US Army Corps
of Engineers
Hydrologic Engineering Center

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

Appendix J - Analysis of Storms Antecedent and Posterior to Extreme Storms for the American River Watershed

September 2005

RD-48J

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* September 2005	**2. REPORT TYPE** Research Document	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Stochastic Modeling of Extreme Floods on the American River at Folsom Dam Appendix J - Analysis of Storms Antecedent and Posterior to Extreme Storms for the American River Watershed	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) MGS Engineering Consultants, Inc. 7326 Boston Harbor Road NE Olympia, WA 98506	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5F. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC) 609 Second Street Davis, CA 95616-4687	**8. PERFORMING ORGANIZATION REPORT NUMBER** RD-48J
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/ MONITOR'S ACRONYM(S)** **11. SPONSOR/ MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
.

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.

15. SUBJECT TERMS
Stochastic, Precipitation, Frequency Analysis, Frequency Curve, Exceedance Probability, Temperature, Snow, Wind, Volume, Folsom, American, Corps of Engineers, MGS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	14	**19b. TELEPHONE NUMBER**

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

Appendix J - Analysis of Storms Antecedent and Posterior to Extreme Storms for the American River Watershed

September 2005

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

RD-48J

ANALYSIS OF STORMS
ANTECEDENT AND POSTERIOR TO EXTREME STORMS
FOR THE AMERICAN RIVER WATERSHED

February 15, 2000

BACKGROUND

It is common practice in conducting deterministic flood analyses for dam safety to include a storm several days prior to the occurrence of the design storm. The use of an antecedent storm and flood results in wet soil conditions and elevated reservoir levels in advance of the design storm/flood. This practice is one of many conservatisms that are commonly used in deterministic rainfall-runoff modeling of extreme floods for dam safety investigations.

The approach taken in the Stochastic Event Flood Model (SEFM[11]) is that antecedent storms are independent of extreme storms and thus the magnitude of a storm prior to an extreme storm is not related to the magnitude of the extreme storm. This approach is based on the findings of studies on antecedent storms conducted in Washington State[5], British Columbia[7], and miscellaneous studies conducted by the National Weather Service[12].

The chance occurrence of storms/floods antecedent to an extreme storm in the SEFM model is reflected in the magnitude of antecedent soil moisture conditions, initial streamflows, and initial reservoir levels, which vary seasonally. Thus, it is possible to have wet soil conditions, high streamflows, and high reservoir levels prior to an extreme storm, but the likelihood/magnitude of these hydrometeorological conditions are not related to the magnitude of the extreme storm.

This summary report describes the analysis of storms both antecedent and posterior to the occurrence of extreme storms for the west face of the Sierra Mountains. The analysis is intended to answer the question whether larger antecedent storms should be expected in combination with larger extreme storms, or if the storm magnitudes are unrelated. If antecedent/posterior storms are found to be correlated with extreme storms in the study area, changes would be required in the SEFM model to accommodate these storm amounts. If antecedent/posterior storms and extreme storms are found to be independent, then the SEFM model can be utilized as currently configured.

AMERICAN RIVER STUDY AREA

The American River watershed is located on the west face of the Sierra Mountains at/near latitude 39°00′N. The study area (Figure 1) for all precipitation analyses is comprised of the west face of the Sierra Mountains and areas immediately adjacent to the Sierra Mountains between latitude 36°30′N and 41°00′N. This includes three geographic/climatic regions (Table 1). All extreme storms and associated antecedent and posterior storms used in this analysis were based on precipitation stations located in Region 3 residing on the west face of the Sierra Mountains.

