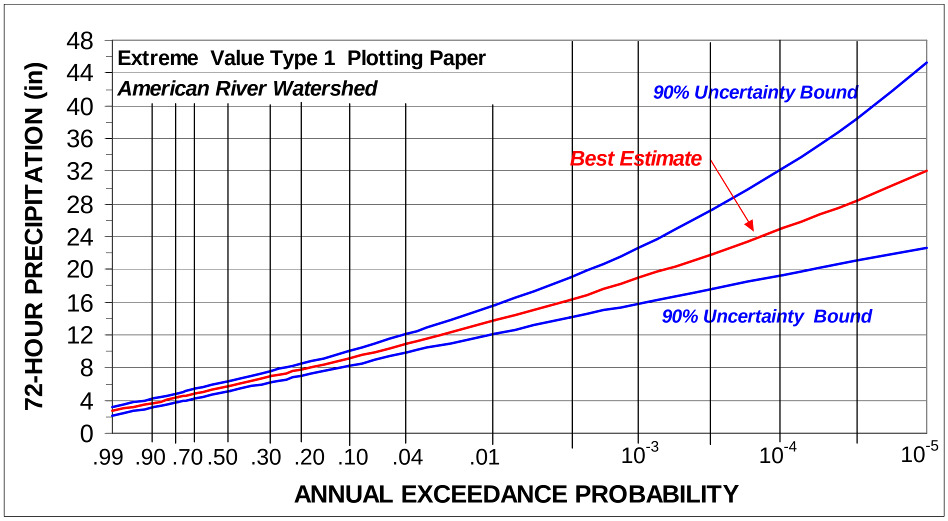

Figure 12 – Computed 72-Hour 1860-mi^2 Precipitation-Frequency Curve and 90% Uncertainty Bounds for American River Watershed

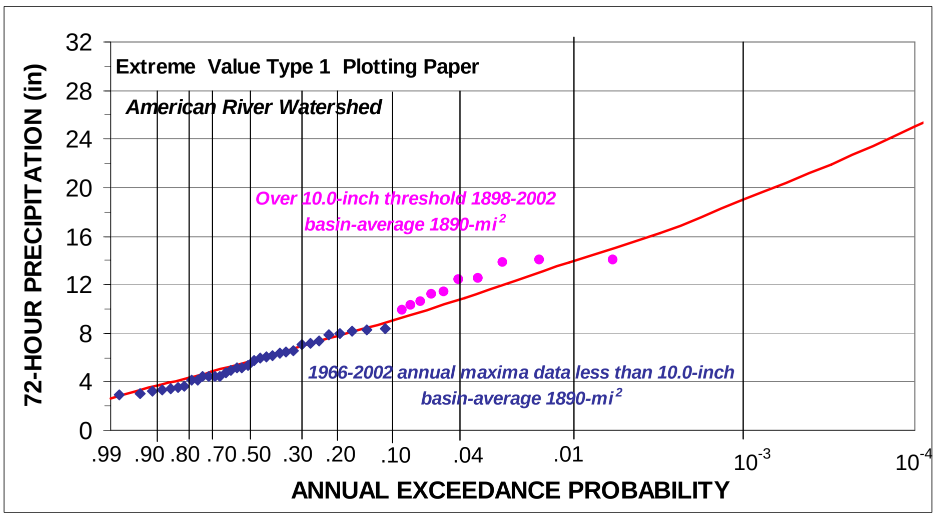

Figure 13 – Comparison of Computed 72-Hour 1860-mi^2 Precipitation-Frequency Curve and Observed 72-Hour Precipitation for American River Watershed

Contributions to the Total Uncertainty

As discussed previously, uncertainty in the 72-hour 1860-mi^2 precipitation-frequency relationship arises from several sources. The total uncertainty includes contributions of uncertainty from estimation of the at-site mean and L-moment ratios L-Cv and L-skewness for the Blue Canyon index station; from selection of the underlying probability distribution for precipitation at the Blue Canyon station; from slope and intercept parameters of the regression relationship relating precipitation for the 1860-mi^2 watershed to precipitation at the Blue Canyon station; and from the unexplained variance in that regression relationship.

