US Army Corps of Engineers
Hydrologic Engineering Center

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

Appendix B - Precipitation Magnitude-Frequency Characteristics for the American River Watershed

September 2005

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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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PRECIPITATION MAGNITUDE-FREQUENCY CHARACTERISTICS FOR THE AMERICAN RIVER WATERSHED

January 15, 2000

PREFACE

The subject of this summary report is the development of precipitation magnitude-frequency relationships for the American River watershed. However, it is not possible to conduct the analyses necessary for development of these relationships without first addressing issues of apparent non-stationarities in the climatic record over the past century in central California. Consideration of issues related to non-stationarity leads to the need for a methodology and strategy for developing precipitation magnitude-frequency relationships that are applicable to the future planning period. Those methodologies and strategies are presented in this report along with the findings of regional analyses for development of precipitation magnitude-frequency relationships.

This should be considered a working paper, subject to revision based on discussions with HEC staff, meteorologists, hydrologists and members of the recent NRC[17] committee on the American River. Undoubtedly, analyses presented here, interpretation of results from those analyses, and application of relevant experience will lead to refinements for selecting precipitation magnitude-frequency relationships that best characterize the current/future state of the climate system for generation of extreme storms.

Recognizing the uncertainties inherent in estimating precipitation magnitude-frequency relationships for the American River watershed, it is anticipated that several plausible candidate relationships will be used in the stochastic flood model to evaluate the effect on the resultant magnitude-frequency relationships for flood peak discharge, flood runoff volume, and maximum reservoir level. Thus, the precipitation magnitude-frequency relationships presented here are anticipated to be one of several relationships used in assessing flood likelihoods on the American River.

OVERVIEW

This summary report presents the findings of the regional analyses for precipitation magnitude-frequency relationships for the American River watershed for durations of 24-hours, 72-hours, and 10-days. The regional precipitation frequency analyses were complicated by the high variability exhibited in the precipitation time-series records for stations in the Sierra Mountains. In particular, the first half of the century was relatively benign with few noteworthy extreme storms. Conversely, the latter half of the century includes numerous extreme storm events and some clustering of extreme storms. This behavior has raised a number of issues related to stationarity of the precipitation record, and regime-like behavior of the climate. Many of these climatic issues were discussed in the National Research Council's report on *Improving American River Flood Frequency Analyses* (NRC[17]).

Ultimately, the goal of the regional frequency analyses is to obtain the best characterization possible of the precipitation magnitude-frequency relationship for the coming planning period – from the present time outward perhaps twenty to thirty years. However, uncertainties associated with non-stationarities and regime-like behavior of the climate pose problems in developing regional precipitation magnitude-frequency relationships applicable to the future planning period.

It became apparent at the start of the study that the results of the regional frequency analysis would be intertwined with the issues of non-stationarity. It would not be possible to establish a meaningful precipitation magnitude-frequency relationship without first analyzing/establishing the behavior of the precipitation time-series over the past century. The approach adopted was to examine precipitation annual maxima records from the American River study area for non-stationarities and included analyses/tests for serial independence, and stationarity of the mean, variance and skewness. These findings were then compared to the findings of other large regional studies on the west coast that are similarly subjected to winter storms originating over the Pacific Ocean. This latter comparison provided a context for interpretation of the results for the American River watershed.

These findings were then used to develop a strategy for selecting a representative period of the precipitation record for conducting the regional frequency analyses. The precipitation magnitude-frequency relationships presented here are believed to provide a reasonable characterization of the current state of the climate suitable for generation of precipitation annual maxima over the next planning period.

PRECIPITATION STUDY AREA

One of the underlying precepts in conducting regional analyses is to trade space for time. That is, to compensate for short record lengths (sampling over time) by incorporating records from distant but climatologically similar stations (sampling in space). The amount of information added in this manner is dependent upon the homogeneity of the data and degree of statistical independence of the additional data. In applying this approach to the American River watershed, the goal is to utilize as large a study area/precipitation network as possible, consistent with similarity of the climatology, precipitation producing processes, and physical setting of the American River watershed.

The American River watershed is located on the west face of the Sierra Mountains at/near latitude 39°00′N. The study area (Figures 1,2) was selected as the west face of the Sierra Mountains and areas immediately adjacent to the Sierra Mountains between latitude 36°30′N and 41°00′N. Three geographic/climatic regions were identified for grouping of stations for analysis (Table 1).

Table 1 – Geographic/Climatic Regions of American River Study Area

REGION NUMBER	CLIMATIC REGION
1	Non-orographic lowlands of the Sacramento and San Joaquin Valleys
3	Orographic areas on the west face of the Sierra Mountains
5	Mountain areas east of the ridgeline of mean annual precipitation in the Sierra Mountains and eastward to the isopluvial line of 20 inches of mean annual precipitation

These regions were identified based on prior studies of precipitation frequency (Miller[15]), studies of extreme precipitation (NWS[18]), prior regional frequency analyses conducted in coastal mountain areas (Schaefer[21,22,23]), and the spatial characteristics of mean annual precipitation. The map of mean annual precipitation (Figure 2) developed by Daly[3] using the PRISM[3] model provided the basic mapping information for delineating the boundaries of the climatic regions. This map is based on the 1961-1990 time period, which is the most recent NOAA 30-year decadal based climate tracking period. The magnitude and gradient of mean annual precipitation were the primary measures used to define the boundaries between the three regions. More detailed information on climatic region delineation is contained in the section on *Regional Frequency Analysis Methodology*.

Figure 1 – Map of American River Study Area

ANNUAL MAXIMA DATA

Annual maxima data were collected from NCDC and California Department of Water Resources electronic files using a climatic-year basis (October through September). Annual maxima data series were assembled from precipitation measurement stations for the 24-hour, 72-hour, and 10-day durations. This totaled 190 stations (215 gages), and approximately 9,600 station-years of record for each duration. It also included 11 stations with records that began near the turn-of-the-century. This database was reduced by removing stations that were either co-located (both daily and hourly gages at same site) or redundant stations located very near other stations.

Table 2 lists the number of stations and station-years of record for each of the three geographic/climatic regions for the 72-hour duration. Table 3 lists the number of stations in operation in each region during the various time periods. Similar numbers of stations and station-years of record are applicable to the 24-hour and 10-day durations.

Table 2 – Precipitation Station Information for American River Study Area

CLIMATIC REGIONS	REGION NUMBER	NUMBER OF STATIONS	STATION-YEARS OF RECORD
Non-Orographic Lowlands	1	36	1682
West Face of Sierra Mountains	3	96	4254
Mountain Areas East of Ridgeline of MAP	5	34	1495

Table 3 – Stations Operating During Various Time Periods

PERIOD	NUMBER OF STATIONS			
	REGION 1	REGION 3	REGION 5	ALL REGIONS
1890 – 1899	2	1	0	3
1900 – 1909	4	6	1	11
1910 – 1919	4	11	1	16
1920 – 1929	4	18	1	23
1930 – 1939	7	18	4	29
1940 – 1949	8	18	4	30
1950 – 1959	31	72	27	140
1960 – 1969	34	78	32	144
1970 – 1979	33	77	32	142
1980 – 1989	25	66	31	122
1990 – 1998	22	63	28	113

Extensive efforts were made in screening and quality checking the annual maxima data. Quality checking was needed to eliminate false annual maxima associated with a variety of data measurement, reporting, and transcription errors, particularly incomplete reporting during some years. This was accomplished by checking completeness of the record during each climatic-year and scanning records to locate anomalously small or large precipitation amounts. A measure of discordancy (Hosking and Wallis[9,10]) was also used to identify gages whose sample statistics were markedly different from the majority of gages in a given region. Suspicious gages and data were checked to verify the validity of records. Nearby sites were also checked to corroborate the magnitude and date of occurrence of any anomalously small or large precipitation annual maxima.

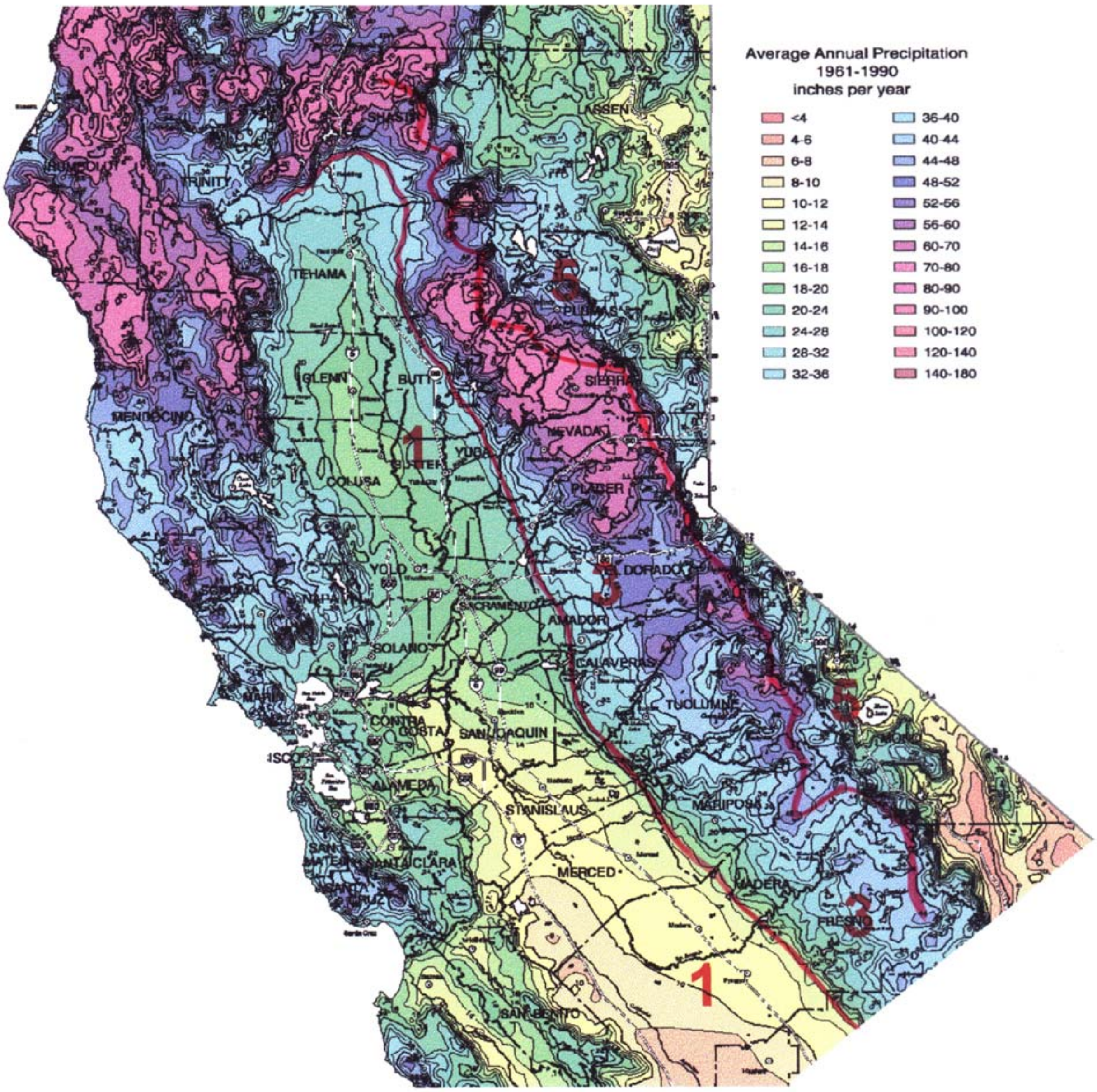


Figure 2 – Map of Mean Annual Precipitation for American River Study Area (Daly, PRISM[3])

Tests for Independence of Annual Maxima Data for Stations in Study Area

Tests for independence of annual maxima data were conducted for stations in each region for each of the three durations. Serial correlation coefficients were computed for all stations in each region for each duration. The collection of serial correlation coefficients for each region was found not to be significantly different from zero for all three durations at the 95% level of significance (Table 4). Thus, the null hypothesis of independence could not be rejected.

If statistically significant values of serial correlation were to be found, one would anticipate positive values consistent with climatic persistence. It is interesting to note that to the contrary, low levels of negative serial correlation were found (Table 4).

Table 4 – Tests for Independence of Annual Maxima Data

REGION	DURATION	# TESTS	# REJECTIONS INDEPENDENCE	AVERAGE SERIAL CORRELATION COEFFICIENT
1	24-hour	36	1	-0.010
1	72-hour	36	1	-0.059
1	10-day	37	1	-0.124
3	24-hour	99	7	-0.099
3	72-hour	98	7	-0.143
3	10-day	100	8	-0.165
5	24-hour	37	0	-0.095
5	72-hour	36	0	-0.098
5	10-day	36	1	-0.138

Tests for Stationarity of Station At-Site Means in Study Area

Standard regression analyses for trends were used to test for stationarity of at-site means. Tests were conducted for stations in each region at all three durations. The tests were conducted by subtracting 1900 from the year of occurrence to have the origin for the abscissa correspond to the year 1900. This allowed the results from all stations to be viewed collectively for trend. The slopes of the regression lines were found not to be significantly different from zero for the collection of stations in each region for all three durations. Thus, the null hypothesis of stationarity of the mean could not be rejected. This is a relatively simple measure of trend over the length of the record. Other measures of trend/stationarity of the mean will be examined later.

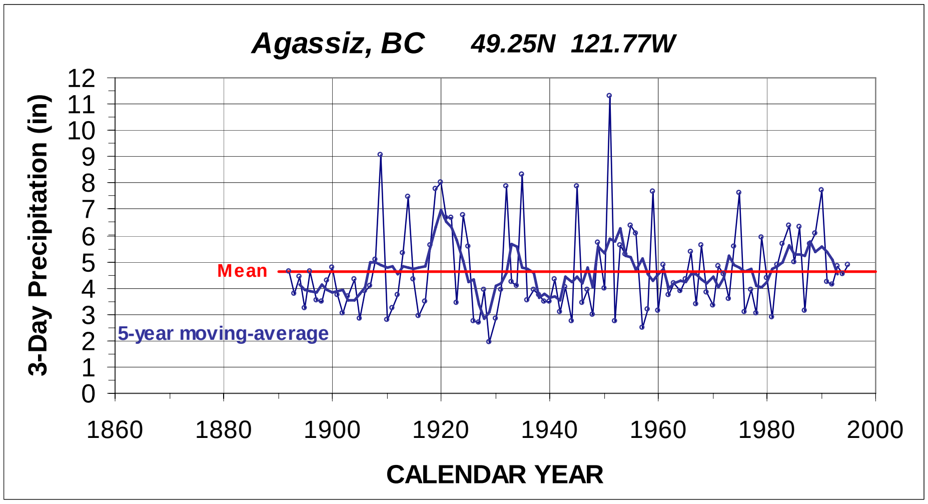
STATIONARITY: EXAMINATION OF LONG TIME-SERIES RECORDS

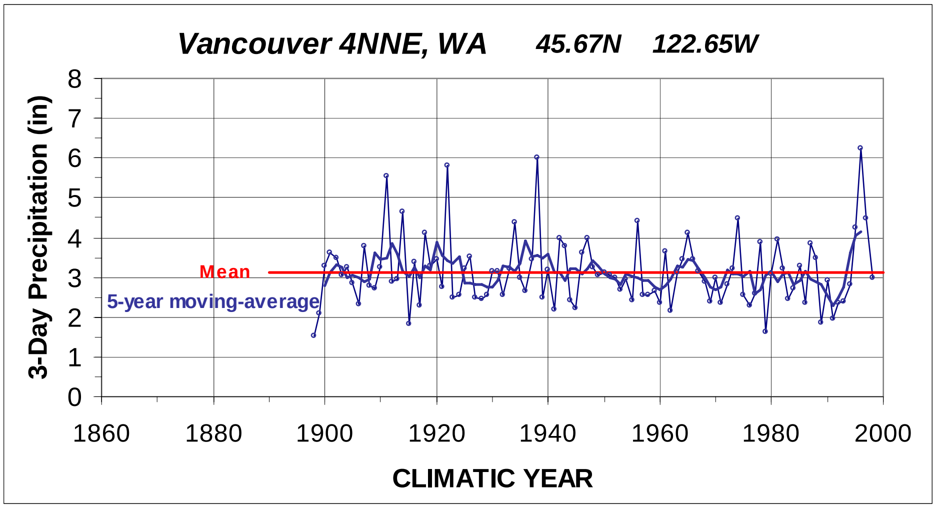
In attempting to answer questions about stationarity of the precipitation record, time-series of 72-hour annual maxima were assembled for 12 stations along the West Coast of North America with long 80-year to 110-year records. This allowed comparisons to be made of the behavior of precipitation annual maxima time-series that reflect winter storms originating over the Pacific Ocean. Stations with long records beginning near the turn-of-the-century were selected from as far north as 50.5°N and as far south as 38.0°N. Figures 3a-3e depict representative time-series along the West Coast. Additional time-series at long-term stations are contained in Appendix A.