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

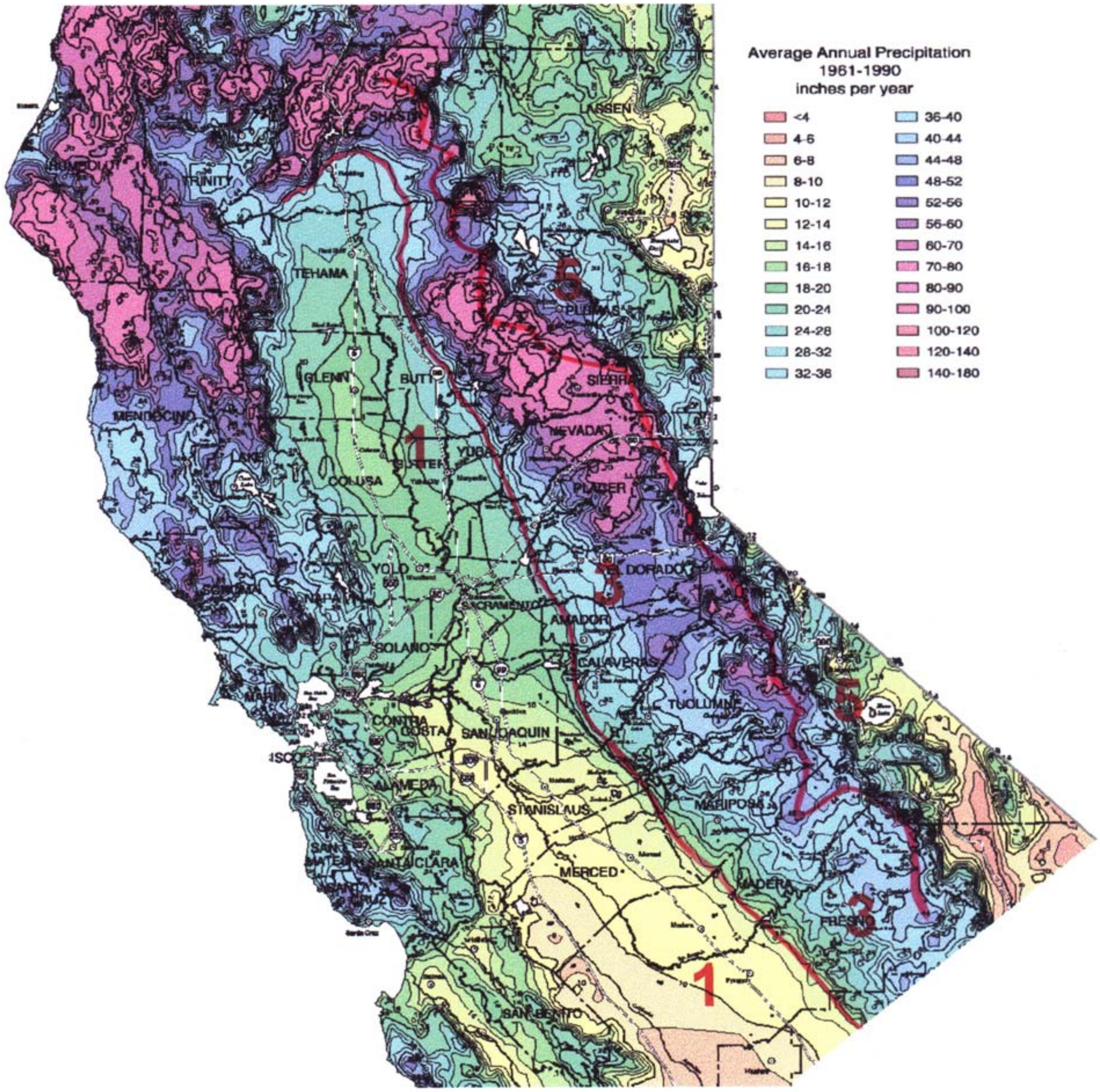


Figure 1 - Geographic/Climatic Regions of American River Study Area
Mean Annual Precipitation Base Map from PRISM (Daly[2])

ANALYSIS PROCEDURE

In prior studies of antecedent storms, a frequency perspective has been found to allow a straightforward interpretation of the behavior of antecedent storms (Schaefer[5,7]). The analysis is accomplished by examining the relationship between recurrence intervals of extreme storms and antecedent/posterior storms. The recurrence intervals for extreme storms are based on the findings of regional precipitation frequency analyses using annual maxima series data. Antecedent storms are often of a magnitude that occur several times per year and thus estimates of recurrence intervals are based on development of partial duration series data.

A variety of definitions have been used by other investigators in analyzing antecedent and posterior precipitation. Thus, it is important to clearly define the meaning of terms as used in this analysis.

Extreme Storm

Extreme storms are defined in the same manner as that used in the seasonality analysis[9]. Extreme storms were identified as those storms/storm dates where the observed 72-hour precipitation amounts exceeded the 10-year event at three or more precipitation stations in the study area.

Antecedent Storms

Antecedent precipitation was examined within the 15-day period prior to the occurrence of an extreme storm at a given station. This included determination of the maximum 3-day precipitation and maximum 10-day precipitation within the 15-day period prior to the extreme storm.

Posterior Storms

Posterior precipitation was examined within the 15-day period following the occurrence of an extreme storm at a given station. This included determination of the maximum 3-day precipitation and maximum 10-day precipitation within the 15-day period following the extreme storm.

