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

Flood-Frequency Curve Extension

September 2005

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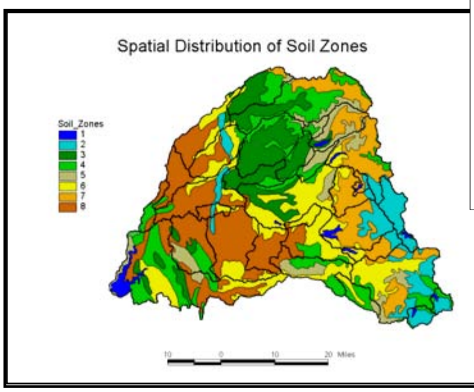

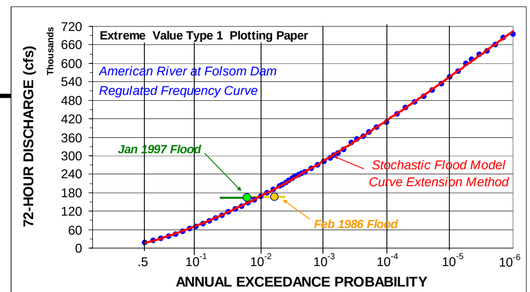

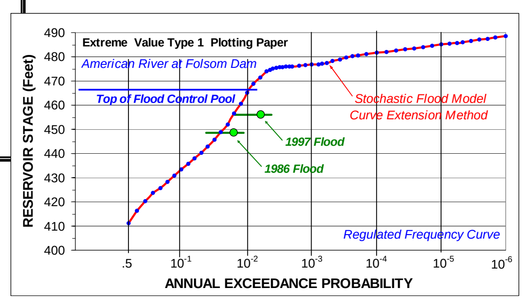

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EXECUTIVE SUMMARY

A stochastic flood model was developed for the American River watershed tributary to Folsom Dam for use in developing flood-frequency estimates for extreme floods. The stochastic flood model utilized a deterministic flood computation model (HEC-1) and treated the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures were used to allow the climatic and storm related input parameters to vary in accordance with that observed in nature. Hydrometeorological inputs that were treated as variables included: seasonality of storm occurrence; magnitude of extreme storm; temporal and spatial distribution of storms; temporal temperature pattern during the storm; sea-level and freezing level temperatures during the storm; antecedent precipitation; antecedent snowpack; antecedent soil moisture; initial storage in major upstream reservoirs; and initial storage in Folsom Lake.

Flood-frequency estimates of extreme floods were made utilizing the stochastic flood model to extend the existing 3-day flood-frequency relationship. This was accomplished in two stages. The first stage utilized four historical floods to calibrate the HEC-1 watershed model. The second-stage was accomplished by adjusting the stochastic flood model to match the 100-year discharge that was computed from the systematic record while reproducing the flood-frequency characteristics of the observed 3-day record to the maximum extent possible.

75,000 computer simulations were conducted to develop magnitude-frequency relationships for the flood characteristics of peak discharge, maximum 24-hour discharge, maximum 72-hour discharge, maximum reservoir release, runoff volume, and maximum reservoir level. Each simulation contained a set of climatic and storm parameters that were selected through Monte Carlo procedures based on the historical record and collectively preserved dependencies between the hydrometeorological input parameters. Execution of the watershed hydrologic model HEC-1 and reservoir routing of the inflow floods yielded the annual maxima flood characteristics of interest.

The flood-frequency relationships generated by the flood model were used to estimate the Annual Exceedance Probability (AEP) of selected flood characteristics. The AEP for floodwaters reaching the top of flood control pool (466.0 feet) was estimated to be 0.0095 (1:105). The AEP for floodwaters reaching the top of dam elevation (480.5 feet) was estimated to be $2x10^{-5}$ (1:5,000). The maximum 72-hour discharge in the US Corps of Engineers Probable Maximum Flood (PMF) is 472,200 cfs and was estimated to have an AEP of $4x10^{-5}$ (1:25,000).

STOCHASTIC MODELING OF EXTREME FLOODS ON THE AMERICAN RIVER AT FOLSOM DAM FLOOD-FREQUENCY CURVE EXTENSION

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INTRODUCTION

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

The report provides an overview of the approach used in the stochastic flood model, a description of the watershed model used to compute inflow floods to Folsom Dam, brief descriptions of the hydrometeorological parameters that are inputs to the stochastic model, and discussion of the findings of the stochastic flood analyses. This summary report utilizes a format that provides brief discussions of the findings of the analyses of the various hydrometeorological inputs without repeating those reports here, as many of the prior analyses are substantial works in themselves. Detailed descriptions of the various hydrometeorological inputs and the probabilistic methods of analysis can be found in the original reports for each of the input parameters of interest and the majority of those reports are includes as appendices here.

OVERVIEW OF THE STOCHASTIC APPROACH

The basic concept employed in the stochastic approach is the computer simulation of multi-thousand years of flood annual maxima. This is accomplished by utilizing a deterministic flood computation model (HEC-1) and treating the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the climatic and storm related input parameters to vary in accordance with that observed in nature. Multi-thousand years of extreme storm and flood annual maxima are generated by computer simulation. The simulation for each year contains a set of climatic and storm parameters that were selected through Monte Carlo procedures based on the historical record and collectively preserve dependencies between the hydrometeorological input parameters.

Execution of the watershed hydrologic model HEC-1 and reservoir routing of the inflow floods provides the computation of a corresponding multi-thousand year series of annual maxima flood characteristics. Characteristics of the simulated floods such as peak discharge, maximum 24-hour discharge, maximum 72-hour discharge, maximum reservoir release, runoff volume, and maximum reservoir level are the flood parameters of interest. An annual maxima series is created for each of these flood parameters and the values are ranked in descending order of magnitude and a non-parametric plotting position formula and probability-plots are used to describe the magnitude-frequency relationships.

Stochastic Event Flood Model

The stochastic flood model employed here is considered an event model. It is termed an event model because each simulation consists of modeling the flood and reservoir response from a specific storm event. Thus, each simulation produces one maximum for flood peak discharge, maximum 24-hour discharge, maximum 72-hour discharge, maximum reservoir release, runoff volume, and maximum reservoir level. These maxima are used in assembling annual maxima series representing multi-thousand years of flood events.

AMERICAN RIVER WATERSHED MODEL

The HEC-1 hydrologic model[37] was used for computing the flood response to rainfall and rain-on-snow events. The original Sacramento District HEC-1 watershed model[4] for the American River (Figure 1a) was modified to provide the versatility needed for conducting stochastic simulations throughout the storm season that historically spans the period from October through April. These changes included: subdividing the North Fork into five subbasins and increasing the number of subbasins in the model from 29 to 33 (Figure 1b); adding an interflow runoff component to the hydrograph computation for each subbasin; replacing the uniform loss rate method with a modified Holtan[8] method; adding a soil moisture accounting routine; adding the USBR snow compaction routine[35] providing the capability to simulate surface and interflow runoff on a distributed basis; and replacing the exponential decay routine for the recession limb of the hydrograph with a linear reservoir routing routine. These changes are discussed in detail in a prior report on calibration of the watershed model[30] (Appendix L).