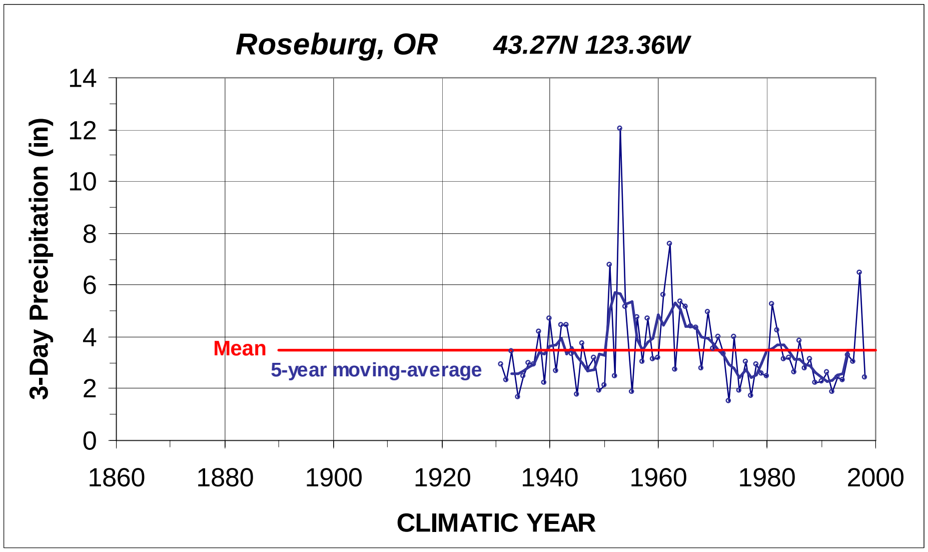
Of particular interest with regard to the American River watershed, is the contrast between the benign period of few extreme storms in the first half of the century and the active period with many extreme storms in the latter half of the century. This behavior is clearly seen in the time-series at Nevada City (Figure 3d) and the areally averaged 72-hour time-series developed for the American River watershed by the NRC[17]. These are consistent with other time-series from stations within/near the American River watershed. Review of the time-series at Sacramento (Figure 3e) indicates that several extreme storms also occurred near the end of the 19th century. Anecdotal information described in the NRC report[17] corroborates this storm activity in discussion of a number of notable floods in the late 1800's. Thus, the benign period of low extreme storm activity in the first half of the century was bracketed by more active periods of extreme storm activity.

A review of the time-series in Figures 3a-3e and in Appendix A shows high year-to-year variability, and the presence of runs of low magnitude events with low variance, as well as some clusters of large events in some of the time-series. This behavior is similar to that seen at stations within/near the American River watershed. Serial correlation coefficients were computed for all 12 time-series. Eleven of the twelve time-series were found to have serial correlation coefficients that were not significantly different than zero at the 95% level of significance. The null hypothesis of independence was rejected at one station where it had a negative value of serial correlation. Standard regression tests for trend were also conducted for each of the 12 time-series. For all 12 time-series, the null hypothesis of stationarity of the mean could not be rejected at the 95% level of significance. Based on these results, one could conclude that the long-term time-series could be reasonably modeled by an independent stationary process.

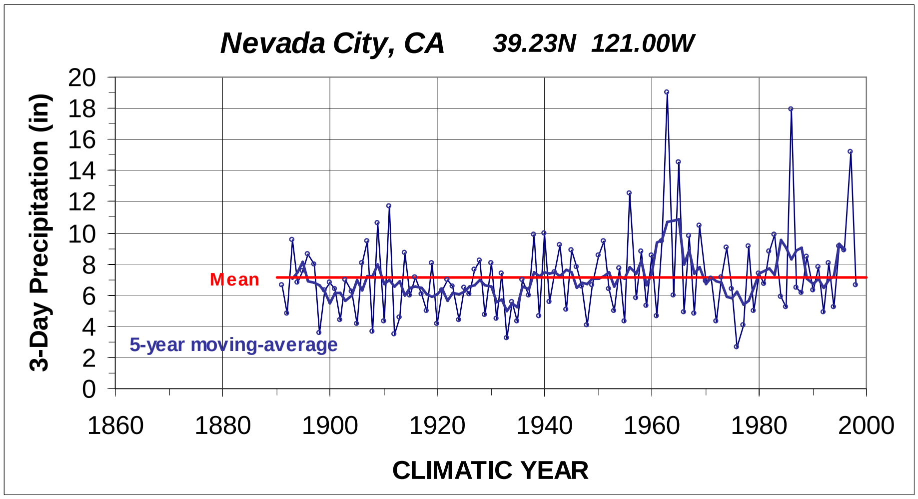
To further examine the behavior exhibited in the long-term time-series, a simple independent stochastic model was developed. This allowed comparisons to be made between the behavior observed in the historical time-series and the type of outputs that could be expected from a purely independent stochastic process of annual maxima. Stochastic simulations of independent time-series were conducted using observed long-term values for the mean, variance, and skewness from the Nevada City station. Simulation realizations for 120-year periods were often found with periods of low variability, and some clustering of extreme events (Figure 3g) similar to that seen at stations in the American River watershed. Thus, an independent stationary process is capable of producing behavior similar to that seen in the annual maxima data for the American River watershed.

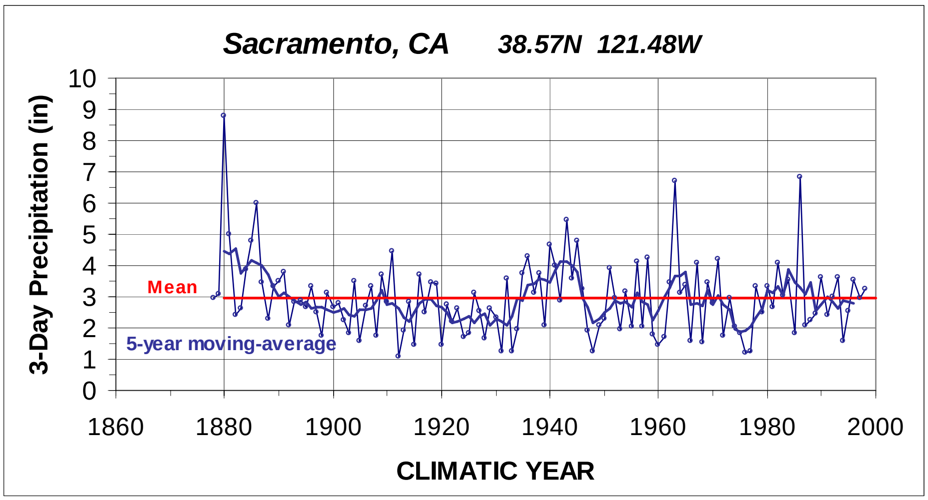






Figures 3a,b,c - 72-Hour Annual Maxima Time-Series at Selected Stations along West Coast





Figures 3d,e - 72-Hour Annual Maxima Time-Series at Selected Stations along West Coast

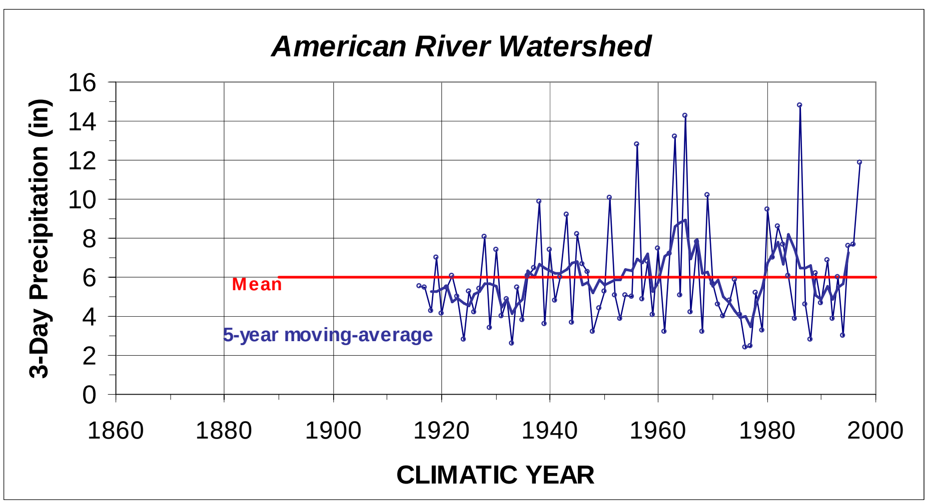


Figure 3f – NRC[17] Estimated Basin-Average 72-Hour Annual Maxima Time-Series for American River Watershed

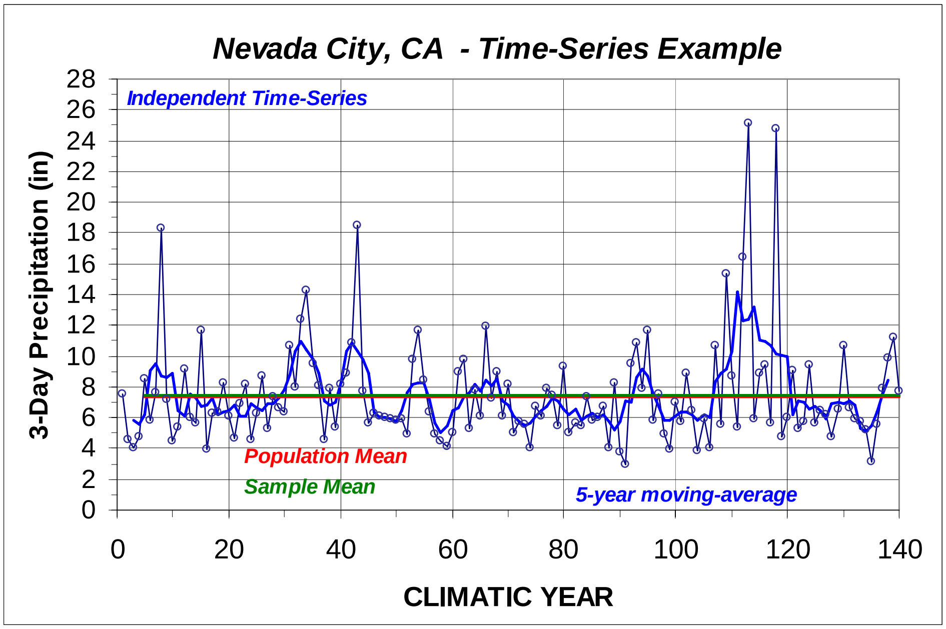


Figure 3g – Computer Simulated Independent Stationary 72-Hour Annual Maxima Time-Series Generated Using Statistics from Nevada City, CA Station

STATIONARITY: COMPARISON OF EXTREME STORM ACTIVITY FOR STORMS HAVING WIDE-SPREAD AREAL COVERAGE

The analysis described above utilizes some of the more basic tools for examining stationarity. Additional insights were obtained by comparison of extreme storm activity in coastal/mountain areas in southern British Columbia and the Sierra Mountains in central California. Specifically, the focus was on the occurrence of extreme events with wide-spread areal coverage. Extreme storms were defined as events where the 72-hour storm amounts for a given storm date exceeded a ten-year event at 10% or more of the gages in the gaging network. Figures 4a, 4b depict the chronology of extreme storm events. For central California, the pattern (Figure 4a) shows the low period of activity from 1916 through 1936 and the more active period at the end-of-the-century. In contrast, extreme storm activity for southern British Columbia and northern Washington State (47°30′N to 52°30′N) appears more uniformly distributed in time (Figure 4b).

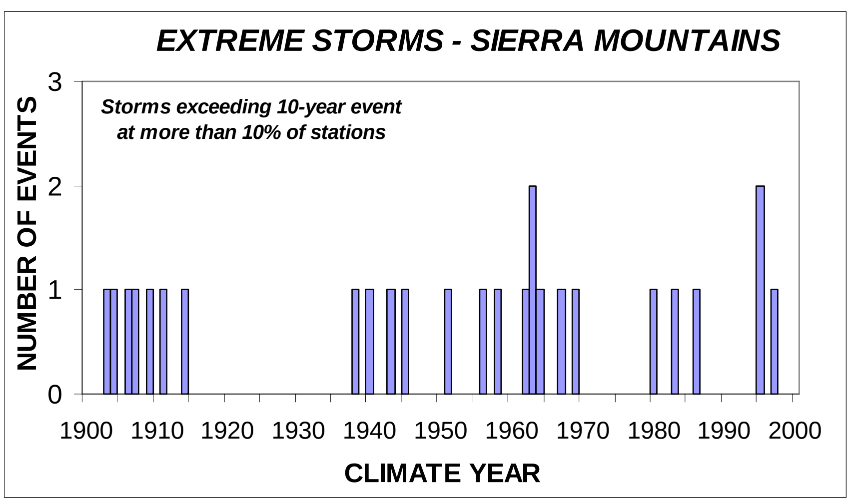


Figure 4a – Occurrence of Extreme Storms in/near the Sierra Mountains

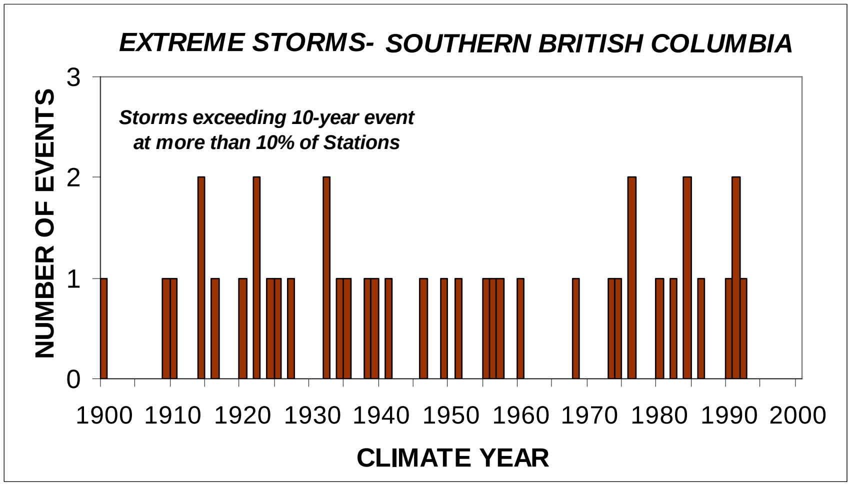


Figure 4b – Occurrence of Extreme Storms in Coastal/Mountain Areas in Southern British Columbia and Northern Washington State

There are three sequences of particular interest that raise questions about non-stationarity in the central California study area. The sequences include: the benign period of no extreme storms from 1916 through 1936; the period from 1963-1965 where 4 extreme events occurred in a three-year period; and the period from 1956-1965 where 3 of the 4 largest basin-average events occurred (Figure 3f). The likelihood of these sequences can be assessed using combinatorial methods for independent events.

1916-1936 Benign Period

If the period from 1937 through 1998 is taken as reasonably representative of long-term storm activity (Figure 4a), the probability of observing a 21-year run of no extreme events in a 100-year period is about 0.006. Use of the full record from 1900 to 1998 for setting the event probabilities, results in a probability of about 0.015 for a 21-year run of no extreme events during the 100-year span of the time-series. Thus, the 21-year run of no extreme events for the entire region would be an unlikely outcome from an independent stationary process. This sequence is suggestive of regime-like behavior rather than a stationary process. To further place the 1916-1936 period in context, tree ring analyses by Earle[29] indicate the 1917-1950 period was the driest in the last 440-year reconstructed tree-ring record in California (NRC[17]). These two pieces of information are suggestive that the anomalous portion of the precipitation time-series for storm activity for central California is not the more active portion in the latter half of the century, but rather the 20 plus year period of low variability in the early portion of the 20th century.

Four Extreme Storms in Three-Year Period (1963-1965)

If the period from 1937 through 1998 is taken as reasonably representative of long-term storm activity, the probability of 4 extreme events occurring in a 3-year period during a 100-year span is about 0.20. Use of the full record from 1900 to 1998 for setting the event probabilities, results in a probability of about 0.11 for 4 extreme events occurring in a 3-year period during the 100-year span. Thus, the flurry of extreme storms from 1963-1965 is not outside the plausible range of behavior for an independent stationary process.

Three of Four Largest Extreme Storms in Ten-Year Period (1956-1965)
The probability of 3 of the 4 largest storm events occurring in the same 10-year period out of the 100-year span is approximately 0.025. Thus, the occurrence of 3 of the 4 largest storm events in the same 10-year span is an unlikely outcome from a stationary process. This sequence is also suggestive of regime-like behavior rather than a stationary process.

In reviewing Figures 4a and 4b, it is seen that the two histograms are inversely related. Periods of frequent storm activity in one region correspond to infrequent storm activity in the other region. This type of inverse behavior has also been seen in the El Nino and La Nina cycles for the Pacific Northwest and southern California areas (NRC[17], Kahya[28]). If southern California is experiencing frequent storms during an El Nino cycle, the Pacific Northwest is likely experiencing a milder than average winter with fewer significant storms. The reverse is often true during La Nina years.

Combining the two histograms (Figure 4c) shows storm activity originating from the Pacific Ocean to be reasonably uniform over the 20th century. This is suggestive that the apparent non-stationarity seen in the central California time-series is not due to the frequency of generation of extreme storms over the Pacific Ocean. Rather, it appears to be due to the synoptic-scale mechanisms that steer storms toward either the Pacific Northwest or to northern and central California. The greater variability of occurrence of extreme storms seen in central California (Figure 4a) may be a logical expression of the fact that central California is on the southerly end of the range of storm tracks for winter storms originating from the Pacific Ocean. As such, it is subjected to greater variability than an area/region more centrally located within the north-south range of storm tracks along the West Coast of North America.