Outline of Analysis Procedure

The analysis of antecedent and posterior storms proceeded as follows:

- The catalog of 72-hour extreme storms (Appendix A) that was developed for use in the seasonality analysis[9] provided the database of extreme events. This database is comprised of storms/storm dates where observed 72-hour precipitation amounts exceeded the 10-year event at three or more precipitation stations on the west face of the Sierra Mountains. This provided 35 extreme storms and associated antecedent and posterior storms for analysis.

- For each extreme storm, the precipitation measurement station where the storm was the rarest (smallest annual exceedance probability) was selected for use in the analysis.

- The regional growth curves obtained from the regional precipitation frequency analysis for the American River study area (Schaefer[8]) were used in combination with at-site mean values to estimate the annual exceedance probability for each 72-hour extreme storm. In most cases, the at-site mean values were based on the 1966-1999 period. However, the period of record at some stations did not cover the entire 1966-1999 period and in those cases the full record was used to estimate the at-site mean value.

- For each storm date/station, the 15-day period prior to the extreme storm was examined and the greatest 3-day and 10-day precipitation amounts were recorded as antecedent storms.

- For each storm date/station, the 15-day period following the extreme storm was examined and the greatest 3-day and 10-day precipitation amounts were recorded as posterior storms.

- Partial duration series data were assembled for the 3-day and 10-day durations for each station used in the analysis. The threshold for storms to be included in a station's dataset was taken sufficiently low to include the antecedent and posterior storms of interest at the particular station and duration. The recurrence intervals of the antecedent/posterior storm amounts were then estimated using a standard plotting-position formula (Cunane[1], Stedinger[10]) based on the full period of record at the station.

- Scatterplots were prepared for comparing the recurrence intervals for the 72-hour extreme storms and antecedent/posterior storms for the 3-day and 10-day durations. Standard regression analyses[3] were conducted and correlation coefficients were computed to evaluate the relationship between antecedent/posterior storms and extreme storms. Standard statistical tests were conducted to determine if the slopes of the regressions were significantly different from zero.

Computation of Annual Exceedance Probabilities for 72-Hour Extreme Storms

As discussed above, Annual Exceedance Probabilities (AEPs) for the 72-hour extreme storms were estimated based on the findings of the regional precipitation frequency analysis[8]. Regional growth curves were used in combination with at-site mean values to estimate the AEP of 72-hour extreme storm amounts. Recurrence intervals were then computed as the inverse of the AEP. An example of the precipitation magnitude-frequency relationship for the Yosemite Park Headquarters station is shown in Figure 2.