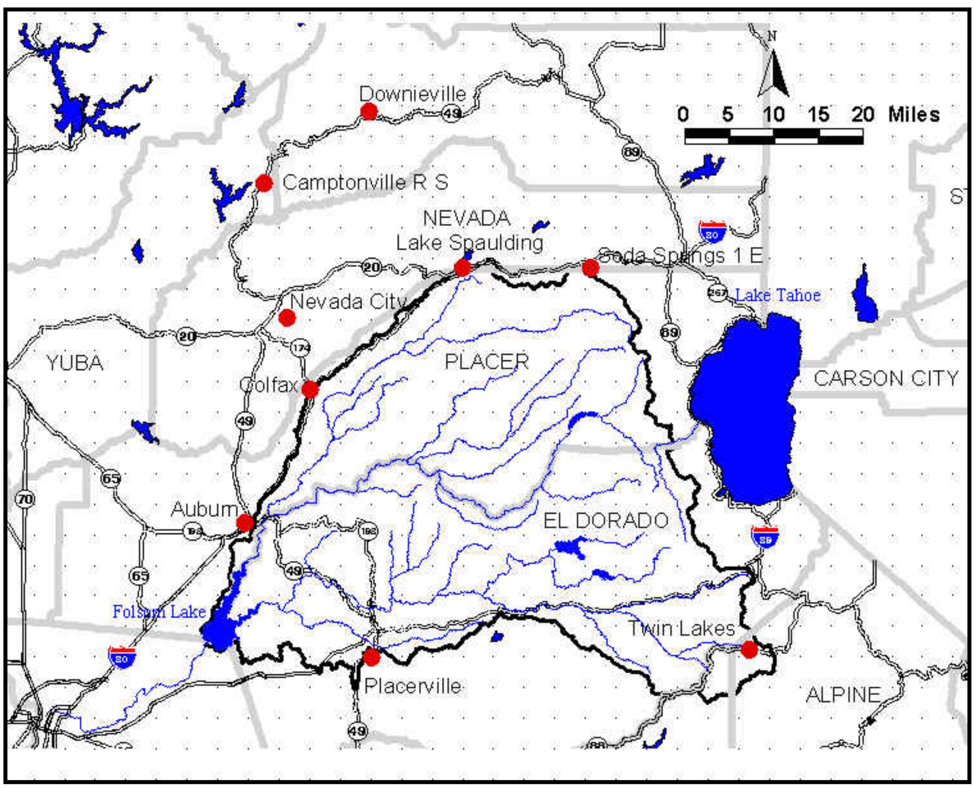

Figure 1a – American River Watershed above Folsom Dam and Surrounding Area

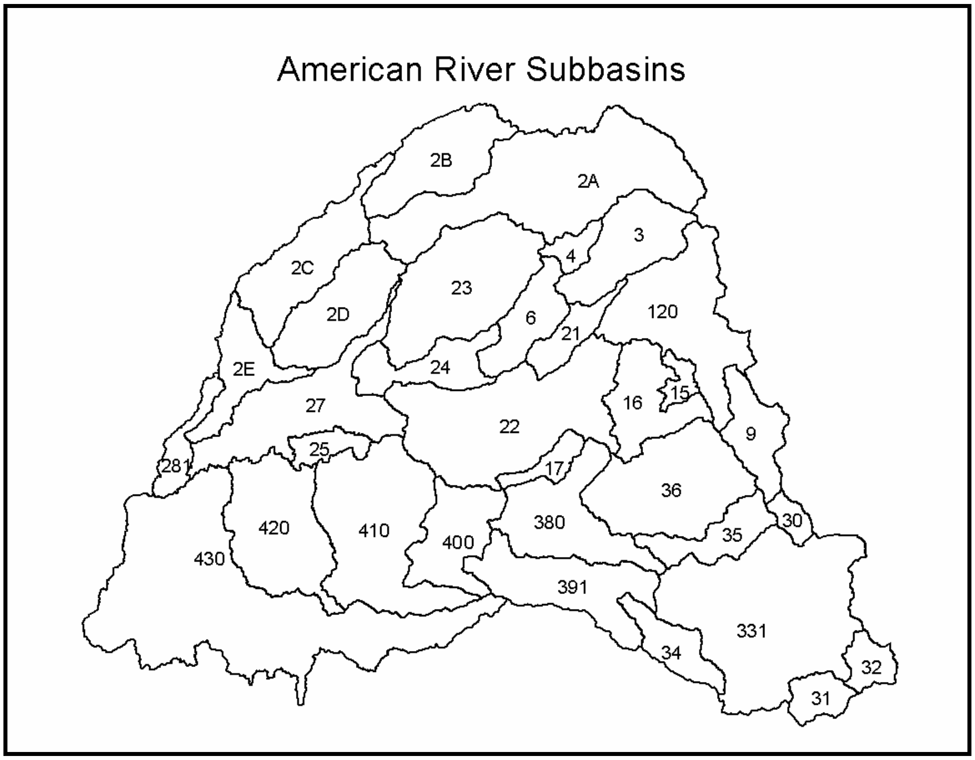

Figure 1b – Layout of 33-Subbasins for American River Watershed

Hydrologic Runoff Units (HRUs)
Hydrometeorological conditions vary dramatically across the American River watershed. This required that many of the hydrometeorological inputs be treated in a distributed manner. This was accomplished by subdividing the watershed into zones with common values of mean annual precipitation, elevation, and soil characteristics. This approach allowed for high spatial variability in allocating antecedent precipitation and snowpack, setting initial soil moisture conditions, applying the spatial and temporal precipitation patterns over the watershed, and computing surface and interflow runoff.

The distributed approach was accomplished through the use of Hydrologic Runoff Units (HRUs), wherein the American River watershed has been subdivided into 11 zones of mean annual precipitation[6,17], 9 elevation zones, and 8 soil zones. This resulted in 792 unique HRU combinations that were possible, of which, 263 HRU combinations actually occur in the watershed. The zones of mean annual precipitation are listed in Table 1a and depicted in Figure 2a. The elevation zones are listed in Table 1b and depicted in Figure 2b.

Eight soil zones were used to describe the soil characteristics for the American River watershed. These zones were identified through information contained in the NRCS STATSGO[33] database. To summarize, the eight soil zones were assembled based on NRCS soil associations[41,42,43,44] (Table 2, Figure 2c), where it was found that soil depth and bedrock parent material provided the greatest distinguishing characteristics between the various soil associations. In establishing the soil zones, soil zone 1 was reserved for water bodies. Soil zones 2 through 6 were ordered with respect to increasing soil depth above bedrock. Soil zone 7 was established for deep soils of glacial origin that had a semi-contiguous till or hardpan layer that locally restricts downward water movement. Soil zone 8 was established for moderately deep soils overlying steeply tilted and/or highly fractured metamorphic rock. The spatial distribution of the eight soil zones is depicted in Figure 2d.

Table 1a – Zones of Mean Annual Precipitation for the American River Watershed

MEAN ANNUAL PRECIPITATION (Inches)											
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Range	20-28	28-32	32-36	36-40	40-44	44-48	48-52	52-56	56-60	60-64	64-72
Median	26 in	30 in	34 in	38 in	42 in	46 in	50 in	54 in	58 in	62 in	67 in
Area (mi^2)	29.2	75.6	125.5	100.0	100.6	279.8	356.8	242.7	195.1	198.8	154.1
Area (%)	1.6%	4.1%	6.8%	5.4%	5.4%	15.1%	19.2%	13.1%	10.5%	10.7%	8.3%

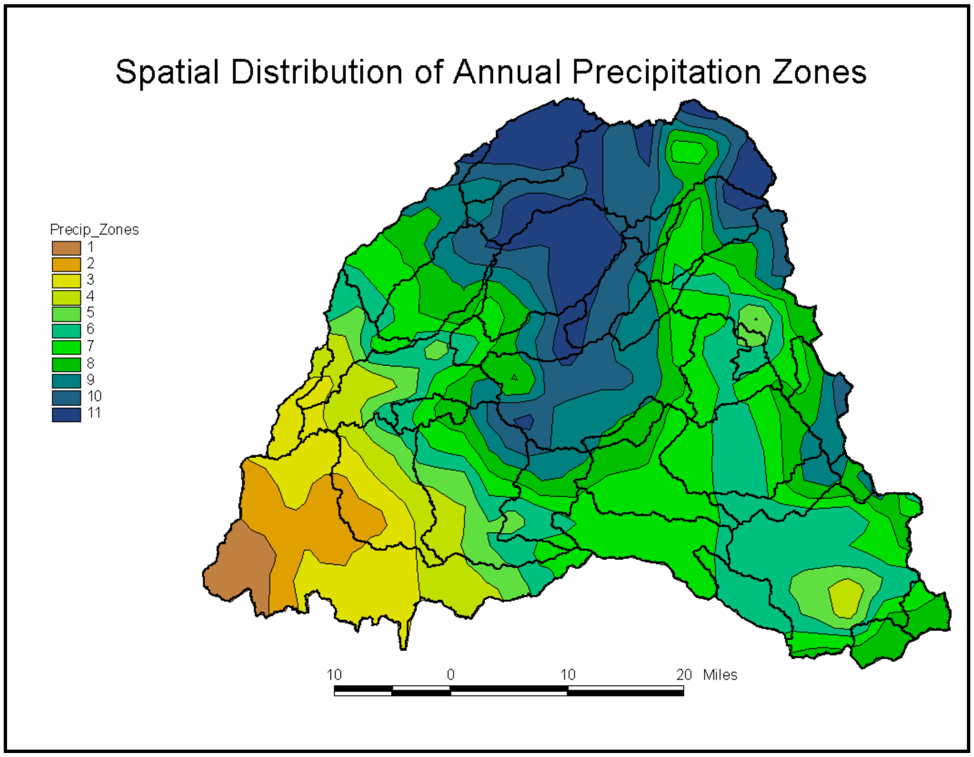

Figure 2a – Zones of Mean Annual Precipitation for the American River Watershed

Soil parameters for the eight soil zones were determined through calibration of the watershed model to four historical floods[30]. The Generalized Likelihood Uncertainty Estimation (GLUE[1]) methodology was used in the calibration of the watershed model. This yielded a parameter set of soil characteristics for the eight soil zones with the highest likelihood in replicating four historical floods (Table 3). Most soil zones are underlain by either highly weathered bedrock or highly fractured bedrock that results in greater moisture storage capacity than would otherwise be indicated by the relatively thin depth of soil coverage. Detailed information on soil characteristics is presented in a prior report (Appendix L) documenting the calibration of the watershed model[30].

Table 1b – Elevation Zones for the American River Watershed

ELEVATION ZONES (Feet)									
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Range	300-2400	2400-3200	3200-4000	4000-4800	4800-5600	5600-6400	6400-7200	7200-8000	8000-12000
Median	2000 feet	2800 feet	3600 feet	4400 feet	5200 feet	6000 feet	6800 feet	7600 feet	8400 feet
Area (mi^2)	424.5	194.0	175.1	206.4	244.0	224.5	193.7	126.9	69.2
Area (%)	22.8%	10.4%	9.4%	11.1%	13.1%	12.1%	10.4%	6.8%	3.7%