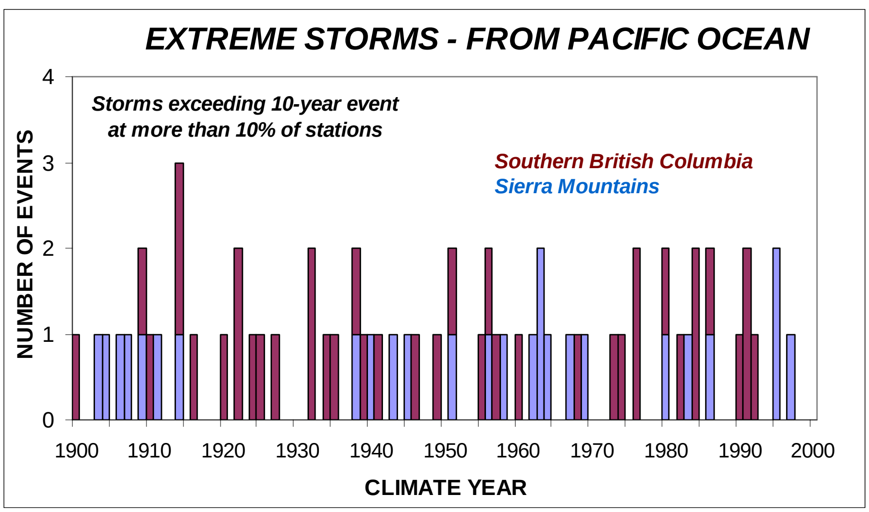


Figure 4c – Occurrence of Extreme Storms Originating from Pacific Ocean with Storm Tracks into Southern British Columbia, Northern Washington, and Central California

STATIONARITY: LONG-TERM MULTI-STATION INDEX

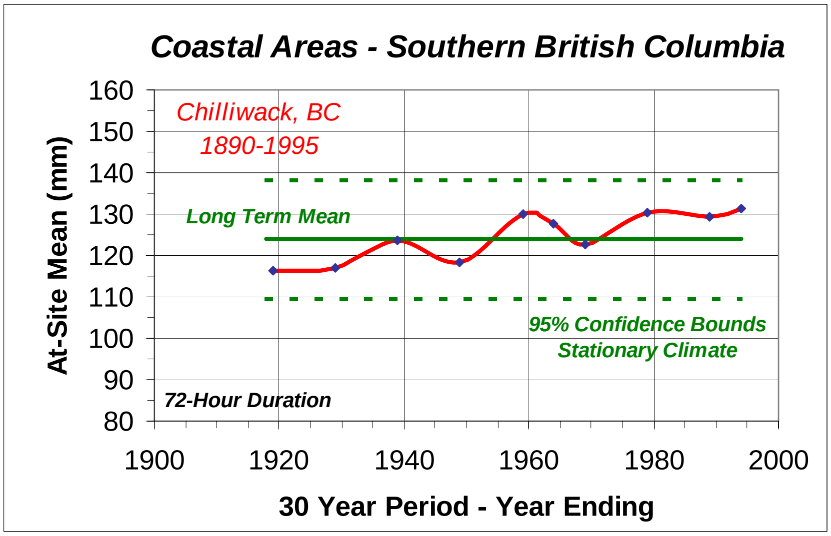
A second set of analyses was conducted to examine stationarity characteristics using groupings of stations with long records dating to the turn-of-the-century. One grouping of 9-stations was assembled for the Sierra Mountains within/near the American River watershed (Table 5). A second group of 11-stations was assembled for coastal/mountain areas in southern British Columbia and Washington State. Regional analyses were conducted of the multi-station groupings to examine stationarity of the mean, variance, and skewness over the past century and to allow comparisons of the two regions.

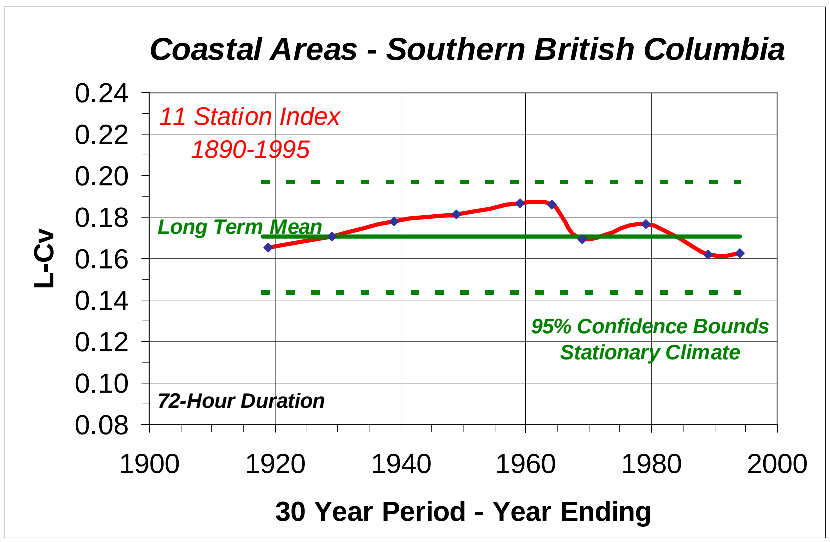
Specifically, regional frequency analysis methods (Hosking and Wallis[6,9,10]) were used to compute dimensionless measures of variance (L-Cv) and skewness (L-Skewness) for 30-year periods over the past century. Moving averages for 30-year periods were also used to examine variability of at-site means for selected stations in the multi-station groupings. These results were then compared to long-term averages to depict the variability of the 72-hour annual maxima data over the past century (Figures 5a-5c and Figures 6a-6c). Confidence bounds are also depicted for multi-station samplings of 30-year datasets. They were developed by Monte Carlo methods assuming a stationary process over the 100-year period and accounting for the inter-station dependence (Schaefer[21,23]), between the multi-station groupings (Appendix A).

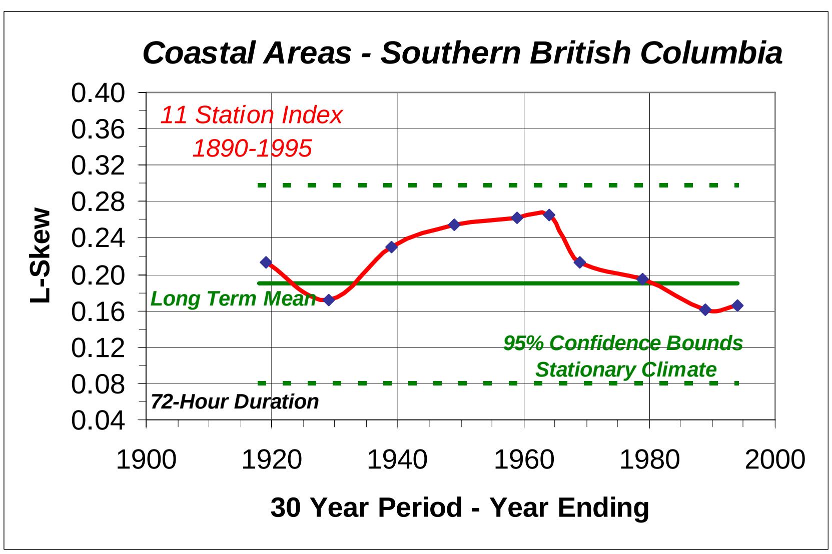
Values of the at-site mean for 30-year periods for the 72-hour duration for stations within the 11-station group in southern British Columbia (Figure 5a) were found to be within the 95% confidence bounds based on the computed long-term means. The regional values of L-Cv (Figure 5b) and L-Skewness (Figure 5c) for the 11-station group were also found to be well within the 95% confidence bounds and exhibited less variability than that of the 9-station group in central California. All analyses and evidence indicates the 72-hour annual maxima data for the coastal mountains of the southern British Columbia study area can be treated as arising from an independent stationary process.

In contrast, some measures of stationarity for the 9-station index in central California exhibited variability at the 24-hour, 72-hour, or 10-day durations beyond what would be expected for a stationary process. Figures 6a-6c depict examples of 30-year moving averages of at-site means for the three durations. It is seen that some 30-year averages approach the 95% confidence bounds for a stationary process. The regional values of L-Cv (Figure 7a-7c) and L-Skewness (Figures 8a-8c) for the 9-station index were also found to be more variable over the century and approached or exceeded the 95% confidence bounds for several 30-year periods. These results are consistent with the variability exhibited in the long-term time-series (Figures 3d-e, Appendix A) and are consistent with the variability seen in Figure 4a for the frequency of extreme storms with wide-spread areal coverage.

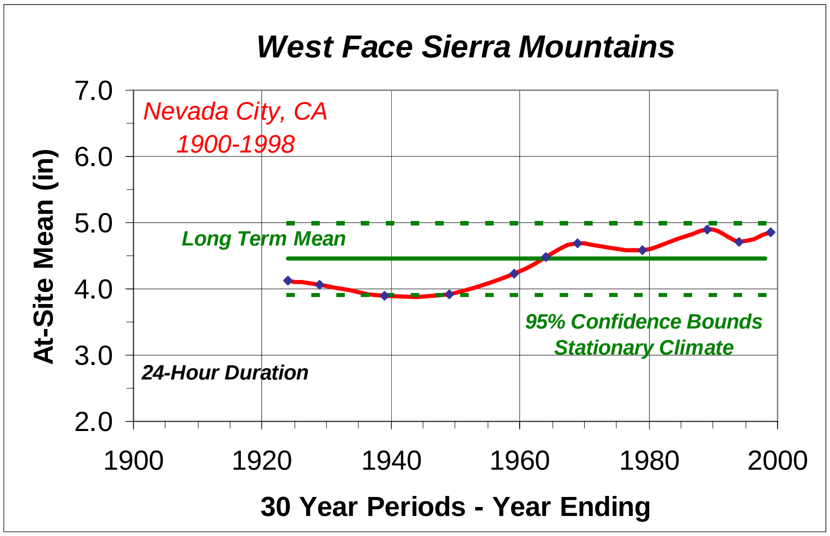
A review of the results from the multi-station analyses of stationarity indicate the 1916-1936 time period of low storm activity contains the greatest departures from long-term averages and provides the strongest evidence of non-stationarity.

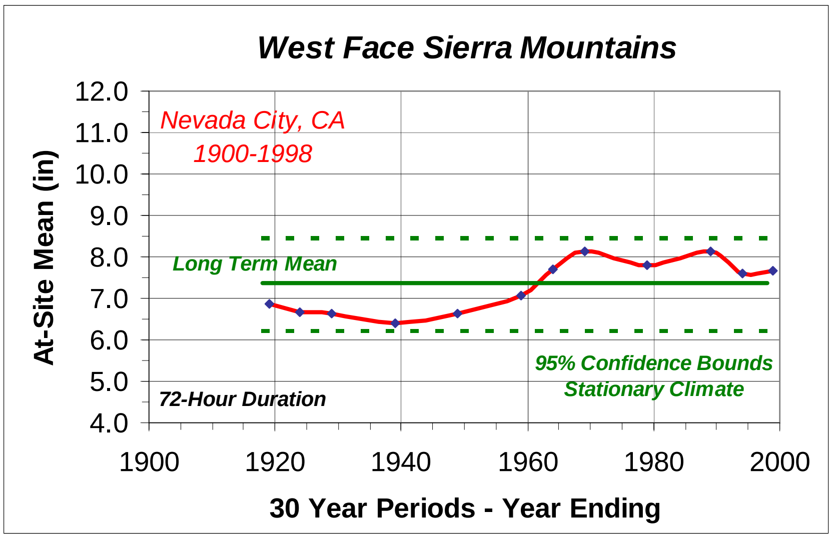


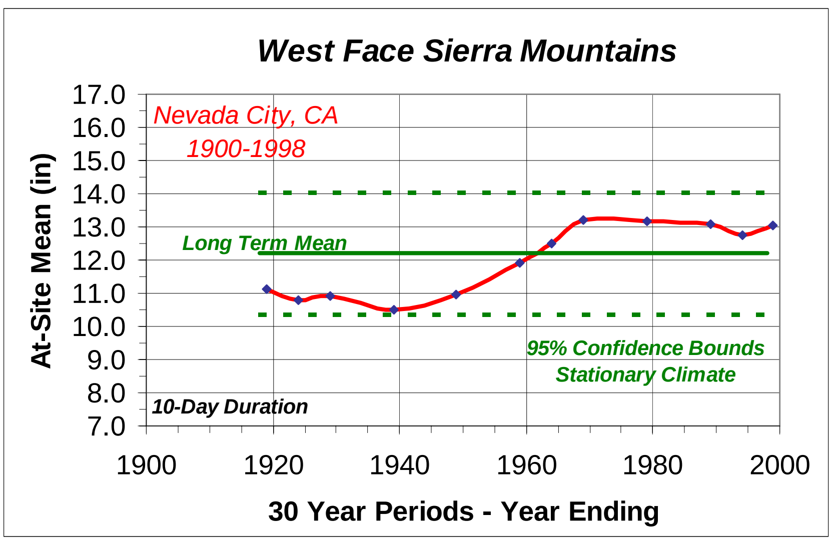




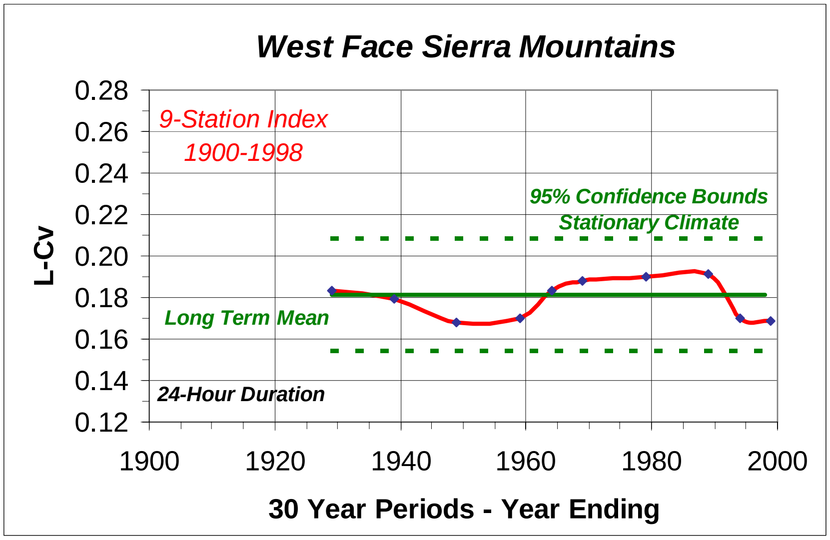
Figures 5a,b,c - Regional Measures of Mean, Variance and Skewness for 72-Hour Annual Maxima for 11-Station Index in Coastal/Mountain Areas of Southern British Columbia

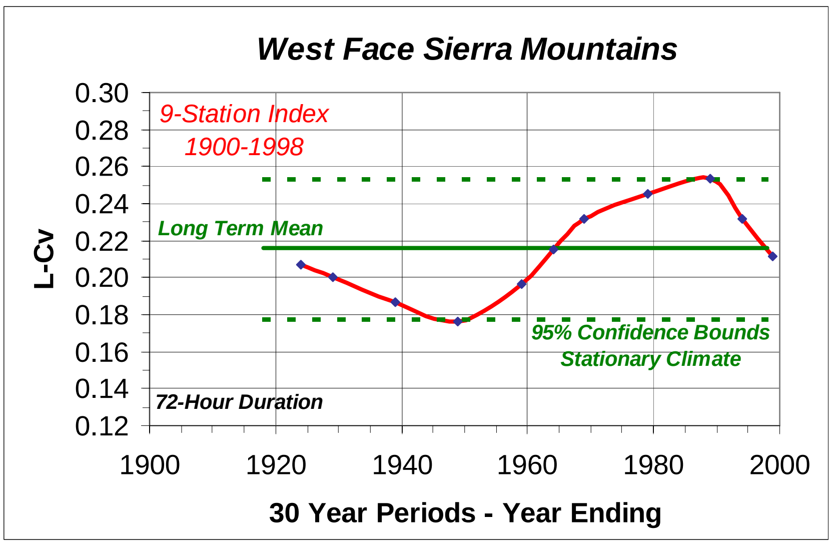


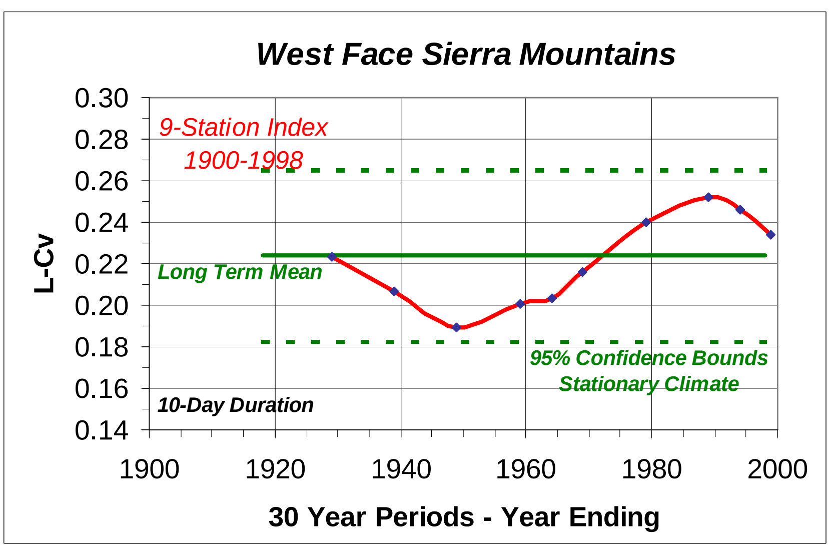




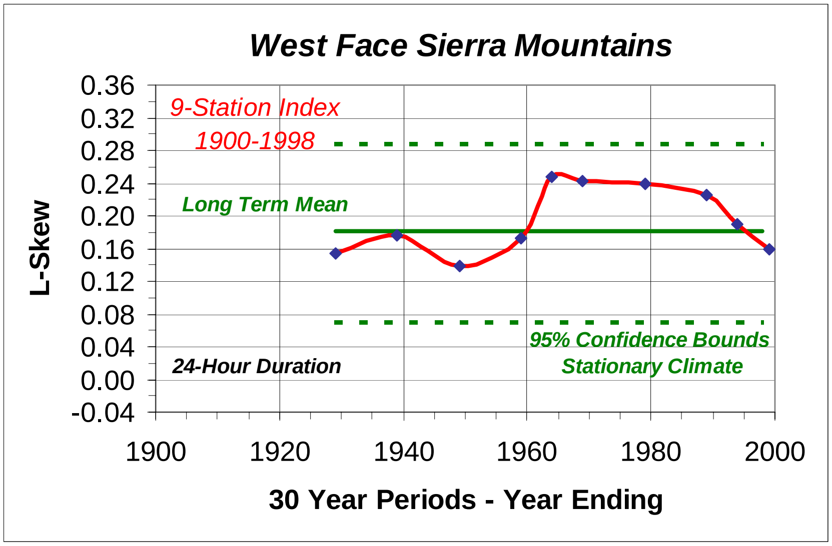
Figures 6a,b,c - 30-Year Moving Averages for the At-Site Mean at the Nevada City Precipitation Measurement Station