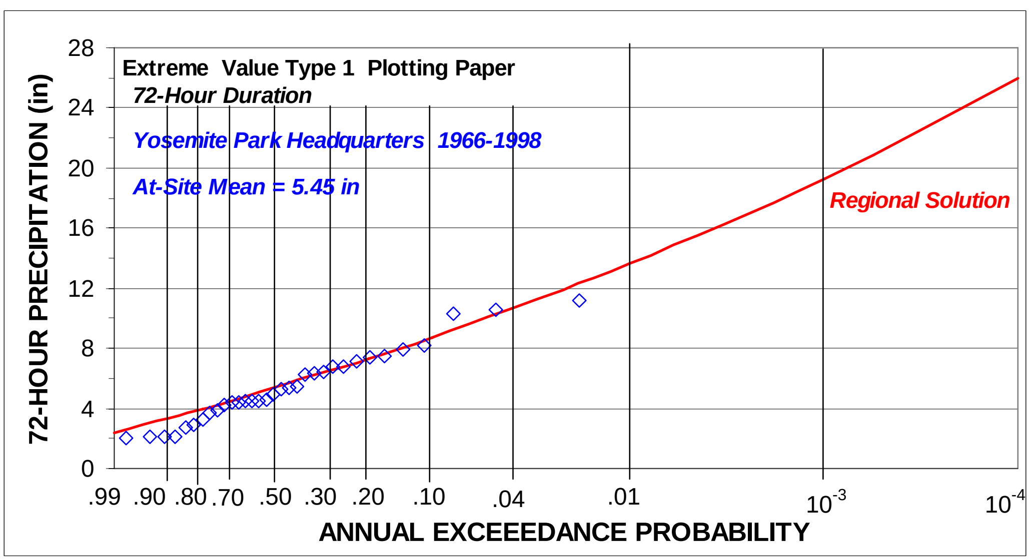
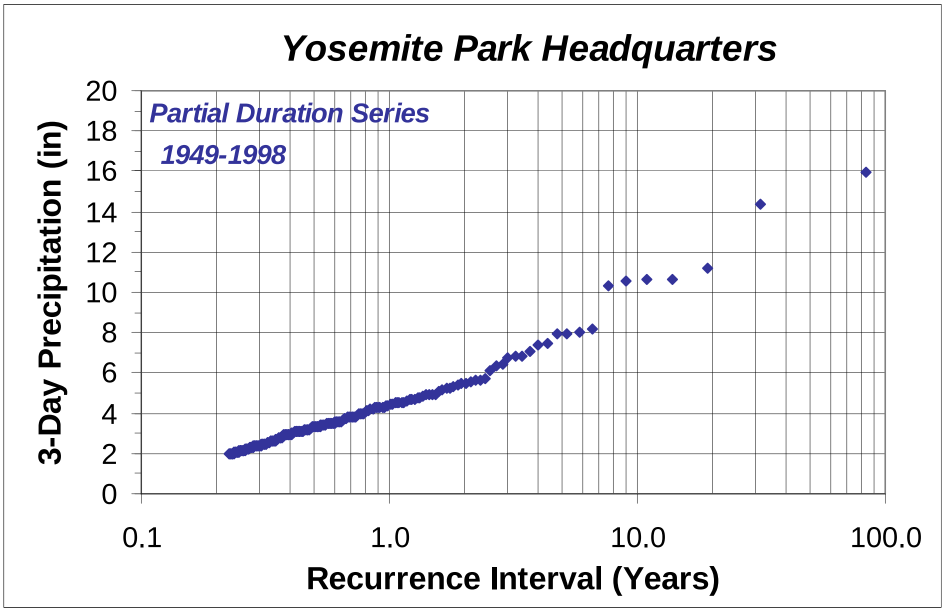
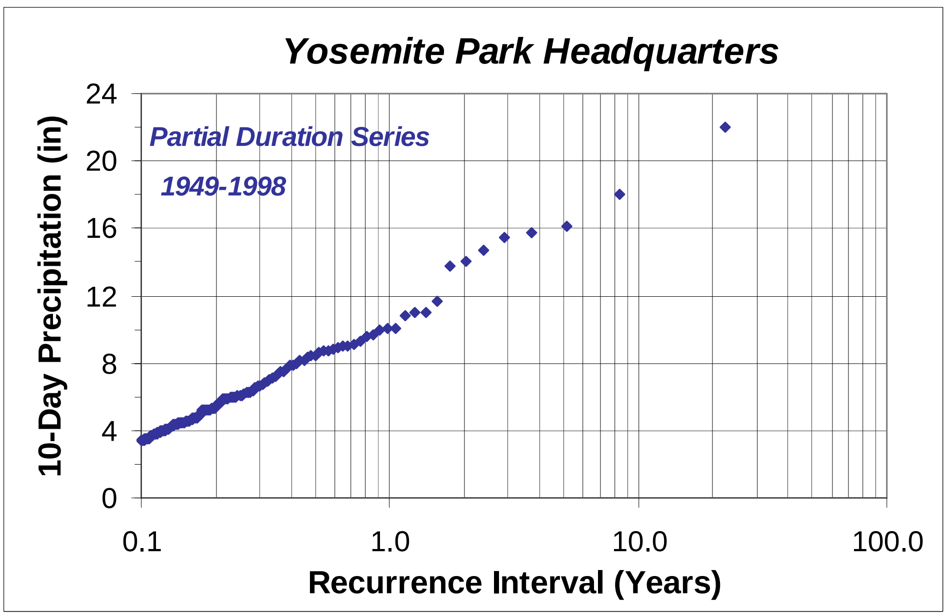


Figure 2 – 72-Hour Precipitation Magnitude-Frequency Curve for Yosemite Park Headquarters

Computation of Recurrence Intervals for Antecedent/Posterior Storms

Recurrence Intervals for 3-day and 10-day antecedent and posterior precipitation were estimated utilizing partial duration series data. The threshold for storms to be included in a station's dataset was taken sufficiently low to include the antecedent and posterior storms of interest at the particular station and duration. The recurrence intervals of the antecedent and posterior storm amounts were estimated using a standard plotting-position formula (Cunane[1], Stedinger[10]) based on the full period of record at the station. Examples of the precipitation magnitude-frequency relationship for the partial duration series are shown in Figures 3a,b for the Yosemite Park Headquarters station.