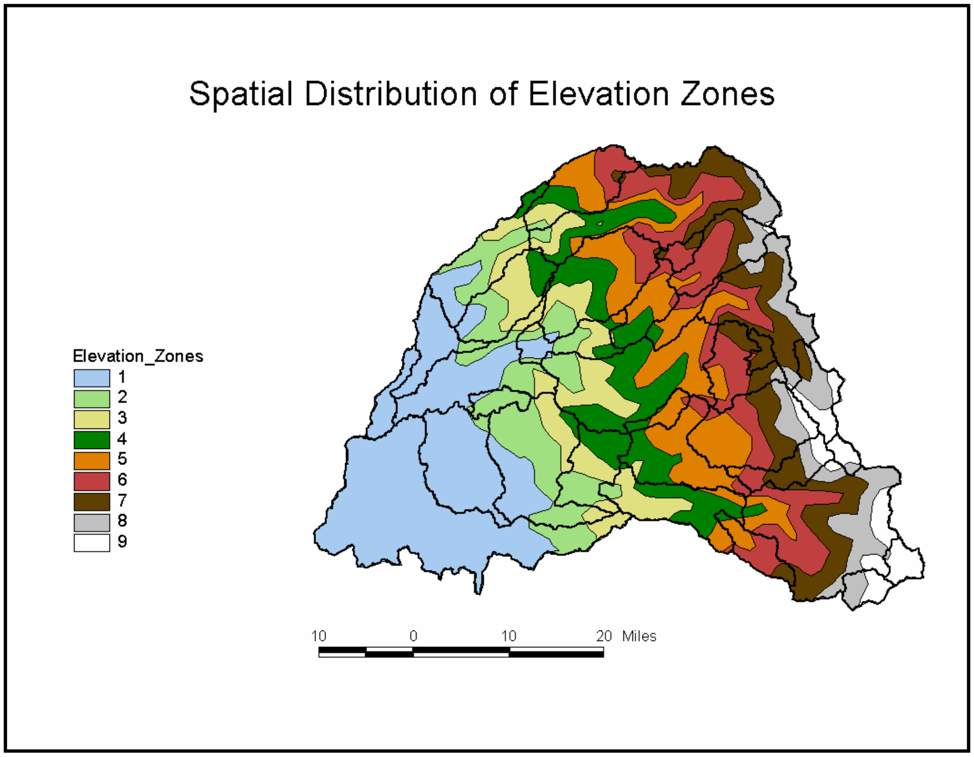

Figure 2b – Elevation Zones for the American River Watershed

Table 2 – Grouping of NRCS Soil Associations into Soil Zones with Similar Characteristics

SOIL ZONE	NRCS SOIL ASSOCIATION	NRCS MUID	AVERAGE SOIL DEPTH (in)	COMMENTS
2	Rock Outcrop-Dubakella	CA455	7.2	extensive rock outcrops and very thin soils
	Rock Outcrop-Cryumbrepts-Tinker	CA861	7.2	extensive rock outcrops and very thin soils
3	Rock Outcrop-Cagwin-Rubble Land	CA413	14.4	
	Rock Outcrop-Delpiedra-Henneke	CA434	11.5	
	Hurlbut-Rock Outcrop-Deadwood	CA857	19.1	
4	Waca-Meiss-Rock Outcrop	CA416	23.8	
	Auburn-Sobrante-Rock Outcrop	CA438	20.9	
	McCarthy-Ledmount-Crozier	CA850	25.5	
	Andic Cryumbrepts-Rock Outcrop-Meiss	CA862	25.0	
	Smokey-Woodseye-Rock Outcrop	CA863	24.6	
5	Holland-Rock Outcrop-Sheephead	CA316	35.0	
	Andregg-Caperton-Sierra	CA401	30.1	
	Sierra-Ahwahnee-Auberry	CA439	36.7	
	Waca-Windy-Jiggs	CA853	33.3	
6	Cohasset-Aiken-McCarthy	CA141	52.5	
	Holland-Musick-Hoda	CA443	57.5	
	Rescue-Rescue Variant-Argonaut	CA454	49.1	
	Chaix-Pilliken-Zeibright	CA851	43.1	
	Hartless-Neuns-Mieruf	CA852	46.8	
	Ledford-Notned-Bucking	CA855	43.6	
7	Tallac-Gerle-Rock Outcrop	CA860	39.6*	deep glacial soils, interbedded till layer
8	Jocal-Mariposa-Rock Outcrop	CA448	35.8	highly fractured and/or tilted bedrock
	Boomer-Rock Outcrop-Sites	CA453	36.4	highly fractured and/or tilted bedrock

* average soil depth for soil zone 7 is measured above cemented till or hardpan layer, till layer within deeper soil profile

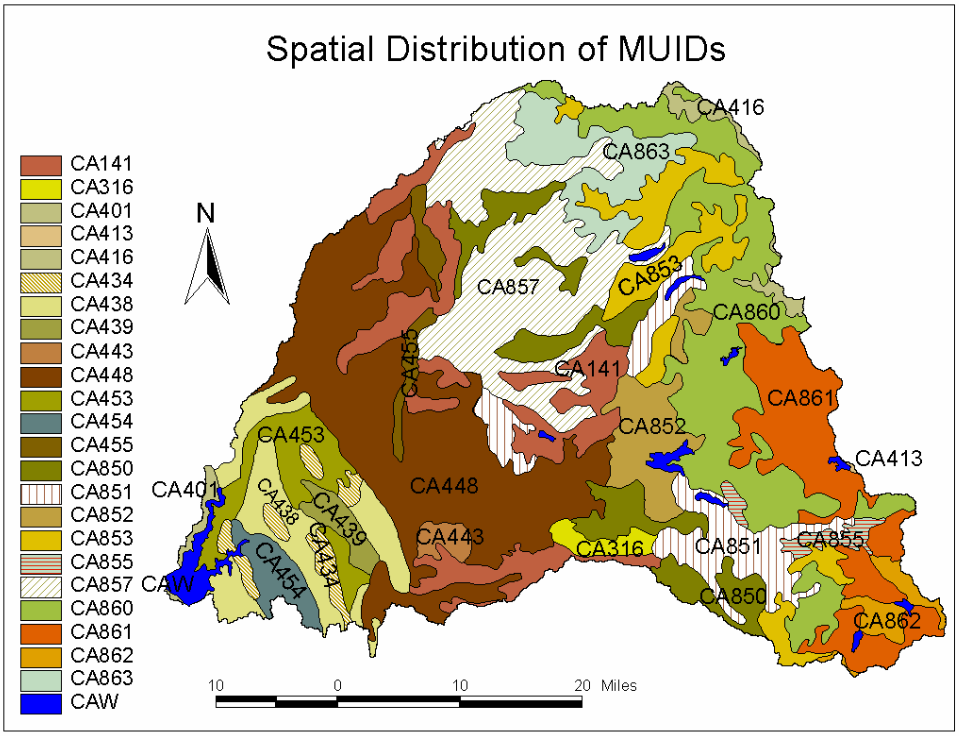

Figure 2c – NRCS Soil Associations as Delineated by Map Unit Identifiers (MUID) for the American River Watershed

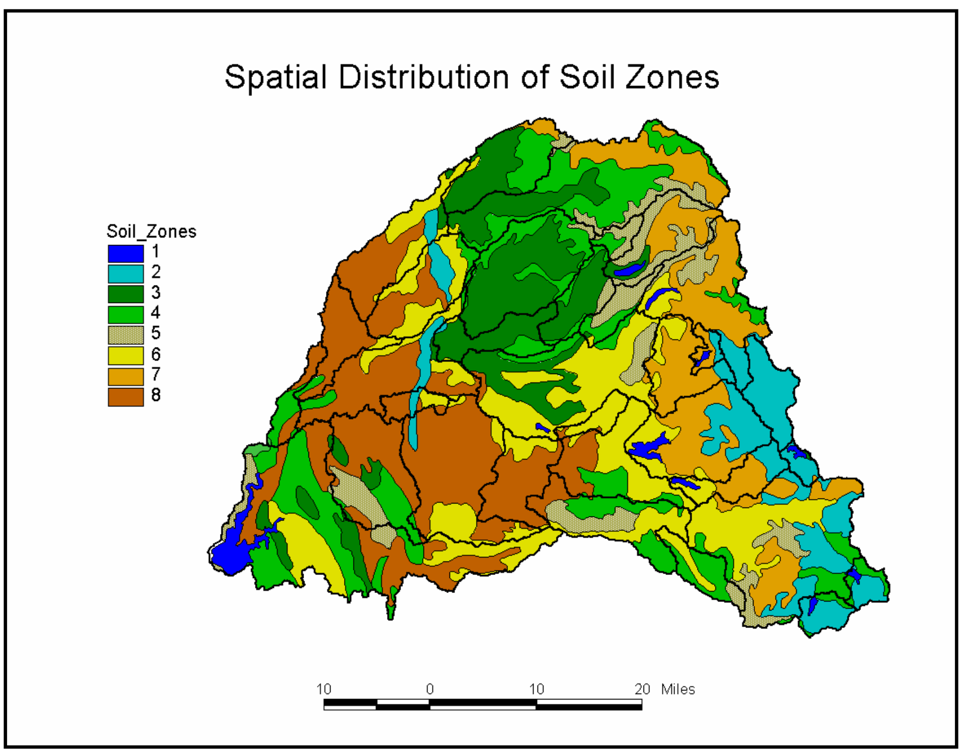

Figure 2d – Soil Zones for the American River Watershed

Table 3 – Final Calibrated Parameter Set of Soil Characteristics based on GLUE[1] Procedures

SOIL ZONE	MEDIAN SOIL DEPTH (in)	(f_d) DEEP PERCOLATION (in/hr)	(f_c) MINIMUM SURFACE INFILTRATION (in/hr)	(f_{max}) MAXIMUM SURFACE INFILTRATION (in/hr)	(S_{max}) EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (in)	COMMENTS
1	0	0.000	0.000	0.0	0.0	water bodies
2	5	0.022	0.071	3.2	3.8	very shallow soils over bedrock
3	15	0.016	0.071	3.2	11.3	
4	25	0.048	0.100	3.2	9.1	
5	35	0.023	0.065	3.2	13.7	
6	50	0.035	0.094	3.2	20.4	
7	36	0.023	0.060	3.2	12.6	underlain by deep outwash soils
8	40	0.078	0.136	3.2	17.1	fractured and/or tilted bedrock

Distributed Runoff Modeling
Surface and interflow runoff were computed on a distributed basis for each Hydrologic Runoff Unit (HRU) and then aggregated to the subbasin level (Figure 1b) for application by the HEC-1 watershed model. Specifically, surface runoff was converted to a runoff hydrograph using a unit-hydrograph and interflow runoff was converted to a runoff hydrograph using a linear reservoir routing routine. Surface runoff unit-hydrographs were applied within HEC-1 and all other runoff computations[32] were done externally to the HEC-1 watershed model.