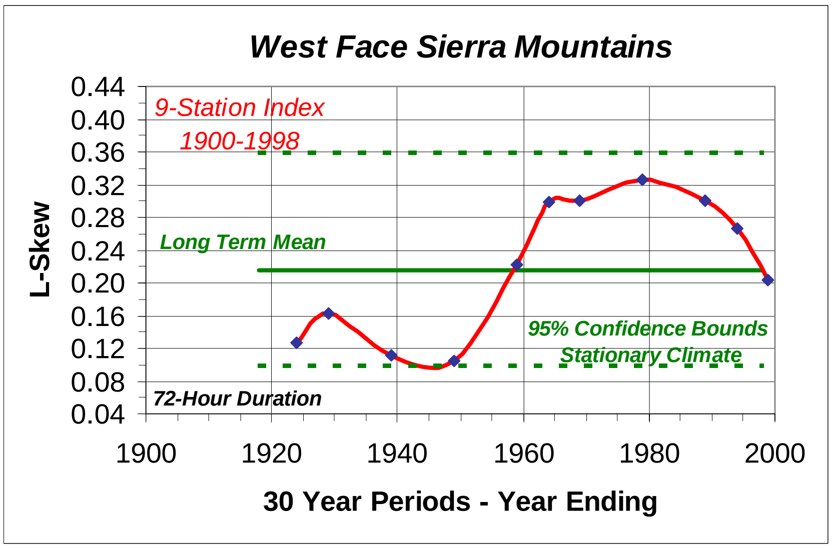


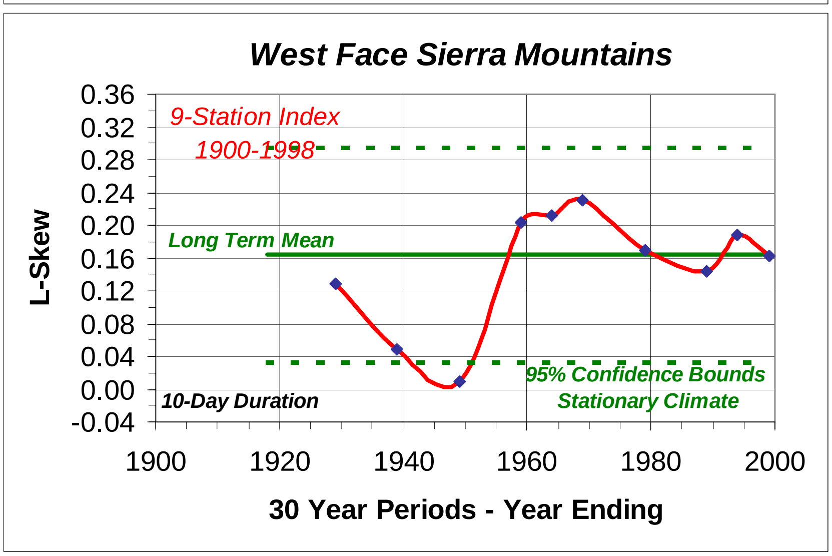




Figures 7a,b,c - Regional Measures of Variance for 9-Station Index in Sierra Mountains near American River Watershed







Figures 8a,b,c - Regional Measures of Skewness for 9-Station Index in Sierra Mountains near American River Watershed

Table 5 – Stations Included in Long-Term 9-Station Index
for the American River Watershed

ID	STATION	GAGE	LATITUDE	LONGITUDE	ELEVATION (Feet)	MAP[3] (in)	YEAR START	YEAR END
04-0383	AUBURN	Daily	38.9000	121.0833	1292	35.0	1898	1998
04-1462	CAMPTONVILLE RS	Daily	39.4500	121.0500	2755	65.0	1908	1998
04-1912	COLFAX	Daily	39.1167	120.9500	2400	46.0	1898	1998
04-2500	DOWNIEVILLE	Daily	39.5667	120.8333	2914	55.0	1909	1998
04-4713	LAKE SPAULDING	Daily	39.3167	120.6333	5155	69.0	1898	1998
04-6136	NEVADA CITY	Daily	39.2333	121.0000	2781	56.0	1891	1998
04-6960	PLACERVILLE	Daily	38.6833	120.8167	1850	38.0	1898	1998
04-8332	SODA SPRINGS 1 E	Daily	39.3167	120.3667	6883	63.0	1898	1998
04-9105	TWIN LAKES	Daily	38.7000	120.0333	8000	48.0	1920	1998

In reviewing the results of the analyses conducted herein, it suggests the annual maxima data for the west face of the Sierra Mountains are independent but display some non-stationarities and regime-like behavior. It is difficult to be more specific or quantitative about the non-stationarities because of the high natural variability in the annual maxima data. Dramatic shifts are needed to provide compelling evidence that the shifts/changes are outside of what could be expected by chance alone.

It is important to note that the values of L-Cv and L-Skewness for the most-recent 30-year period are very near the century-long averages at all three durations. This happenstance is favorable for selecting strategies for choosing representative values of L-Cv and L-Skewness for stochastic simulation of extreme storms/floods. This consideration is discussed further in the following section.

STRATEGY FOR DEVELOPING PRECIPITATION MAGNITUDE-FREQUENCY RELATIONSHIPS

The goal of the regional analyses is to obtain the best characterization possible of the precipitation magnitude-frequency relationship for the coming planning period – from the present time outward perhaps twenty to thirty years. However, uncertainties associated with non-stationarities and regime-like behavior of the climate pose problems in developing regional precipitation magnitude-frequency relationships applicable to the future planning period. In attempting to obtain the best characterization of the climate state for this future period, the NRC[17] committee stated the problem well, " *…. it is unclear whether the full record, the first half or last half of the record, or some other suitably selected portion is most useful for future decisions without a better understanding and prediction of the climatic regimes* ". However, at the present time, there are no credible approaches for prediction of the climate state for occurrence of annual maxima over the future planning period. Thus, one is left with using the past record, or portion thereof, for characterizing the future planning period.

There are several logical choices of a strategy for selecting a representative period for conducting regional analyses for precipitation annual maxima (Table 6). In concept, each of the strategies has advantages and disadvantages, primarily based on the bias-variance tradeoff problem referred to in the NRC[17] report. Specifically, bias can likely be reduced by selecting the most recent time period for analysis. The premise being that the near future is most likely to be similar to the recent past. However, use of the short near-term record increases the sampling variance and uncertainties about the true values of the parameters being estimated. Conversely, use of long-term records may introduce bias by including time periods which are not representative of the present/future climate state. However, use of the longer record length will reduce the variance and uncertainties about the true values of the parameters being estimated.

Table 6 – Possible Strategies for Selection of a Representative Period for Regional Frequency Analyses of Precipitation Annual Maxima

OPTION	STRATEGY FOR SELECTING SAMPLE PERIOD OF RECORD	ADVANTAGES	DISADVANTAGES
1	Use most recent n-year record	Reflects current climate state	High sampling variance due to short record length
2	Use full record length	Reduces sampling variance due to longer record length	Long-term may not reflect current climatic state
3	Use portion of record believed to be most representative of future state	Reflects future climatic state	Little or no ability to define representative period
4	Use portion of record believed to be most representative of long-term averages	Reflects long-term averages	Limited ability to define representative period

If the process is stationary, or nearly so, and the sample is reasonably representative, then use of the entire record (Option 2) is the best choice for reducing both bias and sampling variance. If however, the process is non-stationary, and there is little or no ability to predict the near-term future climatic conditions, then the problem of selecting a representative period for analysis is much more difficult. Options 1, 3, and 4, or combinations/variations, would be more applicable to the latter situation.

The following list summarizes the findings and conclusions of analyses conducted to date. All things considered, the latter case of non-stationarity is the more-likely situation for the American River watershed in the Sierra Mountains of central California.

- The February 1986 storm is the largest 3-day basin-average storm event since the turn-of-the-century and likely the largest since 1862.

- The 1976-1977 drought produced the smallest annual maxima in the data series at 55 of the 92 stations in the Sierra Mountains portion of the study area that were operating during the drought.

- There is no evidence of year-to-year persistence for annual maxima data as indicated by the lack of serial correlation for the collection of 170 stations in the study area.

- The 1916-1936 period of low-variability is outside the range of expected behavior for an independent stationary process based on based on the frequency of occurrence of extreme storms over the past century. It is not deemed representative of what would be expected in a typical record length of 100-years and is suggestive of regime-like behavior. Tree ring analyses by Earle[29] provide evidence that the 1917-1950 period was the driest in the last 440-year reconstructed tree ring record in California (NRC[17]). These two pieces of information are suggestive that the greatest departure from long-term averages for multi-day precipitation annual maxima in central California is not the more active period in the latter half of the century, but rather the 20 plus year period of low variability in the early portion of the 20th century.

- The clustering of 4 extreme events with wide-spread areal coverage in a 3-year span (1963-1965) is within the plausible range of behavior for an independent stationary process based on the frequency of occurrence of extreme storms over the past century.

- The clustering of 3 of the 4 largest storms occurring in a 10-year span (1956-1965) is very unlikely for an independent stationary process. This sequence is suggestive of regime-like behavior.

- The frequency of generation of extreme storms over the Pacific Ocean appears to be reasonably uniform over the past 100-years. The high variability seen in time-series in the Sierra Mountains in central California appears to be due to the variability induced by the synoptic-scale mechanisms that steer storms to various locations along the West Coast of North America.

- Regional values of L-Cv and L-Skewness for 30-year periods for the 9-station index, approach or exceed the 95% confidence bounds for an independent stationary process based on the 1900-1998 record. This is contributing evidence that the process is non-stationary. Alternatively, we have had the misfortune of experiencing two unrepresentative periods in the available record. The benign period from 1916-1936 having low variance, and the active period from 1956-1965 having high variance and skewness with 3 of the 4 largest basin-average storm events occurring in a 10-year period.

- Regional values of L-Cv and L-Skewness for the 9-Station index from the most recent 30-year period are very near to century-long values. This indicates that use of either the near-term record or the long-term record, would yield similar results from a regional frequency analysis.

RECOMMENDED APPROACH FOR SELECTING REPRESENTATIVE TIME PERIOD FOR DEVELOPING PRECIPITATION MAGNITUDE-FREQUENCY RELATIONSHIPS

A review of the findings and conclusions presented above, indicates there is substantial evidence of a non-stationary process and regime-like behavior. Given the likelihood of an independent non-stationary process, the following approach was adopted for developing precipitation magnitude-frequency relationships applicable to the future planning period. It represents a combination of Options 1 and 4 (Table 6) and recognizes that long-term values of L-Cv and L-Skewness are very similar in magnitude to values for the most recent period of the record (Figures 7a,b,c and 8a,b,c).

Adopted Methodology

1. Compute at-site mean values and regional values of L-Cv based on the most recent record. The record from 1966-1998 will be used to reflect the most recent climatic conditions and maximize the record length outside of the very active period from 1956-1965.

2. Use the computed values of L-Cv and L-Skewness from the most recent period in goodness of fit tests for identification of the probability distribution that best describes the annual maxima data. Also use the computed values of L-Cv and L-Skewness from the 9-station index in goodness of fit tests for identification of the probability distribution that best describes the long-term annual maxima data. Use these findings for selection of a probability distribution for developing the regional growth curves.

3. Use the regional values of L-Skewness based on the full record (1900-1998) from the 9-station index for developing the regional growth curves. This takes advantage of longer record lengths to reduce sampling variance and recognizes that values of L-Skewness from the most recent time period are near the long-term averages for the 9-station index.

4. Use the regional values of L-Cv (Step 1) and L-Skewness (Step 3) for fitting the distribution parameters of the selected probability distribution (Step 2). Use the computed distribution parameters to develop the regional growth curve(s).

REGIONAL FREQUENCY ANALYSIS METHODOLOGY

The cornerstone of a regional frequency analysis is that data from sites within a homogeneous region can be pooled to improve the reliability of the magnitude-frequency estimates for all sites. A homogeneous region may be a geographic area delineated on a map or it may be a collection of sites having similar characteristics pertinent to the phenomenon being investigated.

Early in the study it was recognized that the climatic and topographic diversity in the study area would likely preclude the use of large geographic areas that would meet statistical criteria for homogeneity. It was decided to employ climatic/geographic regions that had basic similarities in the climatic and topographic setting. It was anticipated that these regions may require further sub-division to meet homogeneity criteria for use in regional frequency analysis. The three regions were briefly described earlier and that discussion is expanded here.

DESCRIPTION OF CLIMATIC/GEOGRAPHIC REGIONS

As discussed previously, identification of climatologically similar regions meant delineating broad geographic areas that had similar climatological and topographical characteristics. To assist in this effort, a literature review was conducted to examine region designations utilized in prior studies. This included a review of NOAA Atlas 2[15], a precipitation frequency analyses conducted in the western United States, studies of extreme precipitation in California (NWS[18]), and prior regional frequency analyses conducted in coastal mountain areas (Schaefer[21,22,23]).

Based on information in those studies and the spatial characteristics of mean annual precipitation, three climatic/geographic regions were identified (Figure 2, Table 1). In particular, the map of mean annual precipitation (Figure 2) developed by Daly[3] using the PRISM[3] model provided the basic mapping information for delineating the boundaries of the climatic regions. This map is based on the 1961-1990 time period, which is the most recent NOAA 30-year decadal based climate tracking period. The magnitude and gradient of mean annual precipitation were the primary measures used to define the boundaries between the three regions. Those regions include:

Lowlands , West of Sierra Mountains (Region 1) - This non-orographic lowlands region includes areas below a generalized elevation line of 300 feet that lies to the west of the Sierra Mountains. This includes non-orographic areas in the Sacramento Valley and San Joaquin Valley.

West Face of Sierra Mountains (Region 3) - This region is comprised of mountain areas west of a line drawn through the ridgeline of mean annual precipitation[3] just westward of the crest of the Sierra Mountains (Figure 2). These areas are subjected to increased precipitation from the orographic lifting of atmospheric moisture as storms from the Pacific Ocean pass over the Sierra Mountains. Region 3 includes areas above a generalized elevation line drawn at 300 feet. The presence of orographic influence is indicated by the increased gradient of mean annual precipitation in moving west to east from the valley floor into the Sierra Mountains. These two measures were used in delineating the boundary between Regions 1 and 3.

East Slopes of Sierra Mountains (Region 5) - This region (Figure 2) is comprised of mountain areas east of Region 3. This is a leeward area partially sheltered from Pacific storms with mean annual precipitation declining sharply to the east. The eastern boundary of this region is taken to be the isopluvial line of 20 inches of mean annual precipitation.

REGIONAL GROWTH CURVE

Implicit in the definition of a homogeneous region is the condition that all sites can be described by one probability distribution having common distribution parameters after the site data are rescaled by their at-site mean. Thus, all sites have a common regional magnitude-frequency curve (regional growth curve, Figure 9) that becomes site-specific after scaling by the at-site mean of the data from the specific site of interest. Thus,

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

where $Q_i(F)$ is the at-site inverse Cumulative Distribution Function (CDF), $\hat{\mu}_i$ is the estimate of the population at-site mean, and $q(F)$ is the regional growth curve, regional inverse CDF. This is often called an index-flood approach to regional frequency analyses and was first proposed by Dalrymple[2] and expanded by Wallis[26].