After the total uncertainty and the uncertainty bounds were computed, separate analyses were conducted to identify the relative magnitude of uncertainty contributed from each of the sources described above. The relative contribution of a particular source of uncertainty to the total uncertainty was measured by comparing the sample variances for the sample-set of 500 precipitation estimates for a given AEP (Step 10 in simulation procedure). Specifically, the relative contribution from a given source was computed as a ratio of the variance from that source to the total variance from all sources, and expressed as a percentage. The results of that analysis are listed in Table 14 and Figure 14. It is seen that contributions of uncertainty to the total uncertainty varies with the AEP of the precipitation being estimated.

At-Site Mean, Blue Canyon – Uncertainty for the at-site mean for the Blue Canyon station is the primary contributor to the total uncertainty for estimation of precipitation near 10^{-2} AEP, but is a minor contributor for 10^{-5} AEP. This uncertainty could be reduced if the at-site mean for the 1906-2002 period was deemed representative of the most recent 1966-2002 period of precipitation, owing to longer record length and smaller standard error of estimation.

L-Cv, Blue Canyon – Uncertainty for L-Cv is a minor contributor throughout the range of AEP, owing to the relatively large regional sample used to estimate the L-Cv value.

L-Skewness, Blue Canyon – Uncertainty about L-Skewness is a significant contributor to the total uncertainty. The relative contribution to the total uncertainty increases as storm events become more rare. Little can be done to reduce the uncertainty about L-Skewness as the L-Skewness value was estimated using a regional approach with all available data that were representative of the west face of the Sierra Mountains.

Probability Distribution, Blue Canyon – Uncertainty about the probability model becomes a significant contributor to the total uncertainty as storm events become very rare. Deviations from a GEV model are not significant contributors of uncertainty for precipitation AEPs more common than 10^{-3}. In particular, the GEV distribution has been identified in numerous regional precipitation studies in the Pacific Northwest[12,13,14] as the best 3-parameter distribution for describing precipitation annual maxima data. These studies have included regional datasets ranging from 15,000 station-years to 100,000 station-years of record. Therefore, there is relatively high confidence that the parent distribution of 72-hour precipitation annual maxima is near to the distributional form of the GEV for AEPs in the range of 10^{-3} to 10^{-4}. However, there is no physically based reason to support continued behavior compatible with the GEV for storm events beyond current experience. Extrapolations beyond the experience data should reflect increased uncertainty and, in fact, that is what is demonstrated in the uncertainty analysis as storm events becoming very rare (Table 14, column 5).

Regression Solution, 72-Hour 1860-mi^2 Precipitation Relationship to 72-Hour Precipitation at Blue Canyon – Uncertainty about the regression relationship contributes from 16% to 19% of the total uncertainty and is a contributor throughout the range of AEP. This uncertainty cannot be reduced at this time since it is dependent upon analysis of noteworthy storms over the American River watershed. A GIS analysis has already been conducted for all significant storms that affected the watershed.

Table 14 – Relative Contributions of Uncertainty to Total Uncertainty from Various Sources in Determination of 72-Hour 1860-mi^2 Precipitation-Frequency Relationship for American River Watershed

ANNUAL EXCEEDANCE PROBABILITY	RELATIVE CONTRIBUTION OF UNCERTAINTY TO TOTAL UNCERTAINTY FROM SPECIFIC SOURCES				
	BLUE CANYON STATION				WATERSHED
	AT-SITE MEAN	L-Cv	L-SKEWNESS	PROBABILITY DISTRIBUTION	REGRESSION RELATIONSHIP
10^{-2}	51%	7%	24%	2%	16%
10^{-3}	24%	5%	37%	15%	19%
10^{-4}	12%	3%	40%	28%	17%
10^{-5}	6%	2%	39%	36%	17%