Runoff was computed using a modified Holtan[8] approach which provided the capability to account for the variability in soil moisture during the fall and winter seasons and to provide the capability of modeling both surface runoff and interflow runoff. In particular, soil moisture accounting prior to the storm allows the soil moisture deficit and initial surface infiltration rate to vary during the storm season dependent upon the magnitudes of antecedent precipitation and evapotranspiration. A schematic of surface and interflow runoff for the modified Holtan method is shown in Figure 3.

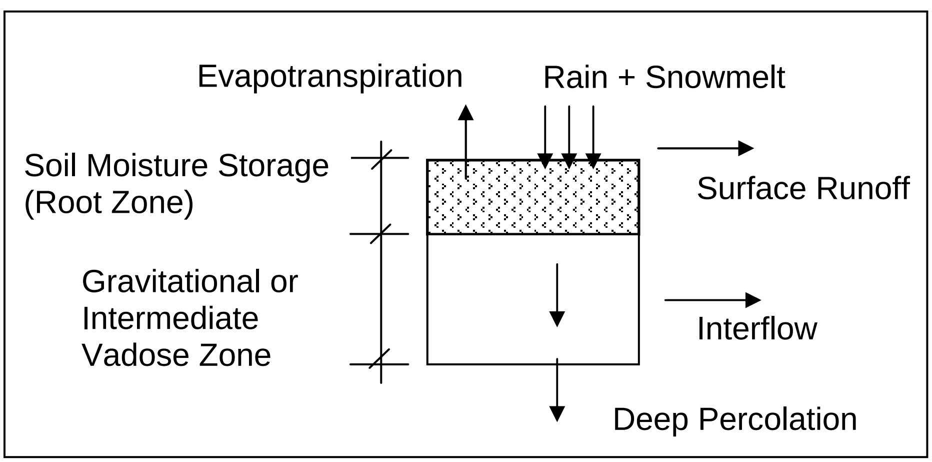

Figure 3 – Schematic of Soil Moisture and Runoff Processes Used in the Stochastic Model

In using the modified Holtan method, the surface infiltration rate at the start of the storm is dependent upon initial soil moisture conditions. Precipitation rates that exceed the surface infiltration rate produce surface runoff. As the moisture input to the soil continues during the storm, the soil column is further wetted and the soil moisture deficit decreases to zero. Concurrently, the surface infiltration decays to a minimum value of f_c (Equations 1a,b).

Interflow runoff occurs after the soil moisture deficit has been satisfied and the rate of moisture input to the soil column exceeds the deep percolation rate (f_d). The maximum interflow rate is the difference between the minimum surface infiltration rate f_c and the deep percolation rate f_d. Moisture lost to deep percolation does not return to the stream system during the simulation period. The modified Holtan method has the following form:

$$f = (C)\, S_d^{1.4} + f_c \tag{1a}$$

$$C = (f_{max} - f_c) / S_{max}^{1.4} \tag{1b}$$

where:
- f is the surface infiltration rate (in/hr),
- C is a soil specific constant that yields the maximum surface infiltration rate when the soil moisture content is equal to the wilting point,
- S_d is the soil moisture deficit (inches),
- S_{max} is the maximum soil moisture deficit, (soil moisture storage capacity (inches)
- f_{max} is the maximum surface infiltration rate (in/hr),
- f_c is the minimum surface infiltration rate (in/hr),
- f_d is the deep percolation rate (in/hr).

HYDROMETEOROLOGICAL INPUT PARAMETERS TO THE STOCHASTIC MODEL

Brief descriptions of the hydrometeorological input parameters are contained in the following sections to provide an overview of the various inputs to the stochastic model. Each of the hydrometeorological inputs was the subject of a separate analysis and report and each is described in a probabilistic manner that was developed through an analysis of historical data. More detailed discussion of the hydrometeorological parameters and the methods used to analyze the probabilistic characteristics of the input parameters are contained in separate reports.

Table 4 lists the hydrometeorological inputs to the stochastic model and the dependencies that exist in the stochastic simulation of a particular input. The magnitude of hydrometeorological inputs numbered five through twelve in Table 4 vary seasonally. Analyses of historical data and computer simulations were conducted for end-of-month conditions to allow the seasonal aspects to be properly represented.

Table 4 – Listing of Hydrometeorological Inputs to Stochastic Flood Model and Dependencies that Exist in Simulation of the Hydrometeorological Inputs

HYDROMETEOROLOGICAL INPUTS FOR STOCHASTIC MODEL			
MODEL INPUT		DEPENDENCIES	COMMENTS
1	Seasonality of Storm Occurrence	Independent	End-of-month storm occurrences
2	72-Hour Storm Magnitude	Independent	
3	Temporal and Spatial Distribution of Storms	Independent	24 Prototype Storms, 4-Day to 8-Day Patterns
4	Temperature Temporal Pattern	Varies by Prototype Storm	10-Day Pattern Indexed to Sea-Level Temperature and Freezing Level
5	Sea-Level Temperature	Storm Magnitude	For Day of Maximum Precipitation in storm
6	Freezing-Level	Sea-Level Temperature and Storm Magnitude	For Day of Maximum Precipitation in storm
7	Antecedent Precipitation	Independent	Precipitation Oct 1st to Date of Storm Occurrence Varies with Zones of Mean Annual Precipitation
8	Antecedent Snowpack	Antecedent Precipitation	Varies by Zones of Mean Annual Precipitation and Elevation
9	Antecedent Soil Moisture	Antecedent Precipitation Antecedent Snowpack	Varies by Zones of Mean Annual Precipitation, Elevation and Soil Type
10	Storage in Upstream Reservoirs	Antecedent Precipitation	Preserves Cross-Correlation of Storage in 5 Upstream Reservoirs
11	Initial Streamflow	Independent	Mean Monthly Inflow to Folsom Reservoir
12	Storage in Folsom Lake	Antecedent Precipitation	Utilizes Folsom Rule Curves and Storage in 5 Upstream Reservoirs

Seasonality of Storm Occurrence

The seasonality of extreme storms was defined by the monthly distribution of the historical occurrences of extreme storms on the west face of the Sierra Mountains for the 72-hour duration (see Seasonality Report[18], Appendix A). The storm dates were converted to numerical dates that were found to be well fitted by a Normal distribution. Figure 4 depicts the distribution of dates of storm occurrence that were used as input to the stochastic model.

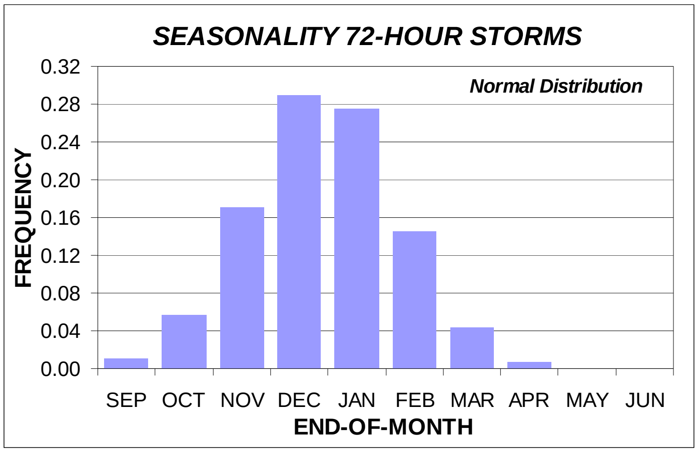

Figure 4 – Seasonality of Extreme Storms for American River Watershed

Magnitude of 72-Hour Precipitation within Extreme Storms

The 72-hour basin-average precipitation-frequency relationship was developed through regional analyses of point precipitation and spatial analyses to determine basin-average precipitation. The methods of analysis and findings of those analyses are described in reports on Regional Precipitation-Frequency Analysis[20] and an Uncertainty Analysis of Precipitation-Frequency[25] (Appendix C). The 72-hour basin-average precipitation-frequency relationship used for conducting the stochastic simulations is depicted in Figure 5 and regional L-moment ratios[9] and Kappa distribution parameters[9] are listed in Tables 5a,b.

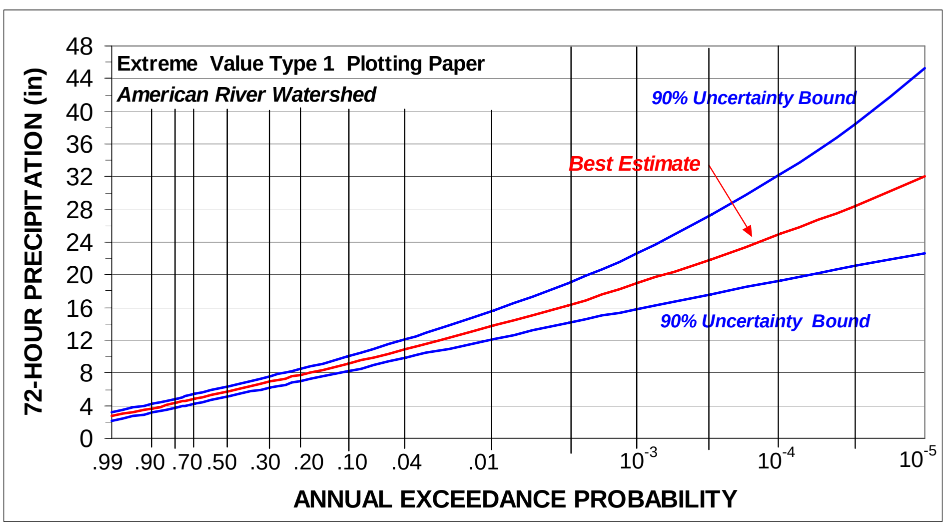

Figure 5 – Computed 72-Hour 1862-mi^2 Precipitation-Frequency Curve and 90% Uncertainty Bounds

Table 5a – Estimates of Population L-Moments for
Basin-Average 72-Hour 1862-mi^2 Precipitation
for American River Watershed

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

Table 5b – Distribution Parameters and Product-Moments
for Four-Parameter Kappa Distribution for Basin-Average 72-Hour 1862-mi^2 Precipitation
for American River Watershed

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

Temporal and Spatial Distribution of Storms

The historical storm record for the American River watershed for the period from 1950 through 2002 was reviewed and 37 candidate storms[21] were identified for analysis. Twenty-four of the largest storms were selected from this group for use in the stochastic generation of storms. Spatial and temporal storm templates were developed for these storms to produce 24 prototype storms. A spatial template contains the spatial distribution of precipitation over the watershed, comprised of the 72-hour precipitation amount for each subbasin that sums to the 72-hour basin-average precipitation for the watershed. The temporal template consists of 33 dimensionless mass curves, one mass curve for each of the 33 subbasins. Construction of the storm templates in this manner allows for scaling of the prototype storms to any desired magnitude.