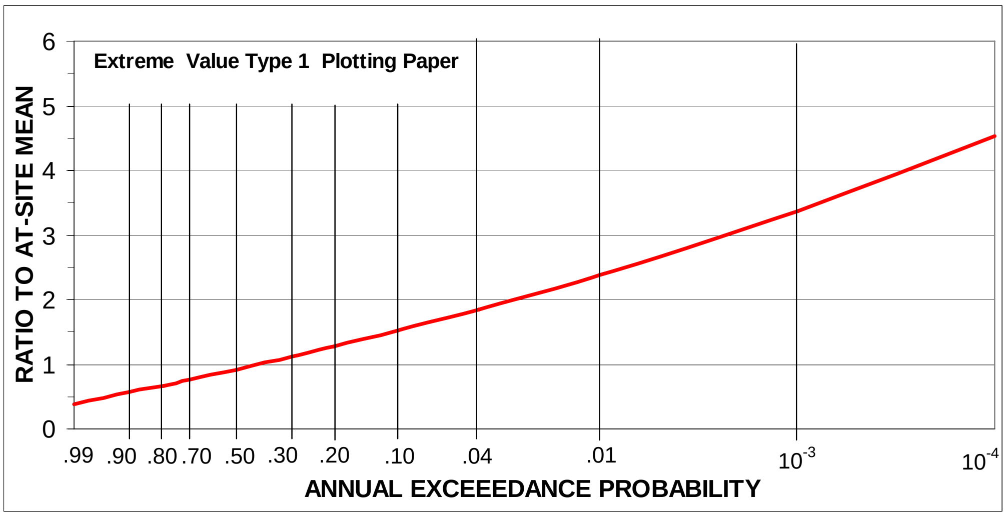


Figure 9 - Example Regional Growth Curve

FORMING HOMOGENEOUS SUB-REGIONS

It was anticipated that the regions defined here would require sub-division to meet homogeneity criteria. The methodology used herein for forming and testing proposed homogeneous sub-regions follows the procedures recommended by Hosking and Wallis[9,10].

The basic approach is to propose homogeneous sub-regions (grouping of sites/gages) based on the similarity of the physical characteristics of the sites. L-moments (Hosking[6,9], Appendix C) are then used to estimate the variability and skewness of the pooled regional data and to test for heterogeneity as a basis for accepting or rejecting the proposed sub-region formulation. When a proposed sub-region is found to satisfy homogeneity criteria, the regional L-moment ratios are then used to conduct goodness of fit tests (Hosking and Wallis[9,10]) to assist in selecting a suitable probability distribution, and to estimate the parameters of the regional distribution. Examples of this type of approach are described by Schaefer in his study of Washington State[21] and southern British Columbia[23]. The basic approach adapted to this study is summarized below:

Adopted Methodology

1) Form proposed homogeneous sub-regions by assigning gages within a region to groups with similar physical and/or climatological characteristics;
2) Compute L-moment sample statistics for gages within the proposed homogeneous sub-regions for the period from 1966-1998;
3) Use L-moment heterogeneity criteria to test proposed homogeneous sub-regions;
4) Develop a mathematical predictor for describing the behavior of regional L-Cv across the region;
5) Conduct goodness of fit tests to identify a suitable probability distribution for the regional growth curve;
6) Solve for the distribution parameters of the selected probability distribution for each sub-region using the regional value of L-Cv (Step 4) and the long-term (1900-1998) value of L-Skewness.

Preliminary Investigation of Behavior of L-Cv by Region

Past experience in coastal and mountain areas (Schaefer[21,23]) suggests that L-moment ratios may vary with either mean annual precipitation or other climatic/geographic characteristic in each of the three regions. It was found that at-site values for L-Cv were smallest in the non-orographic lowlands and largest for the east slopes of the Sierra Mountains. Values of L-Cv for the west face of the Sierra Mountains were intermediate between that for the other two regions. This is consistent with the behavior seen in coastal mountain areas in both southern British Columbia (Schaefer[23]) and Washington State (Schaefer[21]). Figure 10 depicts the variation of at-site L-Cv values with latitude for the three regions for the 72-hour duration.

The differences between the magnitude and behavior of L-Cv in the 3 regions clearly indicates that separate regional growth curves would be applicable to each region. As a result, only the data from the west face of the Sierra Mountains (Region 3) will be useful in determining the precipitation magnitude-frequency characteristics for the American River watershed. Accordingly, the focus of the remainder of the analyses was directed towards regional frequency analyses for Region 3.

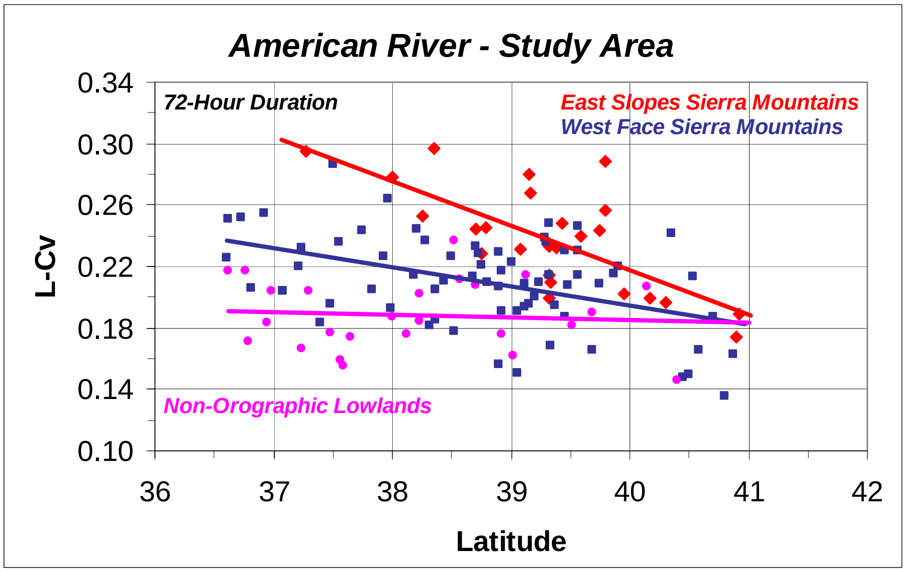


Figure 10 – Relative Magnitudes of L-Cv for the 72-Hour Duration for the Three Regions in the American River Study Area for the 1966-1998 Time Period

REGIONAL ANALYSES OF WEST FACE OF THE SIERRA MOUNTAINS

The regional frequency analyses were conducted by proceeding as indicated in *Adopted Methodology* presented in the previous section. Those tasks are discussed in the following sections.

ANALYSIS OF L-Cv

Preliminary analyses indicated that L-Cv was not constant over Region 3 but varied from north to south. Scatterplots were developed to examine the variation of L-Cv with latitude and Mean Annual Precipitation (MAP). It was found that the variation of L-Cv was reasonably explained by latitude (Figure 11) and no correlation was found between MAP and L-Cv (Figure 12). Accordingly, candidate homogeneous sub-regions were taken to be collection of gages from a limited range of latitude within Region 3 (Table 7). Figure 13 depicts the variation of regional L-Cv values for the three durations based on the use of four sub-regions defined in terms of small ranges of latitude.

Table 7 – Characteristics of Sub-Regions on the West Face of the Sierra Mountains for 72-Hour Duration for Period from 1966-1998

SUB-REGION	RANGE OF LATITUDE	NUMBER OF GAGES	STATION-YEARS OF RECORD
a	39.47° – 41.00°	14	439
b	39.00° – 39.47°	15	469
c	38.10° – 39.00°	16	494
d	36.30° – 38.10°	17	541
Region 3	36.30° – 41.00°	62	1943

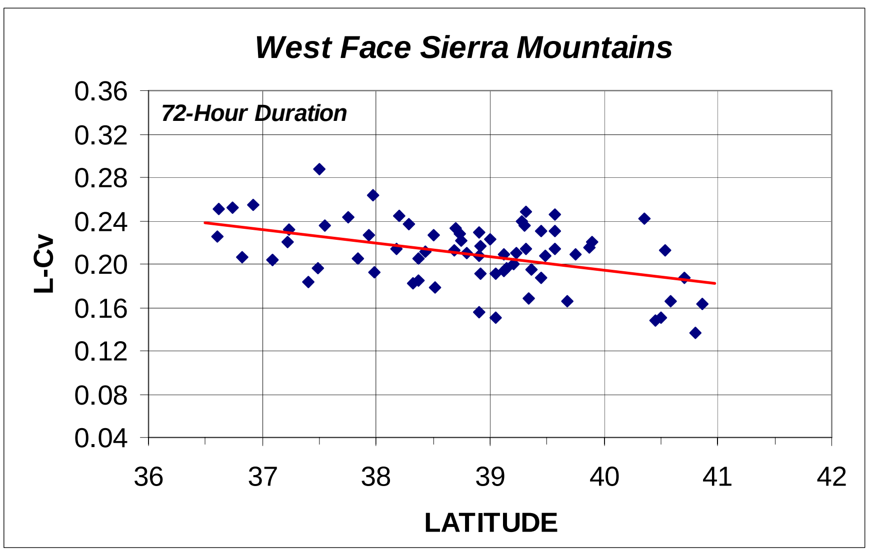


Figure 11 – Variation of L-Cv with Latitude for 72-Hour Duration for the West Face of the Sierra Mountains

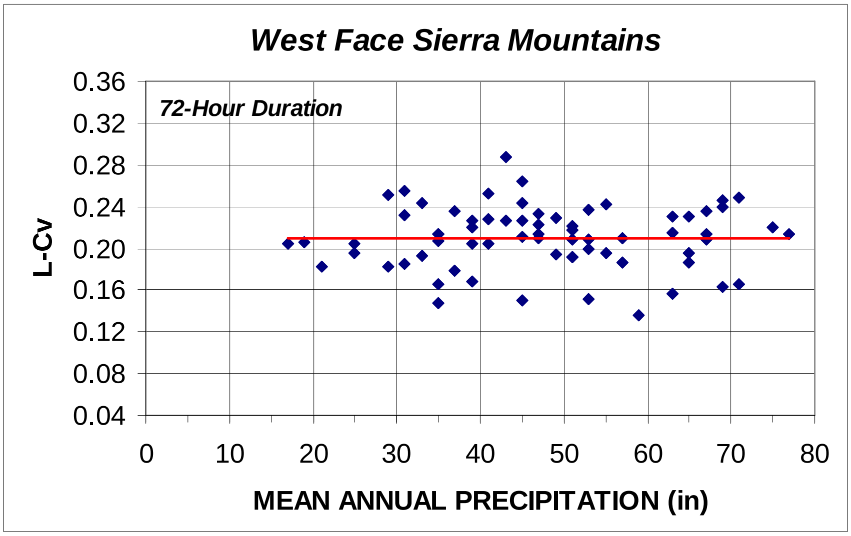


Figure 12 – Variation of L-Cv with Mean Annual Precipitation for 72-Hour Duration for the West Face of the Sierra Mountains

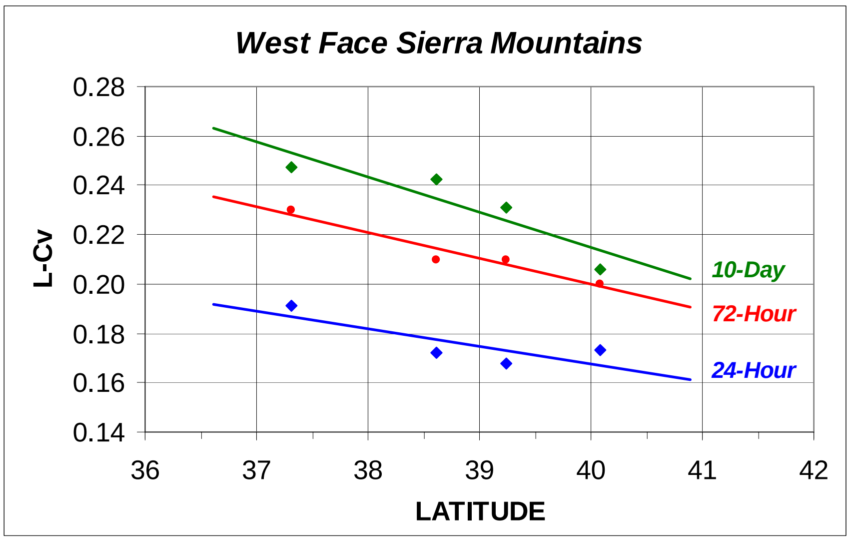


Figure 13 – Variation of Sub-Regional Values of L-Cv with Latitude for the West Face of the Sierra Mountains

Confirmation of Homogeneous Sub-Regions

Homogeneity of the sub-regions was confirmed by use of heterogeneity measures developed by Hosking and Wallis[9,10] as indicators of the amount of heterogeneity in the L-moment ratios for a collection of sites/gages. The statistics H1 and H2 measure the relative variability of observed L-Cv and L-Skewness sample statistics, respectively, for gages/sites in a sub-region. Specifically, these measures compare the observed variability to that expected from a large sample drawn from a homogeneous region from the Kappa distribution[9,12] having weighted average L-moment ratios that were observed in the sub-region. Initial recommendations from Hosking and Wallis[9,10] were that regions with H1 and H2 values less than 1.00 were acceptably homogeneous. Values of H1 and H2 between 1.00 and 2.00 were possibly heterogeneous. Values greater than 2.00 indicated definite heterogeneity and that redefinition of the region and/or reassignment of sites/gages should be considered.

These heterogeneity criteria are intended to measure statistical heterogeneity and do not account for variability that arises from other sources. Most NWS cooperative precipitation measurement networks include gages operated by various organizations and individuals that provide a varied level of quality control. Therefore, precipitation measurements often contain additional variability due to: gages being moved during the many years of operation; frequent change of operators and level of diligence in timely measurement; missing data arising from inconsistent reporting; lack of attention to measurement precision; and localized site and wind condition changes over time. Recognizing this additional variability, Wallis[25] has suggested that for precipitation annual maxima, H1 values less than 2.00 may be considered acceptably homogeneous and H1 values greater than 3.00 would be indicative of heterogeneity.

Both the H1 and H2 measures are used here to assess the relative heterogeneity in the four proposed sub-regions. It is seen in Table 8 that all sub-regions had H1 and H2 values less than the critical values and were deemed acceptably homogeneous. Heterogeneity measures were also computed for the 9-station index for all three durations. The collection of gages for the 9-station index were also found to be acceptably homogeneous.

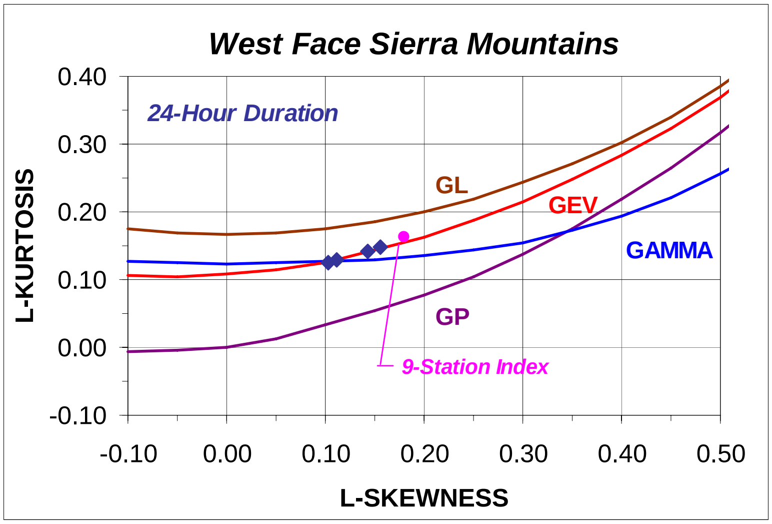
IDENTIFICATION OF REGIONAL PROBABILITY DISTRIBUTION

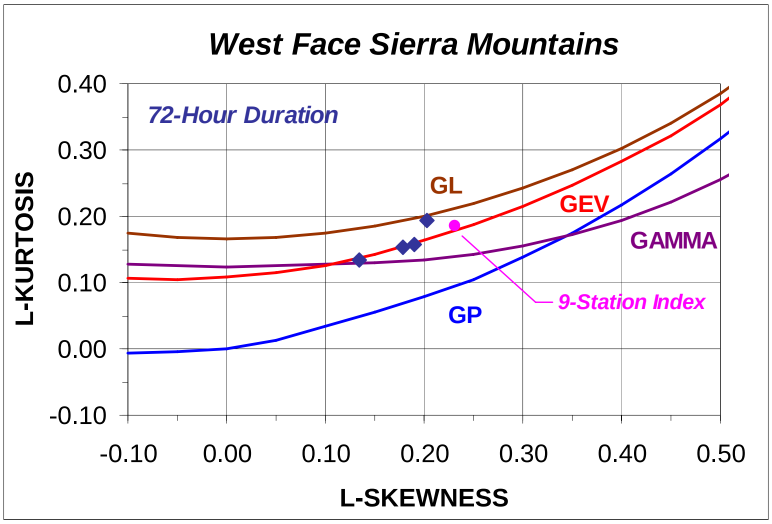
One of the primary tasks in the regional analysis is to identify the best probability distribution for describing the annual maxima data. Accordingly, a goodness of fit test statistic (Hosking and Wallis[12,13]) was computed for each sub-region for use in identifying the best three-parameter distribution. Using the L-moment based test statistic, the Generalized Extreme Value (GEV) distribution was identified most frequently as the best three-parameter probability model (Table 8).