Figures 3a,b – Magnitude-Frequency Curves for 3-Day and 10-Day Precipitation for Yosemite Park Headquarters using Partial Duration Series Data

RELATIONSHIP BETWEEN ANTECEDENT/POSTERIOR STORMS AND EXTREME STORMS

Standard regression analyses were conducted to examine the relationship between recurrence intervals of antecedent/posterior storms and extreme storms. No significant correlation was found to be present between extreme storms and antecedent storms at the 3-day and 10-day durations. Likewise, no significant correlation was found between extreme storms and posterior storms at the 3-day and 10-day durations. In all four cases, the slope of the regression was found not to be significantly different from zero. The scatterplots for antecedent precipitation are shown in Figures 4a,b and the scatterplots for the posterior precipitation are shown in Figures 5a,b.

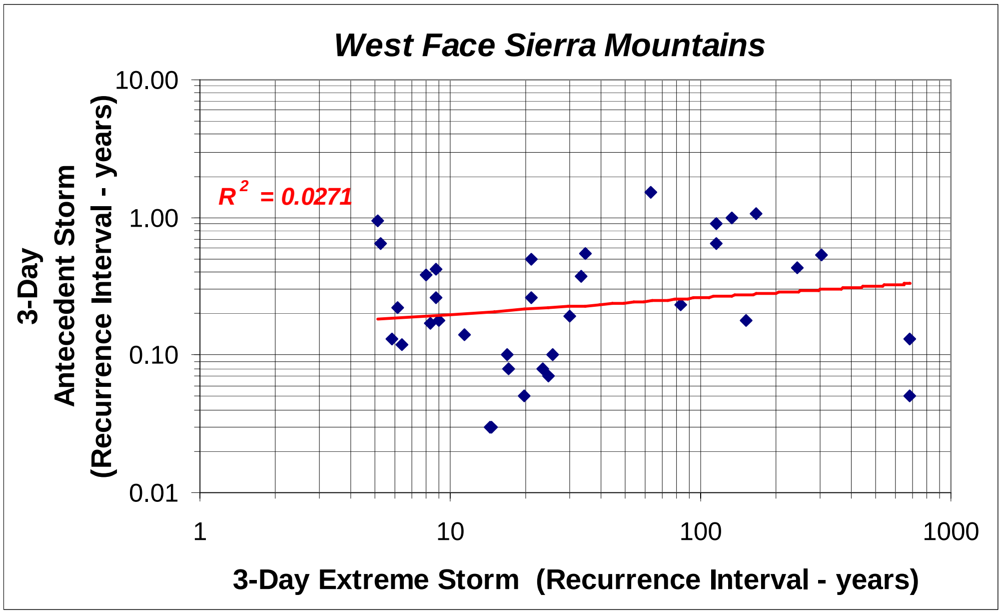


Figure 4a – Relationship Between 3-Day Antecedent Precipitation and 72-Hour Extreme Storm Precipitation for the West Face of the Sierra Mountains

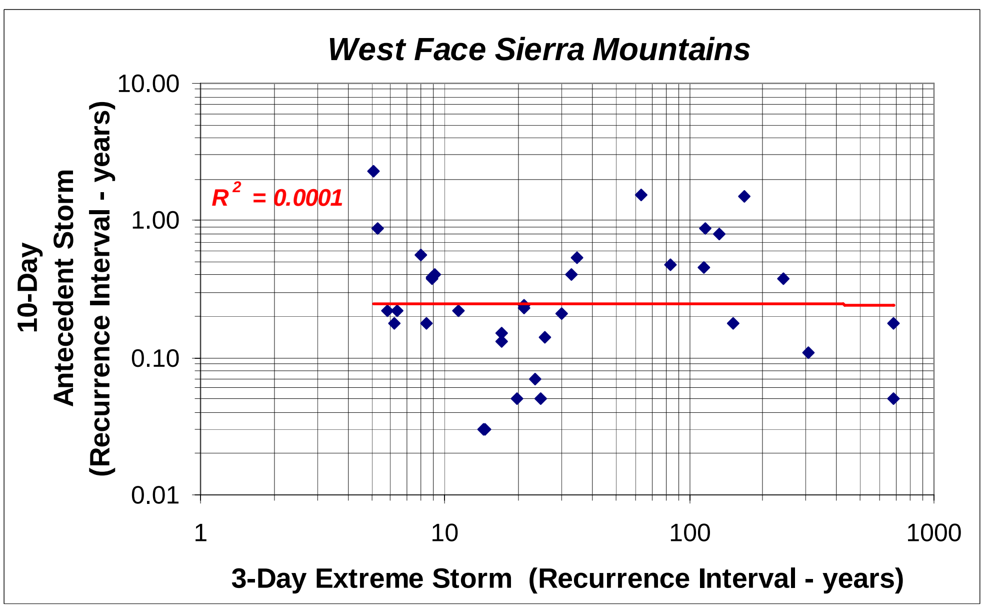


Figure 4b – Relationship Between 10-Day Antecedent Precipitation and 72-Hour Extreme Storm Precipitation for the West Face of the Sierra Mountains