Detailed information on the selection of the 24 storms and the methods for creating the storm templates is contained in the report on stochastic storm resampling[27](Appendices D,E) General characteristics of the 24 prototype storms are listed in Table 6. Examples of the basin-average temporal patterns for three of the prototype storms are shown in Figures 6a,b,c. The temporal patterns in these figures have been scaled to a 72-hour basin-average amount of 19-inches (10^{-3} AEP) to allow comparisons between storm temporal patterns.

Spatial distributions of 72-hour precipitation for the storms of February 1986 and January 1997 are shown in Figures 6d,e. These spatial patterns are for the 72-hour precipitation amounts actually recorded in the storms and have not been scaled to a common level for comparison. Nonetheless, they provide insight into the variation in the relative magnitudes of precipitation across the watershed.

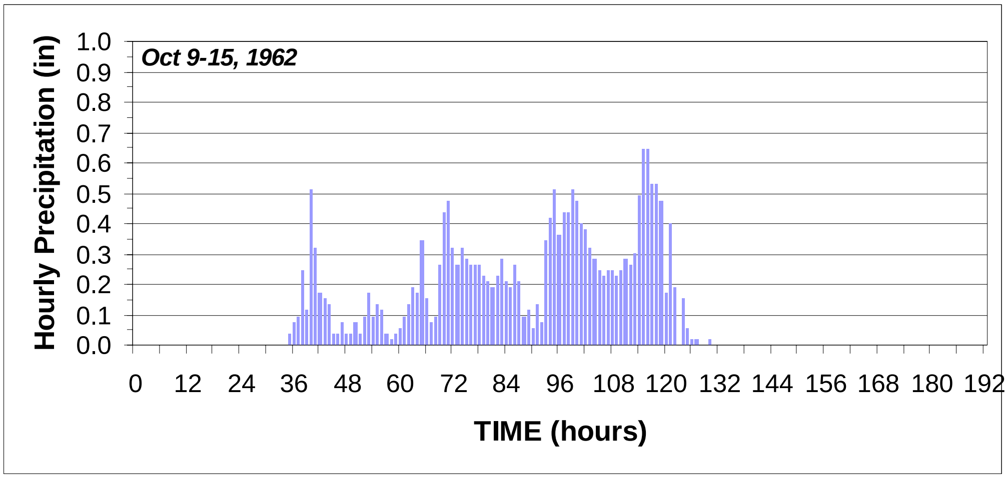

Figure 6a – Prototype Storm 1, Scaled to 72-Hour Basin-Average Precipitation of 19.0-inches

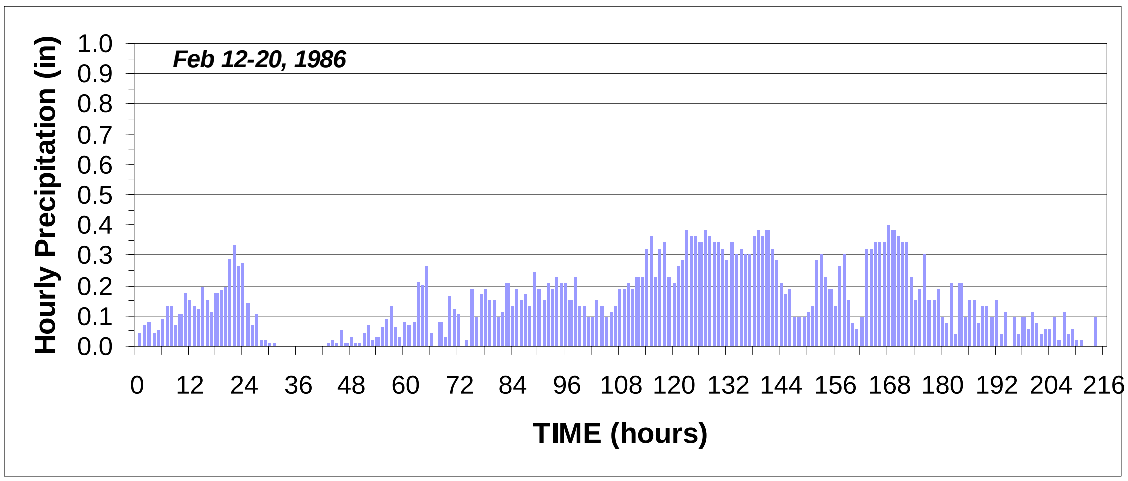

Figure 6b – Prototype Storm 2, Scaled to 72-Hour Basin-Average Precipitation of 19.0-inches

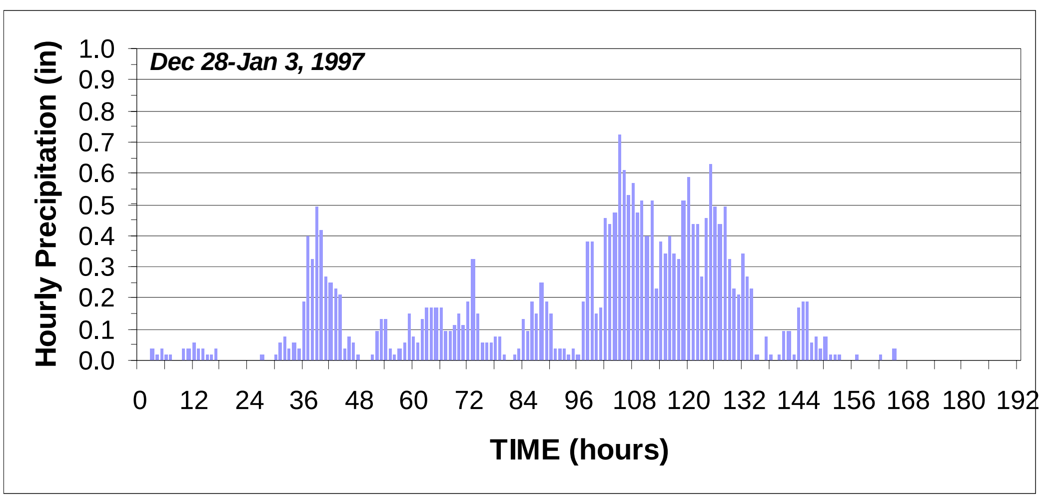

Figure 6c – Prototype Storm 7, Scaled to 72-Hour Basin-Average Precipitation of 19.0-inches