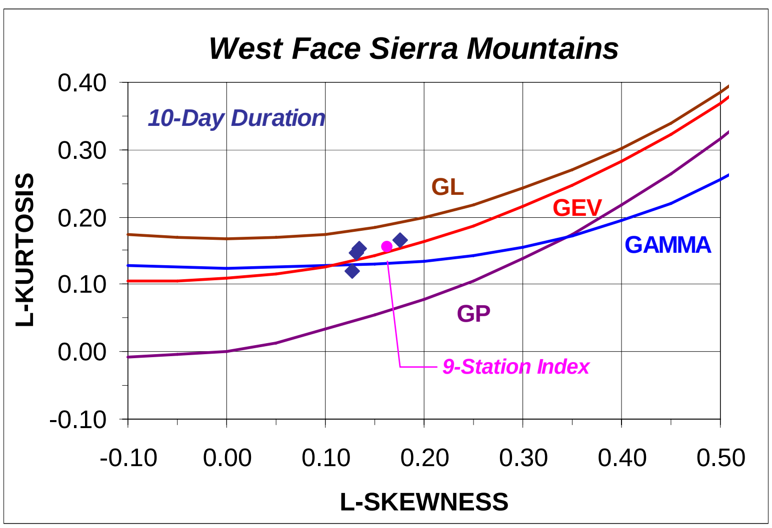
Plots of regional L-Skewness and L-Kurtosis values for the four sub-regions at the three durations are shown in Figure 12a,b,c. Nearness to the GEV distribution is clearly evident and this was substantiated by quantitative goodness of fit test results (Table 8). The L-moment ratios for the 9-station index are plotted for each duration (Figures 12a,b,c), which in conjunction with goodness of fit tests also identifies the GEV distribution as a suitable distribution.

Table 8 – Results of Heterogeneity Measures and Goodness of Fit Tests for Sub-Regions on the West Face of the Sierra Mountains for the Period from 1966-1998

DURATION	NUMBER OF SUB-REGIONS	HOMOGENEOUS SUB-REGIONS H1 ≤ 2.00	HOMOGENEOUS SUB-REGIONS H2 ≤ 1.00	SUB-REGIONS ACCEPTING GEV DISTRIBUTION
24-Hours	4	4	4	4
72-Hours	4	4	4	4
10-Days	4	4	4	4







Figures 12a,b,c - L-Moment Ratio Plots for Four Sub-Regions and 9-Station Index for 24-Hour, 72-Hour, and 10-Day Durations

The primary application of these findings will be in estimating precipitation amounts for rare storm events. Accordingly, a distribution is desired that has flexibility in producing a wide range of regional growth curves. Given this consideration, the four-parameter Kappa[9,12] distribution was chosen, which can mimic the GEV and produce a variety of regional growth curve shapes in the immediate vicinity of those produced by the GEV. The inverse form of the Kappa distribution is:

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

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

An h value of zero leads to the GEV distribution, an h value of 1 produces the Generalized Pareto (GP) and an h value of -1 produces the Generalized Logistic (GL) distribution. Thus, positive values of h produce regional growth curves that are flatter than the GEV, and negative values of h produce steeper regional growth curves. Minor adjustments of h near a zero value (GEV) allow fine-tuning of the regional growth curves. This minor adjustment of the h value only becomes important for the estimation of very rare quantiles and may provide utility for stochastic modeling of extreme storms and floods.

DETERMINATION/SELECTION OF L-SKEWNESS VALUE FOR DEVELOPING REGIONAL GROWTH CURVES

As discussed previously, it is recommended that the long-term (1900-1998) value of L-Skewness be used in developing the regional growth curves for Region 3. This decision was made based on several considerations. First, L-skewness values computed from small samples, such as the 1966-1998 record are subject to high sampling variability. Thus, use of the long-term record affords a significant reduction in uncertainties due to sampling variability. Second, the results of the L-moment regional sample statistics (Figures 8a,b,c) for the 9-station index indicates that the long-term (1900-1998) and near-term (1966-1998) values of L-Skewness are similar. Thus, the long-term regional value may be taken as representative of the near-term regional value of L-Skewness.

One option would be to use the long-term L-Skewness value obtained from the 9-station index. However, it would be preferable to also utilize the record available from gages with shorter record lengths to increase the sample size and reduce uncertainties due to sampling variability. It is seen in Table 3 that the majority of the gages were operating in the period from the late 1940s to present. The problem is how best to incorporate the additional shorter-term records because the values of L-Skewness are period dependent (Figures 8a,b,c).

Ideally, we are interested in estimating what the long-term (1900-1998) values of L-Skewness would have been at the short-term gages had they began operation at the turn-of-the-century. Thus, we want to use the behavior of the collection of short-term gages relative to the behavior of the 9-station index to estimate the long-term L-Skewness value for the collection of all gages. The resultant value of L-Skewness will therefore represent a weighted average of the long-term value of L-Skewness for the 9-station index and the projected long-term value of L-Skewness for the short-term gages.

To further take advantage of larger sample sizes, it was decided to utilize an hierarchical approach (Fiorentino[4]) for estimation of the regional L-Skewness values. Using this approach, the L-Skewness value for each duration is computed as the weighted average value from the collection of stations in the four sub-regions.

The first step is to make a comparison of the behavior of L-Skewness values between the 9-station index and the collection of gages in Region 3. It is seen in Figures 13a, 14a, 15a that the regionwide data from about 60 stations compares well with the 9-station index. Differences are within those expected from sampling variability. The next step is to estimate the long-term (1900-1998) value of L-Skewness for the collection of gages in Region 3 based on correlation with the long-term value of L-Skewness for the 9-station index. This correlation relationship is shown in Figures 13b, 14b, 15b.

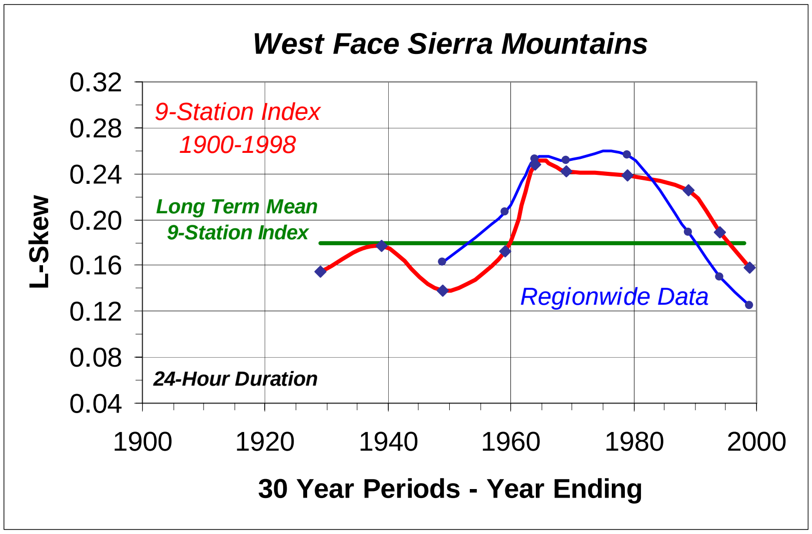


Figure 13a – Comparison of L-Skewness Values for All Gages in Region 3
With L-Skewness Values for the 9-Station Index for the 24-Hour Duration

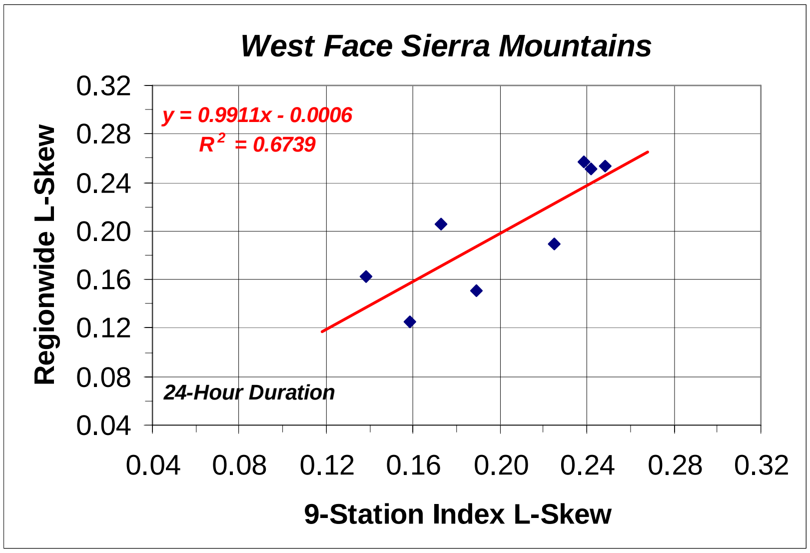


Figure 13b – Correlation Relation Between L-Skewness Values for All Gages in Region 3
and L-Skewness Values for the 9-Station Index for the 24-Hour Duration

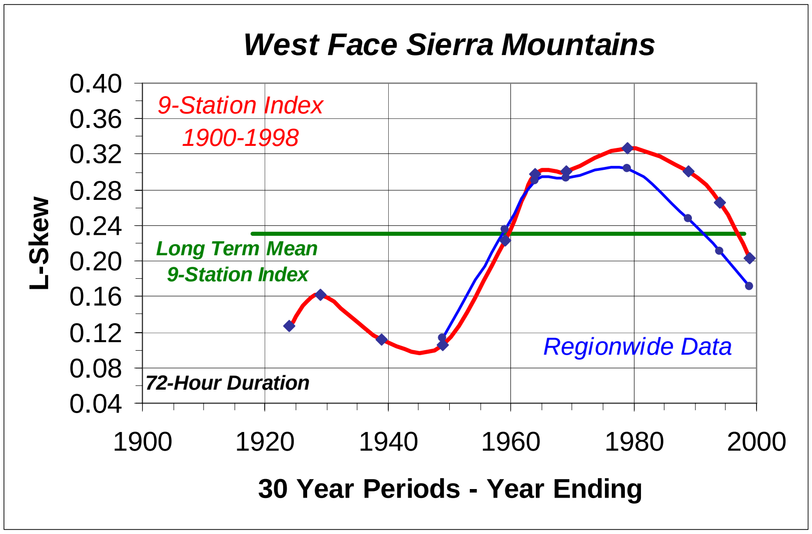


Figure 14a – Comparison of L-Skewness Values for All Gages in Region 3
With L-Skewness Values for the 9-Station Index for the 72-Hour Duration

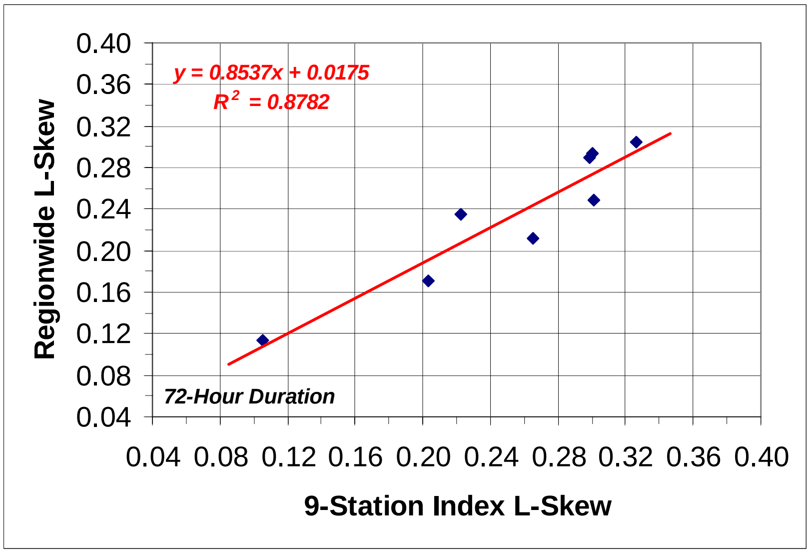


Figure 14b – Correlation Relation Between L-Skewness Values for All Gages in Region 3
and L-Skewness Values for the 9-Station Index for the 72-Hour Duration

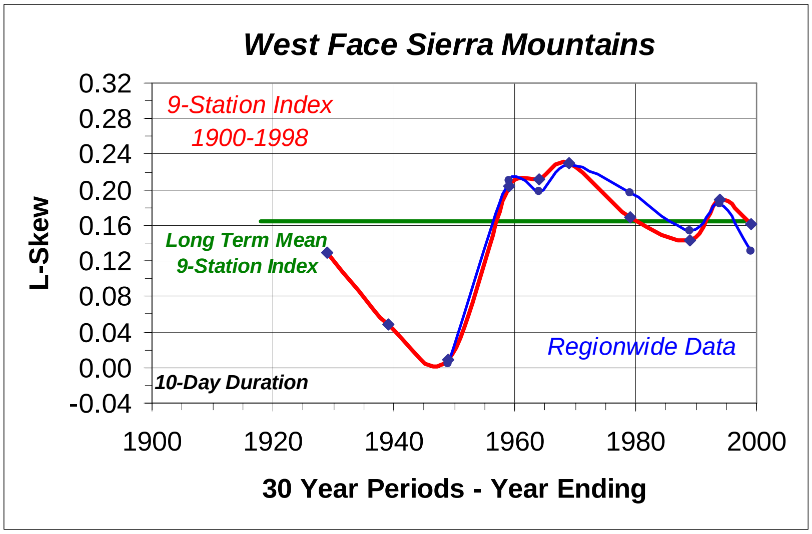


Figure 15a – Comparison of L-Skewness Values for All Gages in Region 3
With L-Skewness Values for the 9-Station Index for the 10-Day Duration

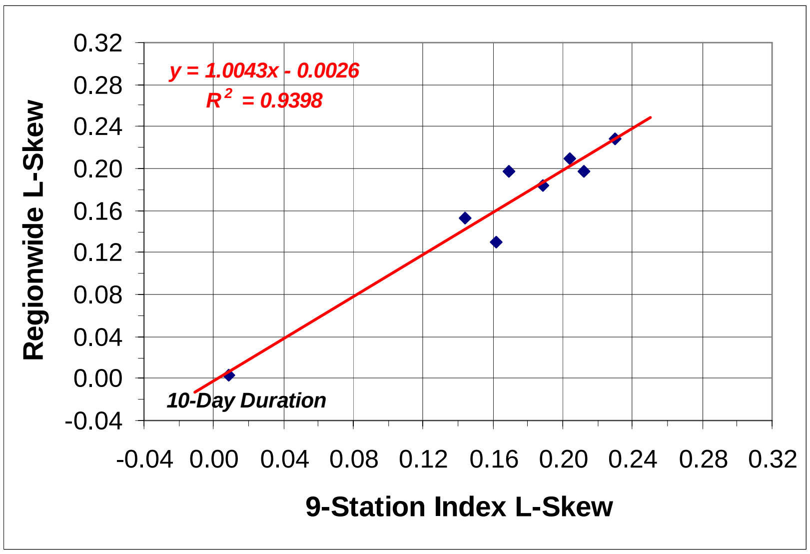


Figure 15b – Correlation Relation Between L-Skewness Values for All Gages in Region 3
and L-Skewness Values for the 9-Station Index for the 10-Day Duration

Use of the relations in Figures 13b, 14b, and 15b provides improved estimates of the long-term values of L-Skewness applicable to the West Face of the Sierra Mountains. Table 9 displays the results of those analyses and compares values of L-Skewness for the 9-station index and the collection of 60 gages used in the regional analyses.

Table 9 – Results of L-Skewness Analyses for Region 3, West Face of Sierra Mountains
Projected L-Skewness Values for Collection of All Gages for Period from 1900-1998

DURATION	L-SKEWNESS 9-STATION INDEX 1900-1998		L-SKEWNESS COLLECTION OF ALL GAGES PROJECTED 1900-1998 VALUES	
24-Hours	0.1796	833 station-years	0.1774	based on 3892 station-years
72-Hours	0.2304	832 station-years	0.2142	based on 3752 station-years
10-Days	0.1638	826 station-years	0.1619	based on 3727 station-years

DEVELOPMENT OF REGIONAL GROWTH CURVES FOR WEST FACE OF SIERRA MOUNTAINS

All regional frequency analyses conducted herein are based on point precipitation measurements. These results are taken as representative of a 10 mi^2 area for general storm precipitation (Miller[15], NWS[18,19]). Application to the 1,890 mi^2 American River watershed will be based on these findings and the results of a separate analysis on the spatial characteristics of observed extreme storms. The following sections depict the development of 10 mi^2 regional growth curves based on the regional analyses of L-Cv and L-Skewness, and identification of the best-fit probability distribution described in the previous sections.