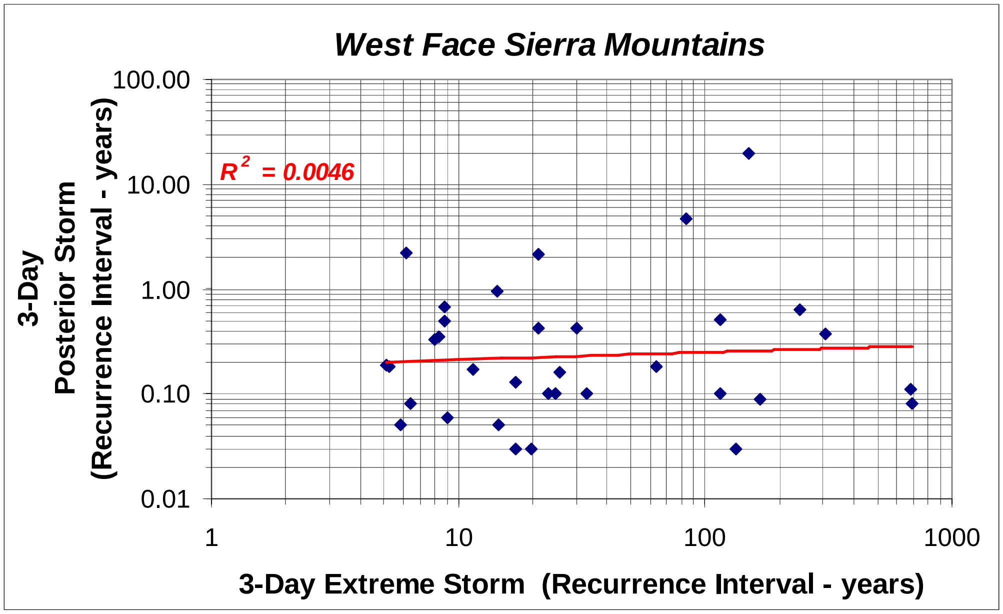


Figure 5a – Relationship Between 3-Day Posterior Precipitation and 72-Hour Extreme Storm Precipitation for the West Face of the Sierra Mountains

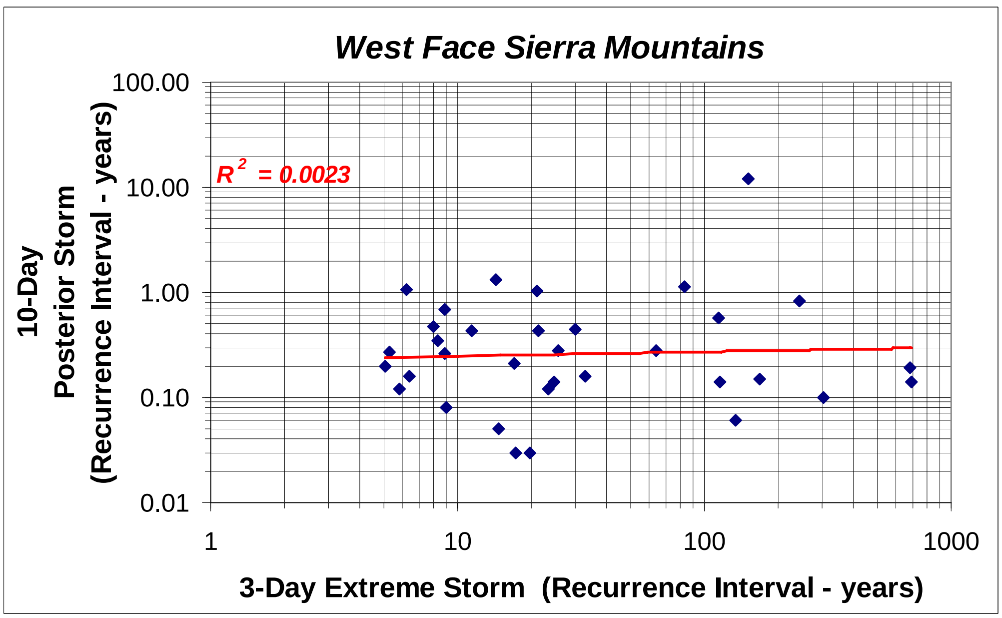


Figure 5b – Relationship Between 10-Day Posterior Precipitation and 72-Hour Extreme Storm Precipitation for the West Face of the Sierra Mountains