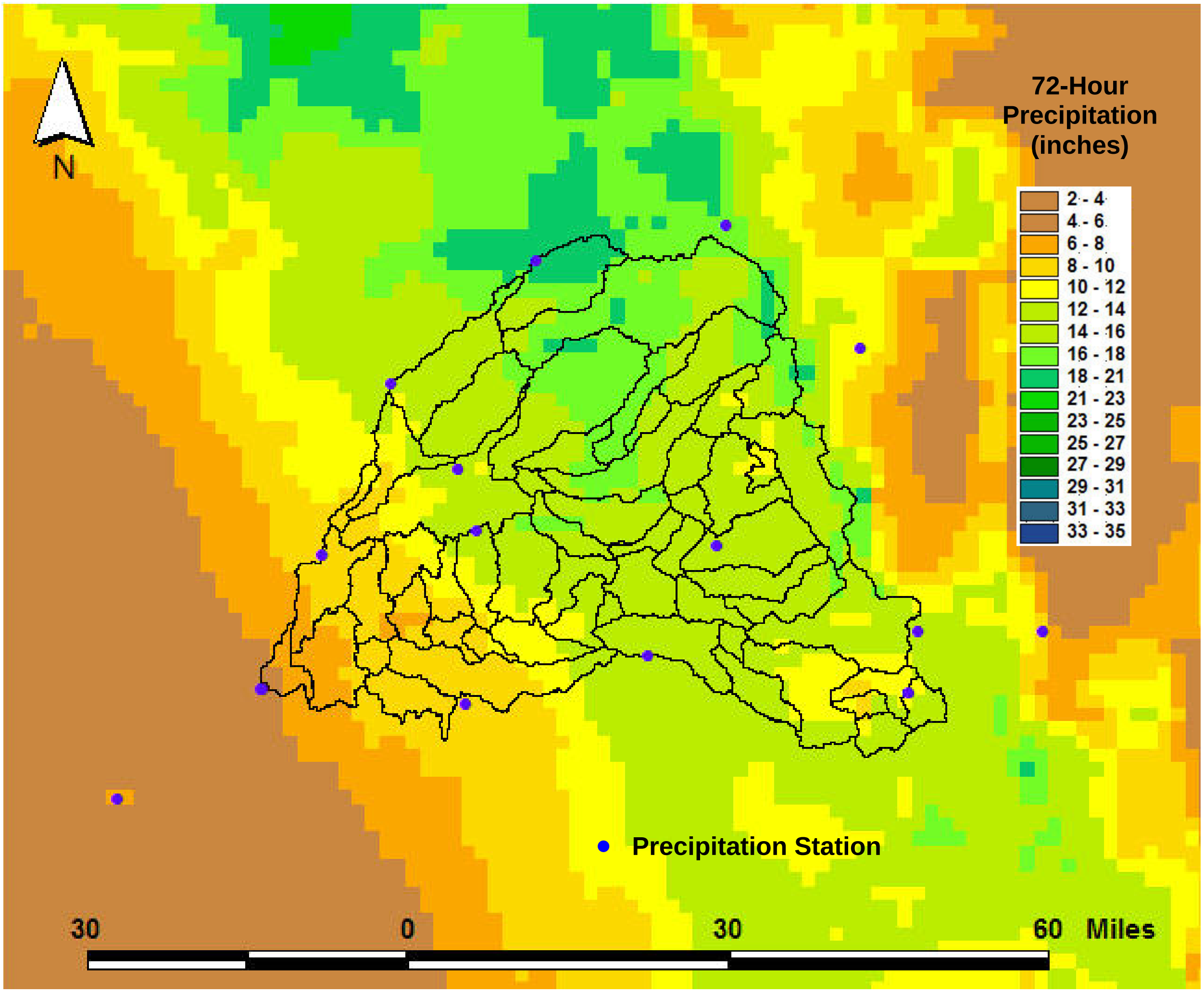

Figure 6d – Spatial Distribution of Maximum Basin-Average 72-Hour Precipitation for Storm of February 12-20, 1986

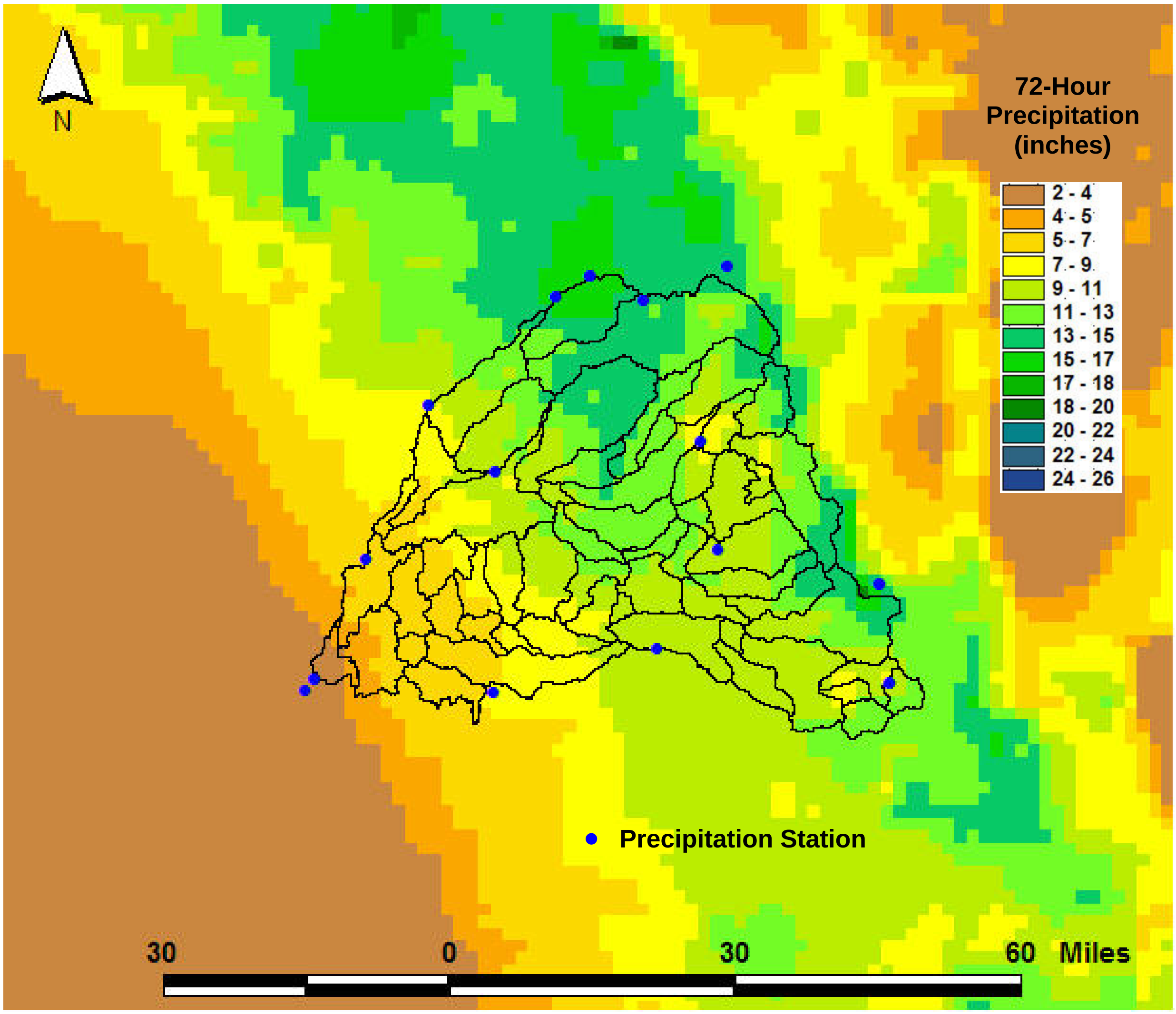

Figure 6e – Spatial Distribution of Maximum Basin-Average 72-Hour Precipitation for Storm of December 28, 1996 - January 3, 1997

Table 6 – Values of Observed 24-Hour, 72-Hour and Total Basin-Average Precipitation for Storms Used to Develop Prototype Storms

RECORDED BASIN-AVERAGE PRECIPITATION IN HISTORICAL STORMS						
PROTOTYPE STORM NUMBER	STORM DATE	24-HOUR (in)	72-HOUR (in)	TOTAL PRECIPITATION (in)	RATIO 24-HR / 72-HR	RATIO TOTAL / 72-HR
1	Oct 9-15, 1962	6.86	14.05	15.84	0.488	1.127
2	Feb 12-21,1986	5.82	13.96	23.77	0.417	1.703
3	Dec 17-24, 1955	6.02	13.81	20.87	0.436	1.511
4	Dec 19-25, 1964	6.06	12.47	18.30	0.486	1.468
5	Nov 16-22, 1950	6.23	12.46	16.56	0.500	1.329
6	Jan 29-Feb 3, 1963	5.97	11.39	11.67	0.524	1.025
7	Dec 28-Jan 3, 1997	6.55	11.22	14.71	0.584	1.311
8	Jan 17-23,1969	3.92	10.34	11.94	0.379	1.155
9	Jan 9-16, 1980	4.30	9.94	15.60	0.433	1.569
10	Feb 5-10, 1999	3.87	8.42	9.08	0.460	1.078
11	Dec 19-24, 1982	3.88	8.24	8.40	0.471	1.020
12	Dec 17-23, 1981	4.49	8.17	8.40	0.550	1.029
13	Feb 13-17, 1982	4.55	8.13	8.13	0.560	1.001
14	Mar 8-14, 1995	3.57	7.93	10.45	0.450	1.318
15	Dec 10-14,1995	5.07	7.88	8.01	0.643	1.016
16	Feb 7-14, 1962	3.64	7.36	11.66	0.495	1.584
17	Jan 6-12, 1995	4.22	7.35	10.78	0.574	1.467
18	Dec 6-12, 1992	4.55	7.19	9.75	0.633	1.356
19	Jan 18-26, 1967	4.81	7.04	10.34	0.683	1.469
20	Nov 11-17, 1981	3.80	6.77	9.46	0.561	1.398
21	Jan 13-18, 1970	3.18	6.46	8.78	0.492	1.360
22	Feb 16-21, 1980	2.85	6.38	9.84	0.447	1.542
23	Jan 26-30, 1981	3.45	6.37	7.16	0.542	1.124
24	Nov 9-16, 1973	2.90	6.20	9.15	0.468	1.476

Temperature Temporal Pattern

Temperature temporal patterns are needed for use in computing snowmelt runoff. A temperature temporal pattern was created for each of the 24 prototype storms using both land-based and radiosonde temperature measurements. Figure 7a depicts a temperature temporal pattern recorded at Auburn CA for the Dec-Jan 1997 storm. Figure 7b shows the same pattern indexed to sea-level by subtraction of the maximum air temperature on the day of maximum 24-hour precipitation. In a similar manner, Figures 8a,b depict freezing level temporal patterns.

During the stochastic simulations, the sea-level temperature and freezing level were generated for the day of maximum 24-hour precipitation. These values were then used to scale the temperature temporal patterns. The scaled sea-level and freezing level temperature patterns were in-turn used to produce temporal patterns for each of the 9 elevation zones. Additional information on this subject is contained in a separate report on air temperature profiles[26] (Appendix F).