WEST FACE OF SIERRA MOUNTAINS

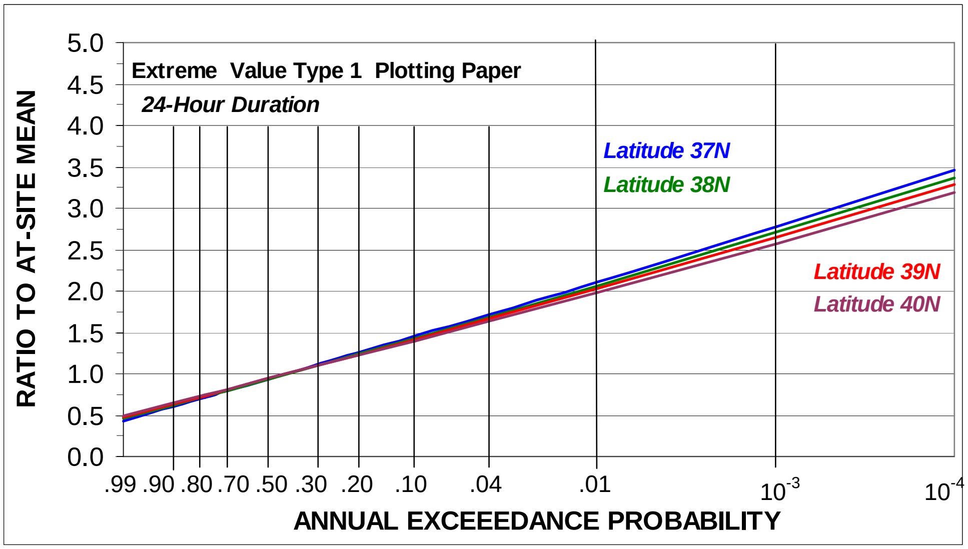
A single regional growth curve cannot be used to describe sites on the West Face of the Sierra Mountains (Region 3) because L-Cv varies with latitude. Thus, a family of regional growth curves is needed to depict the variation of the regional growth curves with latitude. Table 10 contains regional L-moment ratio values at selected latitudes that are applicable to Region 3. A four-parameter Kappa[12] distribution was fitted using the regional L-moment ratio values with the shape parameter *h* set to a value of –0.01 that essentially yields the GEV distribution. Values of the distribution parameters are listed in Table 11. Figures 16a,b,c depict the regional growth curves for selected latitudes.

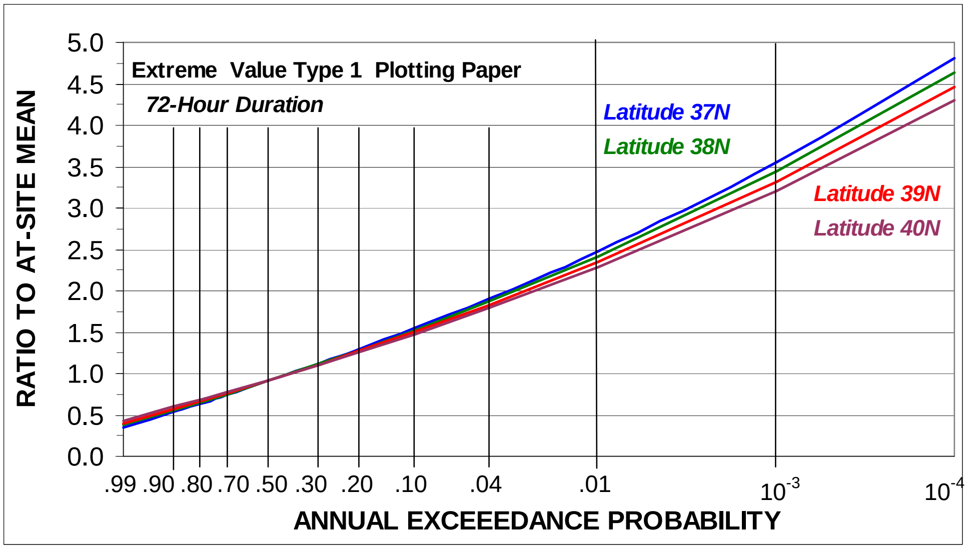
Table 10 – L-Moment Ratio Values for Selected Latitudes on the West Face of the Sierra Mountains

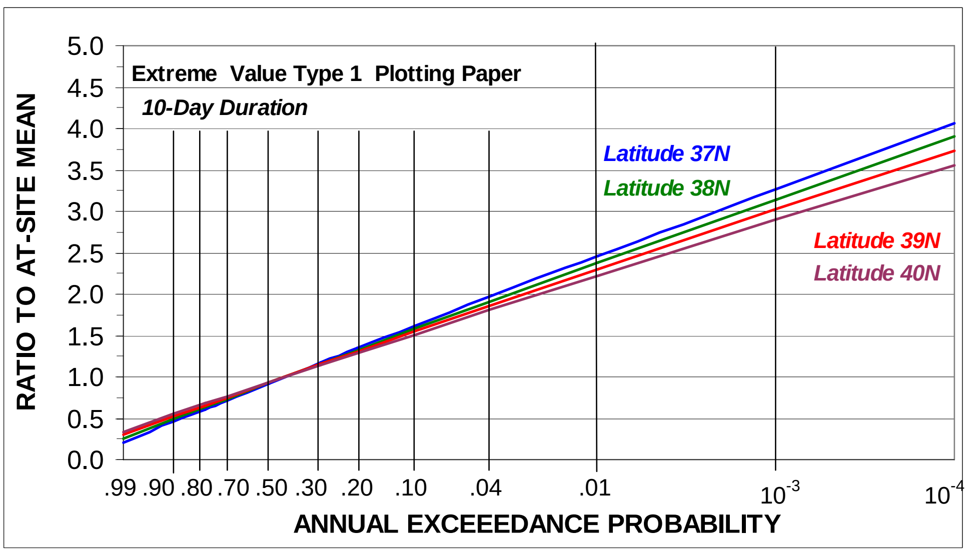
DURATION	LATITUDE	REGIONAL L-Cv	REGIONAL L-SKEWNESS
24-Hours	37°	0.1877	0.1774
24-Hours	38°	0.1807	0.1774
24-Hours	39°	0.1737	0.1774
24-Hours	40°	0.1667	0.1774
72-Hours	37°	0.2307	0.2142
72-Hours	38°	0.2203	0.2142
72-Hours	39°	0.2099	0.2142
72-Hours	40°	0.1995	0.2142
10-Days	37°	0.2565	0.1619
10-Days	38°	0.2423	0.1619
10-Days	39°	0.2281	0.1619
10-Days	40°	0.2139	0.1619

Table 11 – Distribution Parameters for Kappa Distribution for Regional Growth Curves

DURATION	LATITUDE	LOCATION PARAMETER (ξ)	SCALE PARAMETER (α)	SHAPE PARAMETER (κ)	SHAPE PARAMETER (h)
24-Hours	37°	0.8438	0.2663	-0.0143	-0.01
24-Hours	38°	0.8496	0.2563	-0.0143	-0.01
24-Hours	39°	0.8555	0.2464	-0.0143	-0.01
24-Hours	40°	0.8613	0.2365	-0.0143	-0.01
72-Hours	37°	0.7998	0.3096	-0.0702	-0.01
72-Hours	38°	0.8088	0.2957	-0.0702	-0.01
72-Hours	39°	0.8179	0.2817	-0.0702	-0.01
72-Hours	40°	0.8269	0.2678	-0.0702	-0.01
10-Days	37°	0.7907	0.3720	0.00968	-0.01
10-Days	38°	0.8023	0.3514	0.00968	-0.01
10-Days	39°	0.8139	0.3308	0.00968	-0.01
10-Days	40°	0.8255	0.3102	0.00968	-0.01

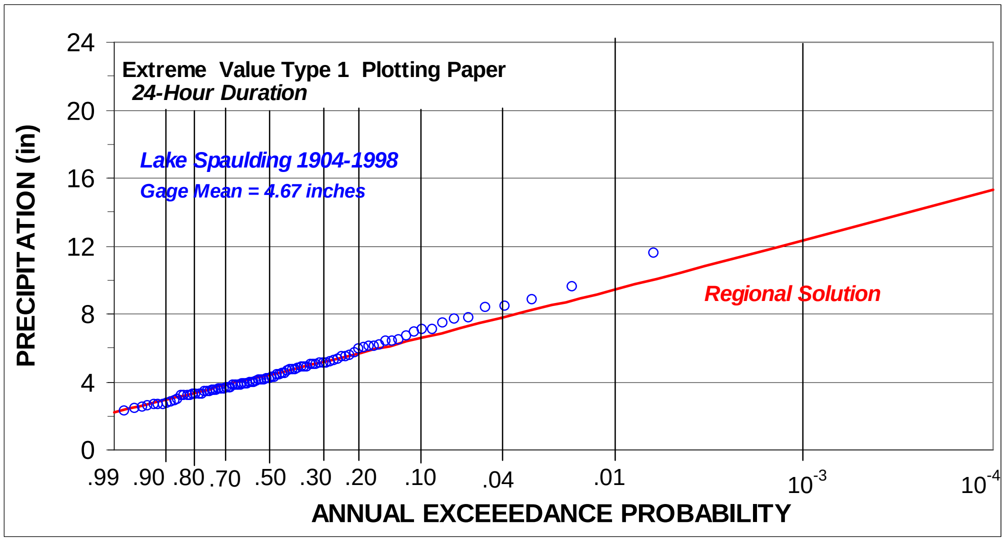


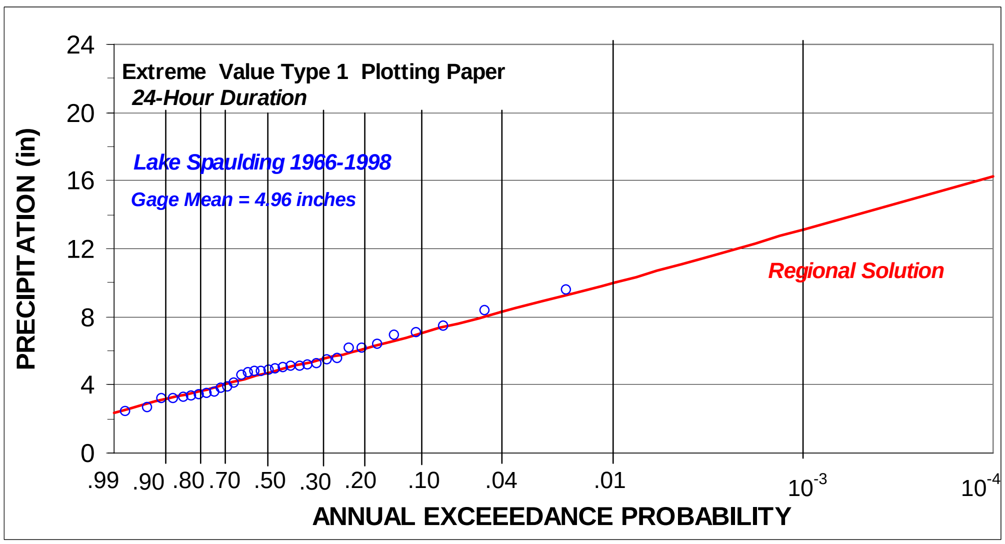




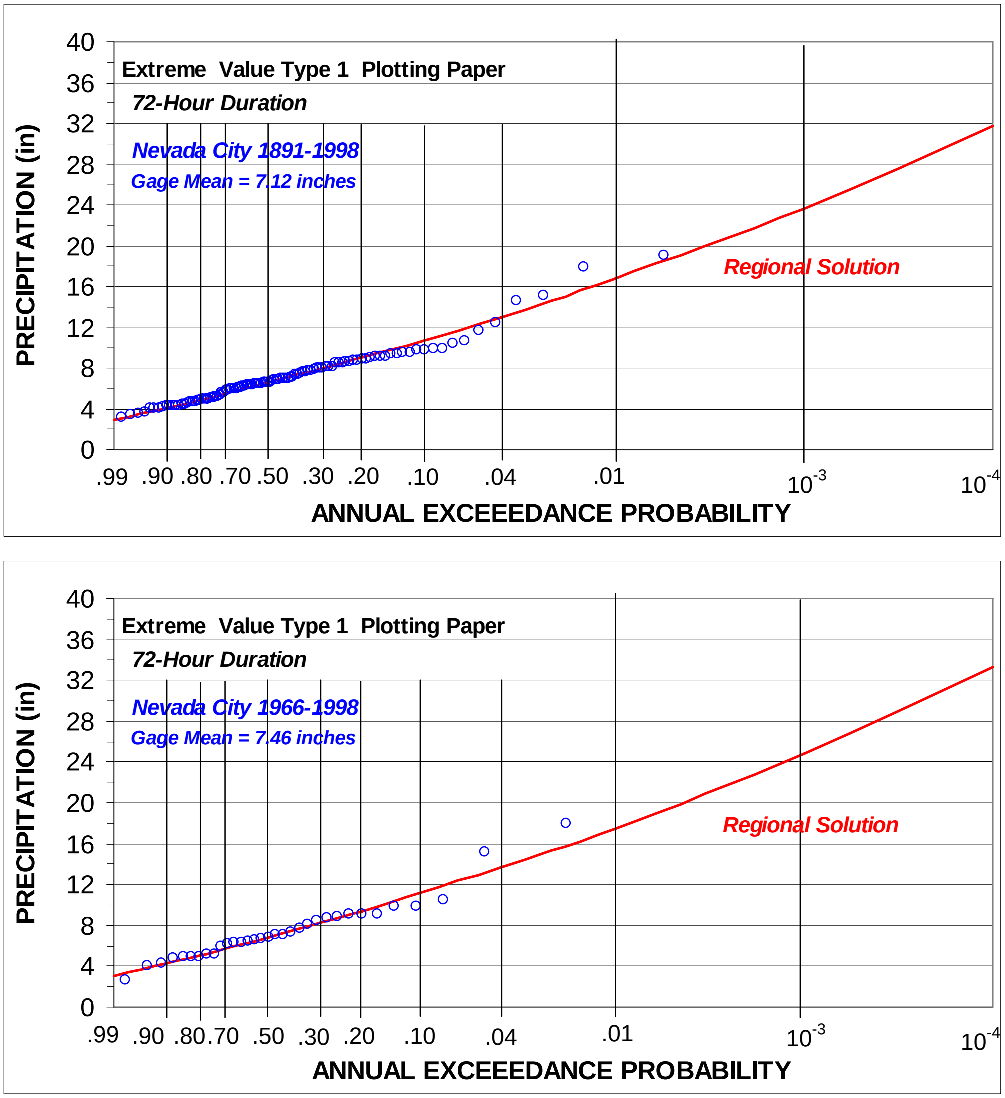
Figures 16a,b,c – 10 mi^2 Regional Growth Curves for 24-Hour, 72-Hour, and 10-Day Durations for Region 3, West Face of Sierra Mountains

Probability plots are presented in Figures 17a,b, 18a,b, and 19a,b depicting observed data at selected sites and durations. The precipitation magnitude-frequency curves were constructed as the product of the gage mean and the regional growth curve. The gage data and gage mean are used to allow probability-plots to be made for direct comparison between the observed data and the predicted magnitude-frequency curve. At-site means are computed from the gage means using minor correction factors to account for the difference between measurements taken on fixed intervals and those obtained from continuous recording (Weiss[27]). Appendix B contains a summary of all station characteristics and lists the gage mean and at-site mean for stations.

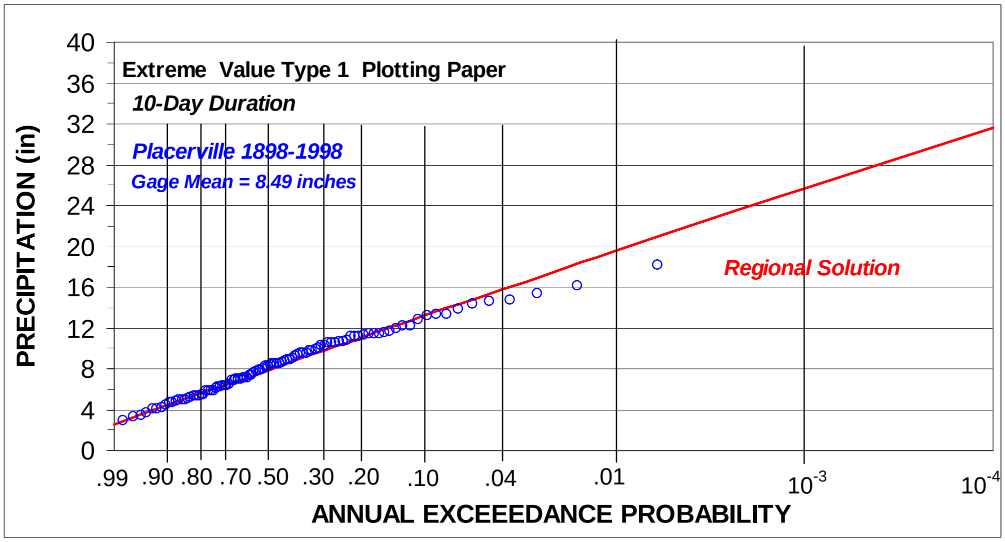


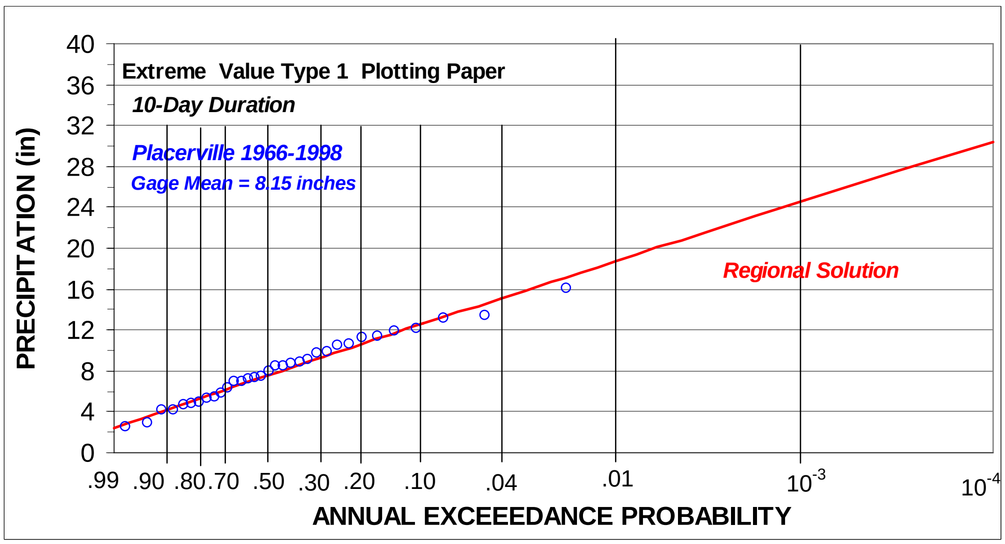


Figures 17a,b – Precipitation Magnitude-Frequency Curves for Lake Spaulding, CA for 24-Hour Duration for 1904-1998 and 1966-1998 Time Periods



Figures 18a,b – Precipitation Magnitude-Frequency Curves for Nevada City, CA for 72-Hour Duration for 1894-1998 and 1966-1998 Time Periods





Figures 19a,b – Precipitation Magnitude-Frequency Curves for Placerville, CA for 10-Day Duration for 1898-1998 and 1966-1998 Time Periods

AMERICAN RIVER WATERSHED

The centroid of the American River watershed is essentially at 39°N latitude. Therefore, the regional growth curves for latitude 39°depicted in Figures 16a,b,c are applicable to the American River watershed. In order to develop basin-average 10 mi^2 precipitation magnitude-frequency curves, it is first necessary to compute an areal average of the at-site means in the watershed. A preliminary estimate of the 24-hour basin-average value can be obtained from NOAA Atlas 2[15]. This is accomplished by computing an areally averaged value of the 2-year, 24-hour partial duration series value using the isopluvials in the Atlas, and subsequent computation of the corresponding mean value. Regionwide mean values of the 72-hour/24-hour ratios and 10-day/24-hour ratios (obtained from Appendix B) can then be used for estimation of the 72-hour and 10-day basin-average values. Frequency information in NOAA Atlas 2 was based on the available data collected through 1966. A review of Figures 6a,b,c indicate that the at-site mean values for the period ending in 1966 are similar to that for the period under consideration 1966-1998. Further, the spatial distribution depicted in NOAA Atlas 2 would be expected to be applicable to current conditions. Thus, this information will suffice for preliminary estimates until more detailed analyses can be conducted. Specifically, improved areal average estimates will be developed through statistical procedures and/or by use of the PRISM[3] model when the analyses of the spatial distribution of precipitation are conducted (future task).