FINDINGS/CONCLUSIONS

A review of the Figures 4a,b and 5a,b shows that the recurrence intervals of both antecedent and posterior precipitation are commonly of a magnitude that occurs several times each year. Antecedent and posterior storms are of a magnitude that would be expected to commonly occur by chance during the winter storm season. Further, there is no trend to indicate that the magnitude of the antecedent or posterior storms is changing with the magnitude of the extreme storm. The data and analyses strongly support that antecedent precipitation and posterior precipitation can be treated as independent of the magnitude of the extreme storm.

REFERENCES

1. Cunnane, C, Unbiased Plotting Positions - A Review, Journal of Hydrology, 37, 205-222, 1978.

2. Daly, C, PRISM, Parameter-Elevation Regression on Independent Slopes Model, Oregon State University, Oregon Climate Service, 1994.

3. Helsel, DR, and Hirsch, RM, Statistical Methods in Water Resources, Studies in Environmental Science 49, Elsevier, 1992.

4. NWS, National Weather Service, Hydrometeorological Report 59, Probable Maximum Precipitation for California, U.S. Department of Commerce, NOAA, US Weather Bureau, Washington DC, February 1999.

5. Schaefer, MG, Characteristics of Extreme Precipitation Events in Washington State, Washington State Dept. of Ecology, Report 89-51, October 1989.

6. Schaefer, MG, Magnitude-Frequency Characteristics of Precipitation Annual Maxima in Southern British Columbia, MGS Engineering Consultants, Inc., prepared for BChydro Power Supply and Engineering, October 1999.

7. Schaefer, MG, and Barker BL, Stochastic Modeling of Extreme Floods for Mica Dam, MGS Engineering Consultants, Inc., prepared for BChydro Power Supply and Engineering, December 1999.

8. Schaefer, MG, Precipitation Magnitude-Frequency Characteristics for the American River Watershed, MGS Engineering Consultants, Inc., prepared for US Army Corps of Engineers Hydrologic Engineering Center, January 2000.

9. Schaefer, MG, Seasonality Analysis of Extreme Storms for the American River Watershed, MGS Engineering Consultants, Inc., prepared for US Army Corps of Engineers Hydrologic Engineering Center, November 1999.

10. Stedinger, JR, Vogel RM, and Foufoula-Georgiou, E, Frequency Analysis of Extreme Events, Chapter 18, *Handbook of Hydrology*, McGraw Hill, 1992.