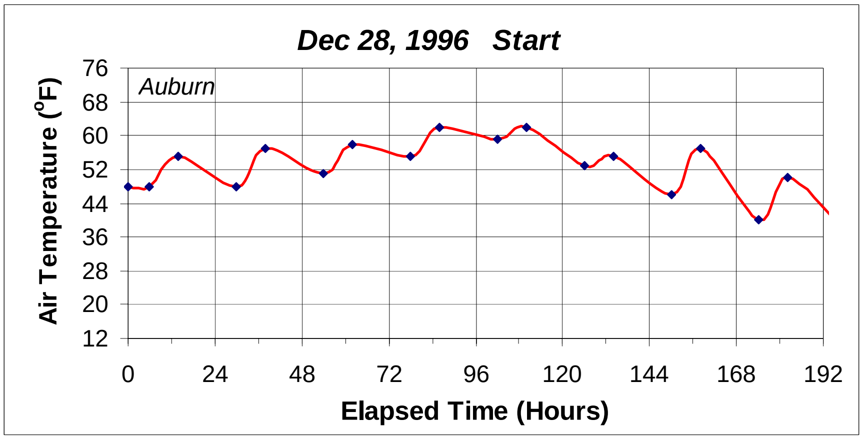

Figure 7a – Air Temperature Temporal Pattern for Storm of Dec 28, 1996-Jan 2, 1997 Observed at Auburn, CA (1,290-feet)

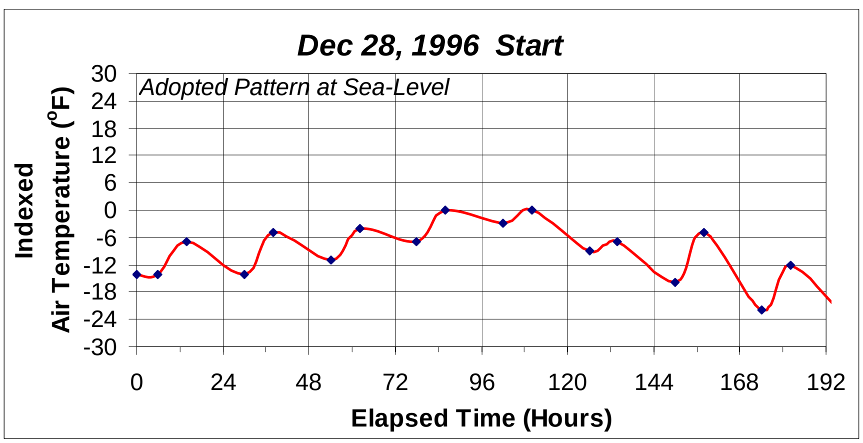

Figure 7b – Air Temperature Temporal Pattern for Storm of Dec 28, 1996-Jan 2, 1997 Indexed for Simulation of Sea-Level Temperatures

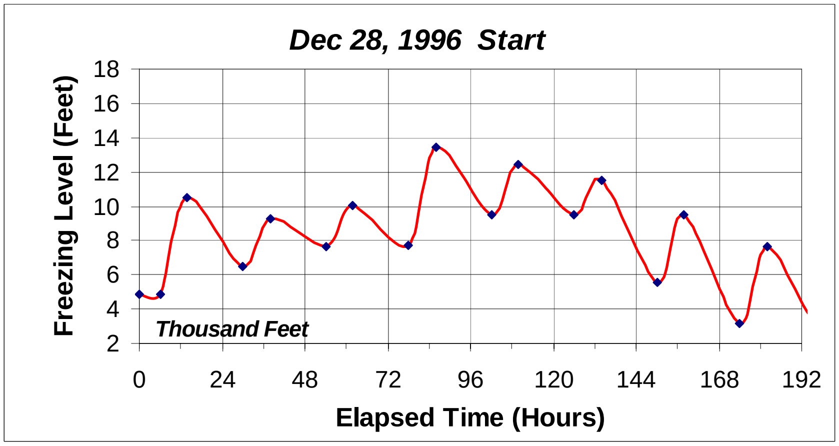

Figure 8a – Freezing Level Temporal Pattern for Storm of Dec 28, 1996-Jan 2, 1997

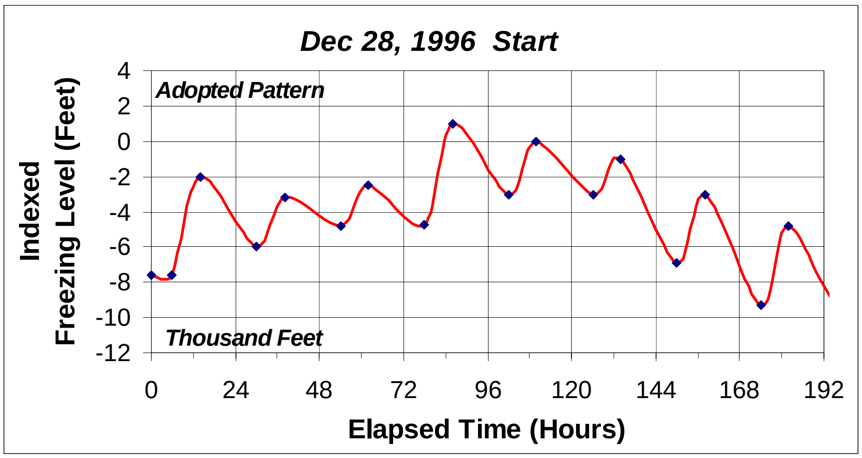

Figure 8b – Freezing Level Temporal Pattern for Storm of Dec 28, 1996-Jan 2, 1997
Indexed for Simulation of Freezing Levels

Sea-Level Temperature

Sea-level temperatures during extreme storms were simulated using a physically based, probability model for air temperatures derived from monthly dewpoint data[32]. This probability model utilizes end-of-month upper limit dewpoint data obtained from HMR-59[16] and the magnitude of the maximum 24-hour precipitation within the storm relative to 24-hour Probable Maximum Precipitation (PMP). The range of possible temperatures for a given maximum 24-hour basin-average precipitation amount within a storm is shown in Figure 9 for the end-of-January. It is seen in Figure 9 that higher dewpoints and sea-level temperatures are associated with larger storm amounts. This occurs because high levels of atmospheric moisture are needed to support large precipitation amounts and higher levels of atmospheric moisture require higher air temperatures to sustain those moisture levels.

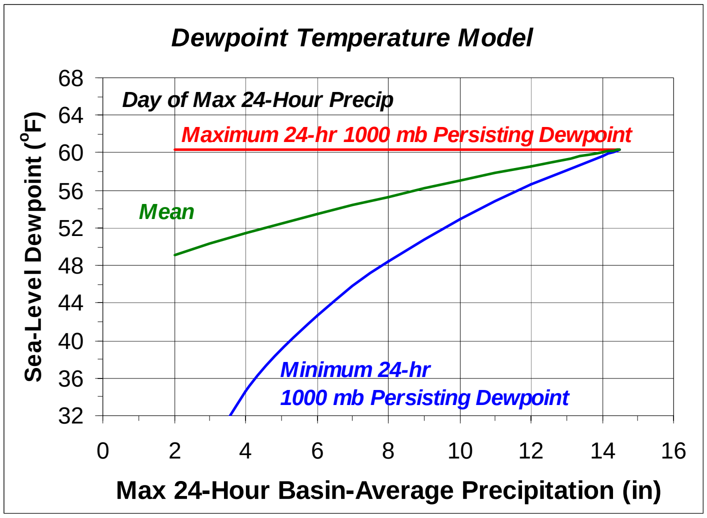

Figure 9 – Example Range of 24-Hour Persisting Dewpoint Temperatures at Sea-Level Utilized by Dewpoint Temperature Probability Model, Example for End-of-January

Freezing Level

Freezing level on the day of maximum 24-hour precipitation is used for scaling the temporal temperature patterns (Figure 8b). Analyses of historical storm events found that freezing level was a function of storm magnitude and sea-level temperature. Higher freezing levels were correlated with high sea-level temperatures and larger storm amounts. Figure 10 depicts an example of 500 computer simulations of freezing level. The simulation preserves both the deterministic component of the relationship (solid red line) with sea-level temperature and storm magnitude, and the random component (unexplained variance). The behavior of freezing level for extreme storms adds some non-linearity to the flood response in that higher temperatures and larger snowmelt contributions are associated with larger storm amounts. Additional information on freezing level is contained in the report on air temperature profiles[26] (Appendix F).

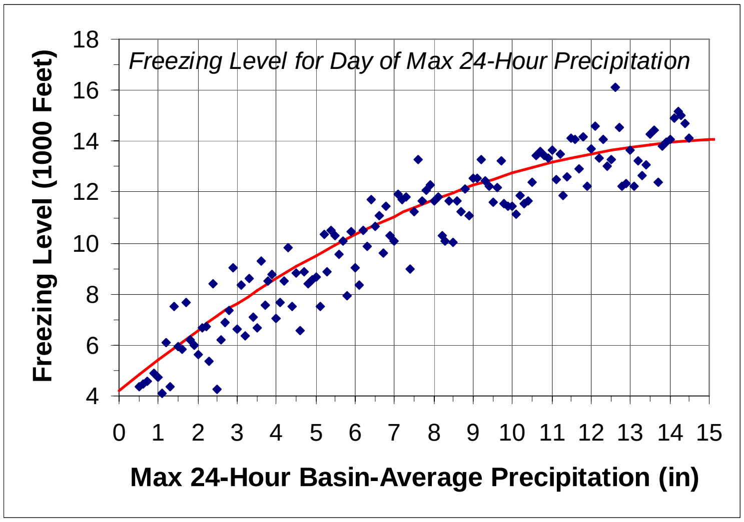

Figure 10 – Example of Variability in Simulation of Freezing Level for American River Watershed Including Variability Due to Sea-Level Air Temperature

Antecedent Precipitation

Antecedent precipitation is defined as the cumulative precipitation from October 1st to the date of storm occurrence and varies by zone of mean annual precipitation. It is used in soil moisture accounting, allocating snowpack, and setting initial reservoir levels in the 5 major upstream reservoirs and at Folsom Lake. Antecedent precipitation at the Lake Spaulding station (near city of Blue Canyon and Interstate Highway 80) was used as the key station for determining correlation relationships with other hydrometeorological variables. Figures 11a,b shows the monthly distribution of annual precipitation and antecedent precipitation for the Lake Spaulding station. Similar monthly distributions apply to locations throughout the American River watershed. Additional information is contained in the report on antecedent precipitation[19] (Appendix G).