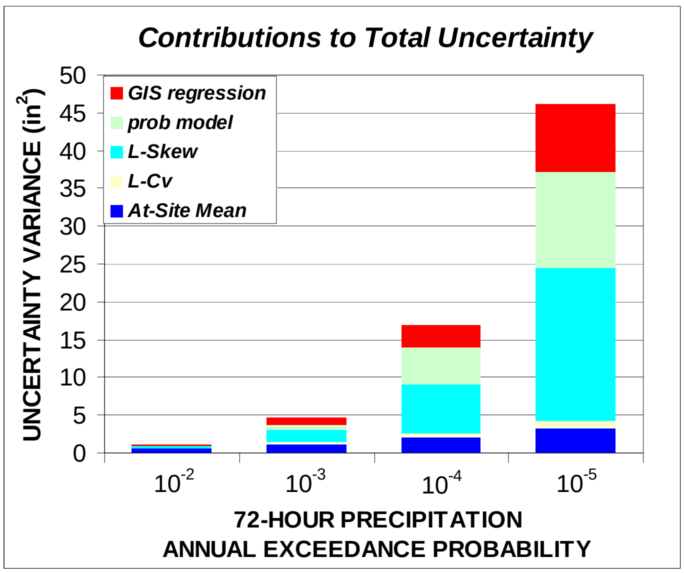

Figure 14 – Contribution of Uncertainty to Total Uncertainty from Various Sources for 72-Hour 1860-mi^2 Precipitation-Frequency Relationship for American River Watershed

DETERMINATION OF AREAL REDUCTION FACTORS

Areal Reduction Factors (ARFs) have been used for many decades for converting from point precipitation to precipitation over watershed-sized areas. Most applications of ARFs in the United States have been with Probable Maximum Precipitation (PMP), which are based on storm-centered analyses[9]. (See Appendix A for a more detailed description of areal reduction factors).

Early in the planning stages for this project, it was anticipated that areal reduction factors would be determined from information obtained from the GIS-based storm analyses and then used for stochastic generation of precipitation over the watershed. As the project evolved, it became apparent that the derivation of the 72-hour precipitation-frequency relationship for the American River watershed was a more direct and superior approach for stochastic generation of precipitation for the watershed. Therefore, there was no specific need for determining areal reduction factors.

Nonetheless, limited studies have been conducted in the US using fixed-area storm analyses that are appropriate for computing ARFs for precipitation-frequency applications. Thus, there is interest in the magnitude and behavior of ARFs for general storms on the west coast of the US. Given this interest, areal reduction factors have been determined for 72-hour precipitation for 1860-mi^2 areal coverage. The computational approach taken was that recommended by Bell[1], Siriwardena and Weinmann[18], wherein, the areal reduction factor is defined as the ratio between precipitation values obtained from area and point precipitation-frequency curves for a common value of annual exceedance probability (Figure 15a). In their procedure, point and area precipitation-frequency curves are computed independently using regional analyses methods[5], and then ARF ratio values are determined based on precipitation values from the computed frequency curves.

The 72-hour precipitation-frequency curves for 10-mi^2 (point) precipitation and 1860-mi^2 (area) precipitation are shown in Figure 15b. Regional L-moment values[5,14] for the 10-mi^2 curve are listed in Table 15a and Kappa distribution parameters are listed in Table 15b. L-moment values for the derived 1860-mi^2 curve are listed in Table 16a and Kappa distribution parameters[5] for the derived 1860-mi^2 curve are listed in Table 16b. Computed values of areal reduction factors are listed in Table 17.

A review of Figure 15b and Table 17 values shows areal reduction factors to decrease with annual exceedance probability. The variation of ARFs with AEPs is depicted in Figure 16 where it is seen that the relationship is similar to that observed in analysis of large areal coverage storms in Australia[18]. The similarity of the relationships between ARFs and AEPs for the American River and Australia is suggestive that this general behavior would be expected in analyses of long-duration storms for other mid-latitude locations in humid climates.

Comparison of Tables 15a,b and 16a,b shows the at-site mean, variance and skewness for the watershed-average 72-hour 1860-mi^2 precipitation are smaller than corresponding values for areally-averaged 72-hour 10-mi^2 precipitation. These results suggest that reductions in skewness are to be expected, in addition to reductions in values of the mean and variance, as the size of the storm area increases. This is consistent with the meteorological interpretation that higher skewness of point (10-mi^2) precipitation of long-duration general storms is associated with more localized storm characteristics, whose effects are moderated over larger areas. These findings should be of interest to those who conduct rainfall-runoff modeling for large watersheds and who are often faced with decision-making about statistical storm characteristics based on limited data.