11. SEFM, Stochastic Event Flood Model, MGS Engineering Consultants, Inc., 1998.

12. Vogel, J, Personal Communication, National Weather Service, Kansas City, MO.

Appendix A

CATALOG OF EXTREME STORMS

AND ASSOCIATED

ANTECEDENT AND POSTERIOR STORMS

CATALOG OF EXTREME STORMS AND ASSOCIATED ANTECEDENT AND POSTERIOR STORMS FOR WEST FACE OF SIERRA MOUNTAINS

Station ID	Station Name	Gage	Latitude	Longitude	EXTREME EVENT			ANTECEDENT		POSTERIOR	
					72-Hour Amount (in)	Ratio to At-Site Mean	Storm Date	3-Day Amount (in)	10-Day Amount (in)	3-Day Amount (in)	10-Day Amount (in)
04-1018	BOWMAN DAM	Hourly	39.5	120.7	10.70	1.28	12/27/1983	5.70	9.40	2.70	4.50
04-1149	BUCKHORN	Daily	40.9	121.8	12.40	1.73	11/17/1981	5.15	5.29	7.54	10.53
04-1161	BUCKS LAKE	Hourly	39.9	121.2	23.40	2.62	12/23/1964	5.20	6.40	6.10	10.90
04-1497	CANYON DAM	Daily	40.2	121.1	8.62	1.60	01/22/1967	0.00	0.00	4.50	7.85
04-1653	CHALLENGE R S	Daily	39.5	121.2	17.21	1.93	12/11/1992	4.75	6.90	1.29	2.14
04-1700	CHESTER	Daily	40.3	121.2	6.11	1.30	02/06/1950	1.14	1.75	0.53	0.70
04-1700	CHESTER	Daily	40.3	121.2	7.78	1.66	02/22/1956	0.83	0.83	1.19	1.55
04-1700	CHESTER	Daily	40.3	121.2	10.96	2.33	01/10/1995	3.26	3.53	2.98	4.21
04-1878	COARSEGOLD 1 SW	Daily	37.3	119.7	7.50	1.76	12/22/1982	0.24	0.50	0.00	0.00
04-1912	COLFAX	Daily	39.1	120.9	18.97	3.15	10/13/1962	1.57	1.57	0.82	0.82
04-3093	FLORENCE LAKE	Hourly	37.3	119.0	14.45	3.36	02/02/1963	0.15	0.15	0.64	1.09
04-3384	GEORGETOWN R S	Hourly	38.9	120.8	11.20	1.64	02/16/1982	0.00	0.00	0.10	0.20
04-3397	GIANT FOREST	Daily	36.6	118.8	15.91	1.91	12/12/1937	0.37	0.37	1.00	1.00
04-3397	GIANT FOREST	Daily	36.6	118.8	16.04	1.92	01/23/1943	1.00	1.00	1.76	2.91
04-3397	GIANT FOREST	Daily	36.6	118.8	21.74	2.60	12/07/1966	6.01	7.69	0.00	0.00
04-5026	LODGEPOLE	Daily	36.6	118.7	19.79	2.66	01/21/1969	2.33	2.33	17.20	27.43
04-5026	LODGEPOLE	Daily	36.6	118.7	17.02	2.29	01/14/1980	7.32	7.41	2.04	3.34
04-5679	MINERAL	Daily	40.3	121.6	12.99	1.73	11/12/1973	3.21	3.87	4.40	6.27
04-5809	MONTGOMERY CREEK 2S	Hourly	40.8	121.9	8.46	1.33	12/28/1951	1.84	2.45	1.16	1.16
04-6136	NEVADA CITY	Daily	39.2	121.0	17.95	2.40	02/19/1986	5.98	9.28	1.53	1.53
04-6963	PLACERVILLE 2 W	Hourly	38.7	120.8	6.26	1.27	04/03/1958	3.60	7.18	1.76	1.76
04-7296	REDDING FIRE STN 2	Daily	40.6	122.4	7.64	1.42	01/13/1969	2.06	2.06	3.02	4.20
04-7581	ROUND MOUNTAIN PG&E	Daily	40.8	121.9	10.44	1.44	01/16/1974	4.84	6.83	5.22	5.22
04-7817	SAN JOAQUIN EXP RANG	Hourly	37.1	119.7	5.67	1.98	02/11/1962	1.10	1.10	1.78	2.41
04-8135	SHASTA DAM	Hourly	40.7	122.4	15.80	1.71	12/04/1980	0.40	0.70	0.00	0.00
04-8332	SODA SPRINGS 1 E	Hourly	39.3	120.4	10.34	1.46	12/21/1981	2.46	3.53	4.49	6.05
04-8332	SODA SPRINGS 1 E	Hourly	39.3	120.4	10.40	1.47	12/13/1995	1.90	3.80	0.30	0.40
04-8353	SONORA RS	Hourly	38.0	120.4	7.55	1.84	02/03/1945	0.22	0.22	0.64	1.05
04-8544	STIRLING CITY R S	Hourly	39.9	121.5	24.40	2.47	01/02/1997	8.10	15.10	0.90	0.90
04-8928	TIGER CREEK PH	Hourly	38.4	120.5	13.83	2.34	11/20/1950	2.32	4.58	6.64	6.90
04-9193	USONA 2N	Hourly	37.5	119.8	5.80	1.47	02/12/1973	2.50	3.60	2.40	3.10
04-9390	VOLTA POWER HOUSE	Hourly	40.5	121.8	5.68	1.52	01/15/1956	1.47	2.28	1.69	3.74
04-9482	WAWONA RANGER STATN	Hourly	37.5	119.7	13.50	2.04	03/11/1995	3.90	5.00	missing	missing
04-9582	WEST POINT	Daily	38.4	120.5	5.82	1.35	02/03/1998	2.17	2.22	4.74	6.47
04-9855	YOSEMITE PARK HDQTRS	Hourly	37.8	119.6	15.98	2.89	12/24/1955	3.36	3.53	2.83	3.36