The areally averaged 24-hour basin-average 10 mi^2 value obtained from NOAA Atlas 2 is listed in Table 12 along with the 72-hour and 10-day basin-average 10 mi^2 values. Basin-average precipitation magnitude-frequency curves are obtained as the product of the basin-average value and the regional growth curve (Equation 1). The preliminary curves for the 24-hour, 72-hour and 10-day durations are depicted in Figures 20,21,22. A comparison of the three curves is made in Figure 23.

Table 12 – Basin-Average 10 mi^2 Precipitation Values for American River Watershed above Folsom Dam

DURATION	24-HOUR	72-HOUR	10-DAY
BASIN-AVERAGE 10 mi^2 VALUE	4.42 inches	7.00 inches	11.53 inches

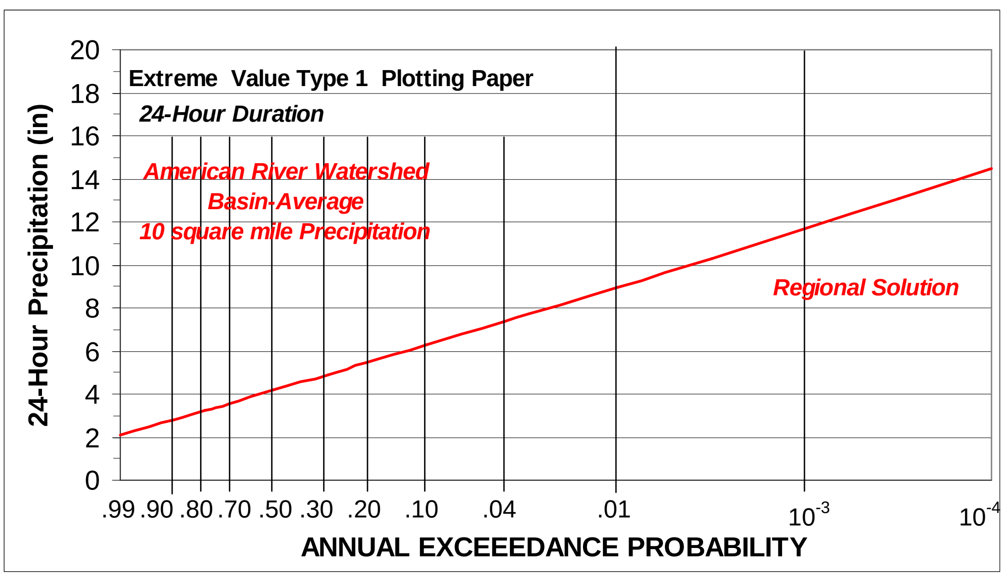


Figure 20 – Basin-Average 24-Hour 10 mi^2 Precipitation Magnitude-Frequency Curve for American River Watershed above Folsom Dam

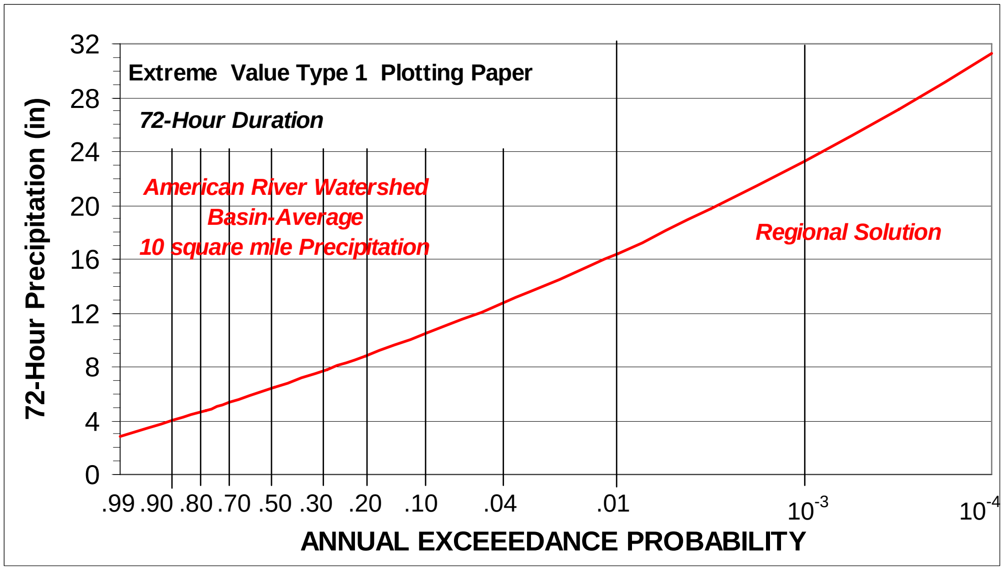


Figure 21 – Basin-Average 72-Hour 10 mi^2 Precipitation Magnitude-Frequency Curve for American River Watershed above Folsom Dam

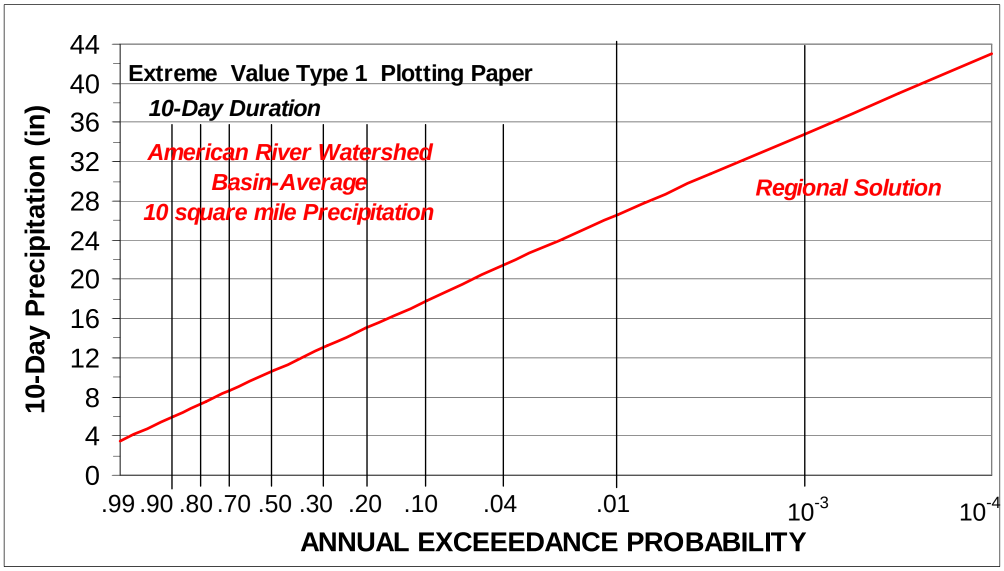


Figure 22 – Basin-Average 10-Day 10 mi^2 Precipitation Magnitude-Frequency Curve for American River Watershed above Folsom Dam

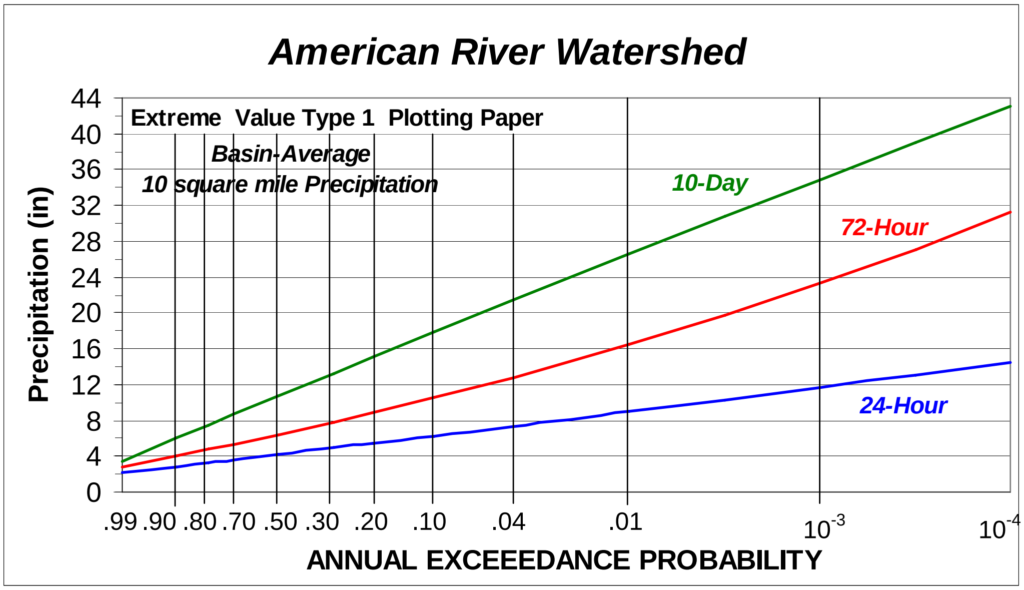


Figure 23 – Comparison of Basin-Average 10 mi^2 Precipitation Magnitude-Frequency Curves for American River Watershed above Folsom Dam

Basin-Average 1,890 mi^2 Magnitude-Frequency Curves

Computation of a basin-average precipitation magnitude-frequency curve applicable to the 1,890 mi^2 American River watershed can be obtained through the application of an areal reduction factor. One such family of areal reduction factors is contained in Hydrometeorological Report 59[18]. Probabilistic analyses of the spatial distribution of precipitation in extreme storms and analyses of areal reduction factors are scheduled as a future task in this on-going study of extreme storms and floods on the American River.

Spatial and Temporal Storm Characteristics

The magnitude-frequency characteristics of flood runoff volume and flood peak discharge are affected by a number of hydrometeorological factors. In particular, the magnitude of precipitation, and the temporal and spatial distribution of precipitation over the watershed are important flood-producing factors. This summary report has discussed the magnitude-frequency characteristics of precipitation. The temporal and spatial distributions of precipitation are being analyzed separately as part of the analyses for extreme storms for the American River watershed. The findings of those analyses are being presented in separate summary reports.

SUMMARY OF FINDINGS AND CONCLUSIONS

The following list summarizes the findings of analyses, and the conclusions reached based on analyses conducted herein. The list also incorporates findings from the NRC report[17] and from investigators of related topics.

1. The February 1986 storm is the largest 3-day basin-average storm event since the turn-of-the-century and likely the largest since 1862.

2. The 1976-1977 drought produced the smallest 72-hour annual maxima in the data series at 55 of the 92 stations in the Sierra Mountains portion of the study area that were operating during the drought.

3. There is no evidence of year-to-year persistence for annual maxima data as indicated by the lack of serial correlation for the collection of 170 stations in the study area.

4. The 1916-1936 period of low-variability is outside the range of expected behavior for an independent stationary process based on based on the frequency of occurrence of extreme storms over the past century. It is not deemed representative of what would be expected in a typical record length of 100-years and is suggestive of regime-like behavior. Tree ring analyses by Earle[29] provide evidence that the 1917-1950 period was the driest in the last 440-year reconstructed tree ring record in California (NRC[17]). These two pieces of information are suggestive that the greatest departure from long term averages for multi-day precipitation annual maxima in central California is not the more active period in the latter half of the century, but rather the 20 plus year period of low variability in the early portion of the 20th century.

5. The clustering of 4 extreme events with wide-spread areal coverage in a 3-year span (1963-1965) is within the plausible range of behavior for an independent stationary process based on the frequency of occurrence of extreme storms over the past century.

6. The clustering of 3 of the 4 largest storms occurring in a 10-year span (1956-1965) is very unlikely for an independent stationary process. This sequence is suggestive of regime-like behavior.

7. The frequency of generation of extreme storms over the Pacific Ocean appears to be reasonably uniform over the past 100-years. The high variability seen in time-series in the Sierra Mountains in central California appears to be due to the variability induced by the synoptic-scale mechanisms that steer storms to various locations along the West Coast of North America.

8. Regional values of L-Cv and L-Skewness for 30-year periods for the 9-station index, approach or exceed the 95% confidence bounds for an independent stationary process based on the 1900-1998 record. This is contributing evidence that the process is non-stationary. Alternatively, we have had the misfortune of experiencing two unrepresentative periods in the available record. The benign period from 1916-1936 having low variance, and the active period from 1956-1965 having high variance and skewness with 3 of the 4 largest basin-average storm events occurring in a 10-year period.

9. Regional values of L-Cv and L-Skewness for the 9-Station index from the most recent 30-year period are very near to century-long values. This indicates that use of either the near-term record or the long-term record, would yield similar results from a regional frequency analysis.

SUMMARY OF ADOPTED METHODOLOGY FOR REGIONAL FREQUENCY ANALYSIS

Based on the above information, the adopted approach was to conduct regional frequency analyses and develop precipitation magnitude-frequency curves based on the near-term record. Specifically, the record from 1966-1998 was used to reflect the most recent climatic conditions and maximize the record length outside of the very active period from 1956-1965. The following list summarizes the basic steps enacted in conducting the regional frequency analyses for the 24-hour, 72-hour, and 10-day durations.

1. Four candidate homogeneous sub-regions were formed within Region 3 (west face of the Sierra Mountains) by assigning gages to groups with each group representing a small range of latitude.

2. L-moment ratio sample statistics were computed for gages within the candidate homogeneous sub-regions for the period from 1966-1998 and tests for heterogeneity confirmed the four groups were acceptably homogeneous.

3. Sub-regional values of L-Cv were computed based on the 1966-1998 record and L-Cv was found to vary by latitude across the west face of the Sierra Mountains

4. Goodness of fit tests were conducted using the sub-regional values of L-Cv and L-Skewness from the four sub-regions for the 1966-1998 period and the Generalized Extreme Value (GEV[9]) was identified as the best choice for describing the annual maxima data and for development of regional growth curves.

5. Goodness of fit tests were also conducted using the regional values of L-Cv and L-Skewness from the 9-station index and the Generalized Extreme Value (GEV) was again identified as the best choice for describing the annual maxima data and for development of regional growth curves.

6. An hierarchical approach was adopted for estimation of the long-term (1900-1998) regionwide value of L-Skewness for Region 3. A methodology was developed that utilized records from the 9-station long-term index in conjunction with shorter records from the additional 50+ stations operating at various times during the 1900-1998 period.

7. The sub-regional values of L-Cv and the regionwide value of L-Skewness were used for fitting the four-parameter Kappa[9,12] distribution in a manner that essentially reproduces the Generalized Extreme Value[9] distribution. The fitted KAPPA distribution parameters were used to develop regional growth curves for each degree of latitude in the range from 37° to 40° for Region 3. The use of the Kappa distribution will provide increased utility for examining a variety of regional growth curve shapes when stochastic simulations of storms and floods are conducted.

8. Preliminary basin-average 10 mi^2 precipitation magnitude-frequency curves were developed for the American River watershed. These curves are preliminary in that basin-averaging of the at-site means was based on the spatial distribution of 24-hour 2-year precipitation contained in NOAA Atlas 2[15]. Improved estimates of the basin-average 10 mi^2 precipitation value will be obtained later when additional analyses are conducted on the spatial characteristics of precipitation.

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