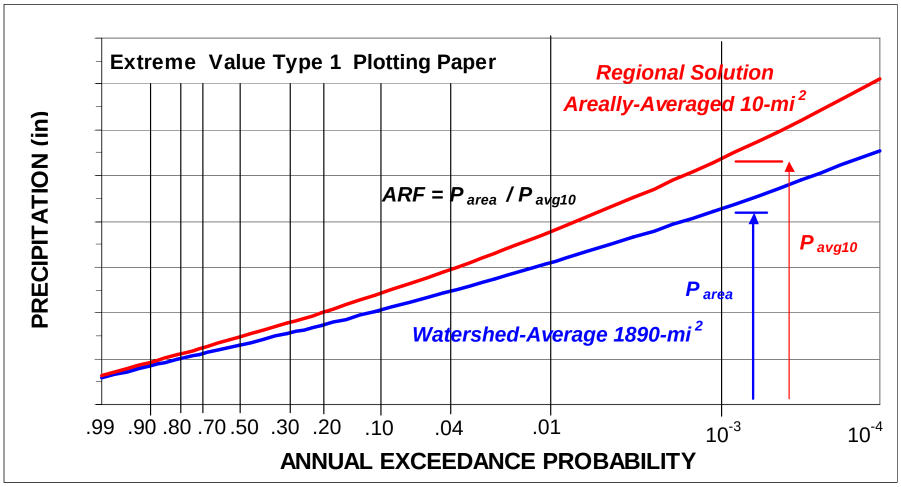

Figure 15a – Frequency-Based Definition of Areal Reduction Factor for Given Duration, Area Size and Annual Exceedance Probability

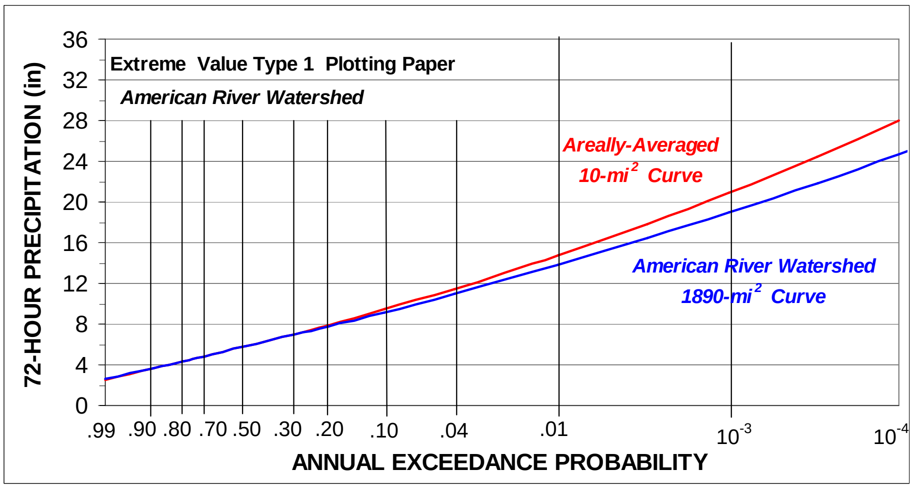

Figure 15b – Comparison of 72-Hour 10-mi^2 Precipitation-Frequency Relationship and 72-Hour 1860-mi^2 Precipitation-Frequency Relationship for American River Watershed

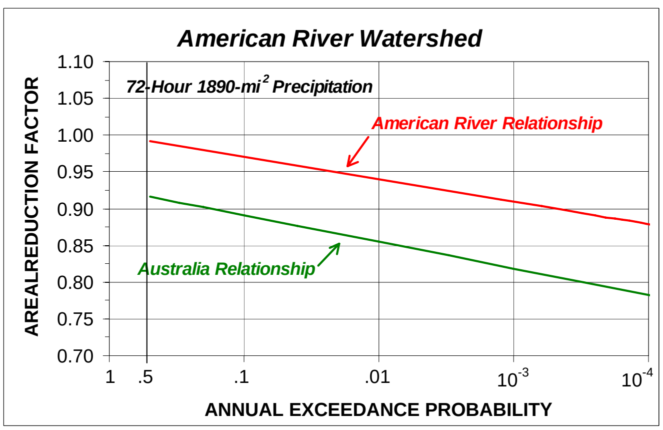

Figure 16 – Comparison of Relationship of Areal Reduction Factors with Annual Exceedance Probability for the American River Watershed and Australian[18] Relationship

Table 15a – Estimates of Population L-Moments for Areally Averaged 72-Hour 10-mi^2 Precipitation for American River Watershed

REGIONAL L-MOMENTS			
At-Site Mean	**L-Cv**	**L-Skewness**	**L-Kurtosis**
6.30-inches	0.2099	0.2142	0.1700

Table 15b – Distribution Parameters and Product-Moments for Kappa Distribution for Areally Averaged 72-Hour 10-mi^2 Precipitation for American River Watershed

DISTRIBUTION PARAMETERS			
Xi (ξ)	***Alpha (α)***	***Kappa (κ)***	***h***
6.7282	2.3173	-0.0702	-0.01
PRODUCT MOMENTS			
At-Site Mean	**Standard Deviation**	**Coefficient Skewness**	**Coefficient Kurtosis**
6.30-inches	2.53-inches	1.62	8.46

Table 16a – Estimates of Population L-Moments for Watershed-Average 72-Hour 1860-mi^2 Precipitation for American River Watershed

REGIONAL L-MOMENTS			
At-Site Mean	**L-Cv**	**L-Skewness**	**L-Kurtosis**
6.21-inches	0.1973	0.1992	0.1636

Table 16b – Distribution Parameters and Product-Moments for Kappa Distribution for Watershed-Average 72-Hour 1860-mi^2 Precipitation for American River Watershed

DISTRIBUTION PARAMETERS			
Xi (ξ)	***Alpha (α)***	***Kappa (κ)***	***h***
5.1643	1.6768	-0.0487	-0.0146
PRODUCT MOMENTS			
At-Site Mean	**Standard Deviation**	**Coefficient Skewness**	**Coefficient Kurtosis**
6.21-inches	2.31-inches	1.45	7.21

Table 17 – Areal Reduction Factors for 72-Hour 1860-mi^2 Precipitation for the American River Watershed

72-Hour 1860-mi^2	**ANNUAL EXCEEDANCE PROBABILITY**								
	10^{-1}	**4×10^{-2}**	**10^{-2}**	**3×10^{-3}**	**10^{-3}**	**3×10^{-4}**	**10^{-4}**	**3×10^{-5}**	**10^{-5}**
Areal Reduction Factor	0.965	0.952	0.934	0.918	0.905	0.890	0.876	0.862	0.848

SUMMARY
Five methods were used for examining the 72-hour 1860-mi^2 precipitation-frequency characteristics for the American River watershed. Three of the methods utilized site-specific data, and two methods utilized a combination of regional information and site-specific data. The Blue Canyon Index Station method was determined to be the most reliable approach and was selected for derivation of the 72-hour precipitation-frequency relationship. This method was chosen because it was a straightforward approach that incorporated both information on regional precipitation statistical characteristics and the findings of site-specific storm analyses. The adopted approach to derivation was conducted as the product of the 72-hour precipitation-frequency relationship for the Blue Canyon station and the correlation relationship between 72-hour precipitation at Blue Canyon with concurrent 72-hour precipitation for the 1860-mi^2 watershed. The derived 72-hour 1860-mi^2 precipitation-frequency curve provided estimates of 13.8-inches, 19.0-inches, and 25.0-inches for annual exceedance probabilities of 10^{-2}, 10^{-3} and 10^{-4}, respectively.

An uncertainty analysis was conducted to develop uncertainty bounds for 72-hour 1860-mi^2 watershed-average precipitation for selected annual exceedance probabilities. In conducting those analyses, it was learned that uncertainty in the estimation of the station mean value at Blue Canyon was the largest contributor to the total uncertainty for estimation of 72-hour 1860-mi^2 precipitation for storms near the 100-year return period. Uncertainty in identification of the underlying probability distribution of 72-hour point precipitation, and skewness of that distribution, were the greatest contributors to the total uncertainty as storm events became very rare.

Computation of areal reduction factors for 72-hour 1860-mi^2 precipitation revealed that areal reduction factors varied with the annual exceedance probability of the precipitation. Areal reduction factors were seen to decrease as 72-hour precipitation events became more rare. In addition, population estimates of the mean, variance and skewness of 72-hour 1860-mi^2 precipitation were found to be smaller than those for 72-hour areally averaged point precipitation. Thus, 72-hour precipitation for large areas has less variability and skewness than that of 72-hour point precipitation for sites in and near the American River watershed.

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