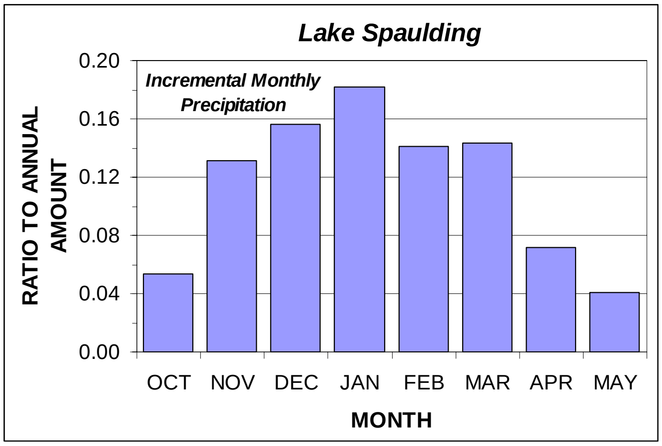

Figure 11a – Monthly Distribution of Annual Precipitation at Lake Spaulding Precipitation Station

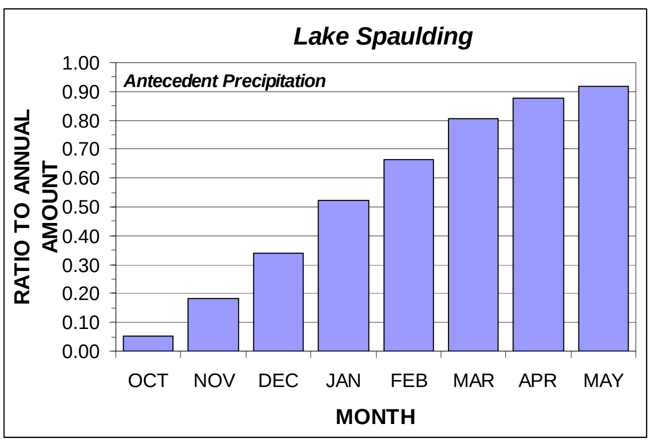

Figure 11b – Distribution of Antecedent Precipitation at Lake Spaulding Precipitation Station

Antecedent Snowpack
The magnitude of snowpack varies throughout the watershed both seasonally and by location (Figure 12b). Snowpack analyses were conducted for end-of-month conditions to determine the frequency of snow-free ground (Figure 12a) and the magnitude of snow-water equivalent (SWE). Table 7 lists quantile estimates for snowpack SWE for various elevation zones for sites with a mean annual precipitation of 50-inches.

Snowpack is allocated in the stochastic simulations using zones of elevation and mean annual precipitation and is dependent upon the magnitude of antecedent precipitation. In wet climatic years, snowpack is generally greater than average. In dry climatic years, snowpack may be small or non-existent. Correlation analyses were conducted with the Lake Spaulding station to establish the relationship between antecedent precipitation and end-of-month snowpack SWE (Figure 13). These correlation relationships were used to allocate snowpack in a manner that preserves the deterministic component of the relationship and the random scatter that is due to the natural variability in snowpack since precipitation occurs in both the liquid and solid phases and freezing levels vary between storm events as well as during storm events. Additional information on snowpack analyses is contained in the report on snowpack[23] (Appendix H).

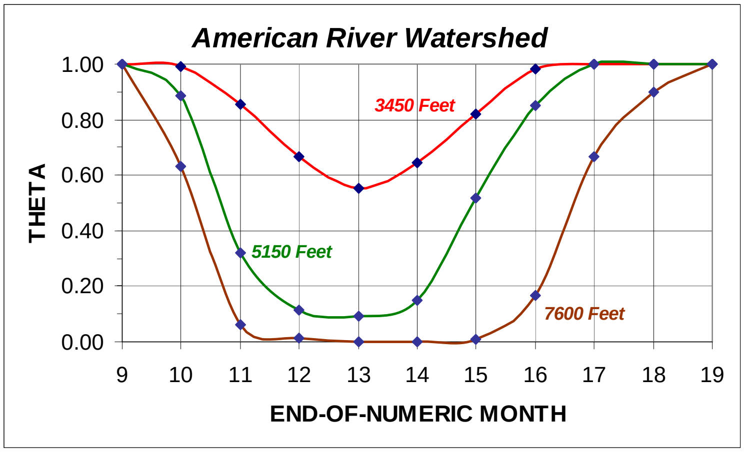

Figure 12a – Seasonal Variation of Mixing Parameter (θ) for Frequency of Snow-Free Ground Conditions at Various Elevations in the American River Watershed

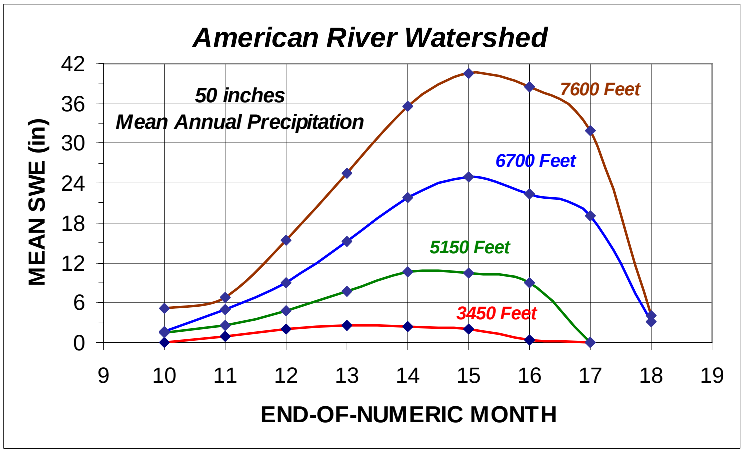

Figure 12b – Seasonal Variation of Mean Values of Snow-Water Equivalent for Various Elevations in the American River Watershed

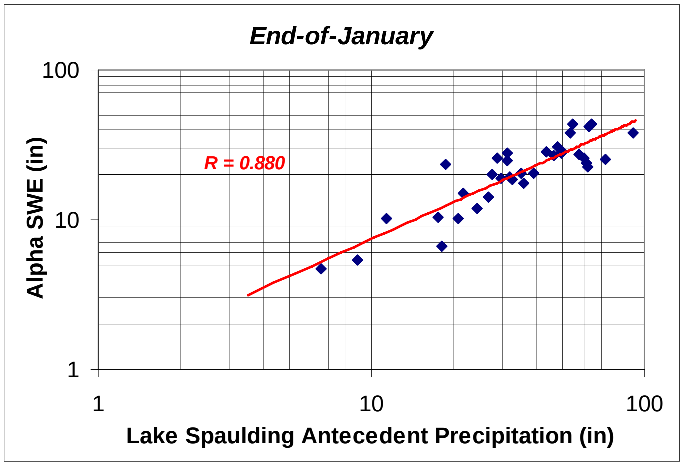

Figure 13 – Example Log-Log Regression of Alpha SNOTEL Snow-Water Equivalent with Lake Spaulding Antecedent Precipitation for End-of-January

Table 7 – Quantile Estimates for Snow-Water Equivalent for End-of-January for Various Zones of Elevation for Sites with a Mean Annual Precipitation of 50-inches

Exceedance Probability	SNOW-WATER EQUIVALENT (INCHES)								
98%	0.0	0.0	0.0	0.0	0.0	0.0	4.1	7.8	8.5
90%	0.0	0.0	0.0	0.0	0.0	4.8	8.3	11.7	12.6
50%	0.0	0.0	0.4	3.0	6.9	12.1	17.6	22.6	24.0
10%	0.0	0.9	4.3	9.7	17.4	26.8	36.4	43.7	46.0
2%	0.0	2.9	9.1	18.0	29.8	43.4	56.6	65.3	68.5
MEDIAN ELEV	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

Antecedent Soil Moisture

Antecedent soil moisture at the onset of the storm is determined through soil moisture accounting for each HRU. Soil moisture accounting begins at the end-of-September and proceeds to the end-of-month of storm occurrence using antecedent precipitation, snowpack SWE, evapotranspiration, and the soil moisture storage characteristics (S_{max}) for the soils for each HRU (Table 3). Evapotranspiration information was obtained through analyses of pan evaporation data for 9 weather recoding stations located within and near the watershed[30]. Table 8 lists the potential evapotranspiration values used for soil moisture accounting for snow-free ground conditions.

Table 8 – Monthly Potential Evapotranspiration Values used in Soil Moisture Accounting for Snow-Free Ground for American River Watershed

ELEV ZONE	MEDIAN ELEV (Feet)	ANNUAL PET (in)	MONTHLY POTENTIAL EVAPOTRANSPIRATION (in)							
			Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
1	2000	48.7	5.50	3.36	1.61	1.17	1.02	1.46	2.53	3.85
2	2800	46.2	5.22	3.19	1.53	1.11	0.97	1.39	2.40	3.65
3	3600	43.7	4.94	3.02	1.44	1.05	0.92	1.31	2.27	3.46
4	4400	41.3	4.66	2.85	1.36	0.99	0.87	1.24	2.15	3.26
5	5200	38.8	4.38	2.68	1.28	0.93	0.81	1.16	2.02	3.06
6	6000	36.3	4.10	2.50	1.20	0.87	0.76	1.09	1.89	2.87
7	6800	33.8	3.82	2.33	1.12	0.81	0.71	1.01	1.76	2.67
8	7600	31.3	3.54	2.16	1.03	0.75	0.66	0.94	1.63	2.48
9	8400	28.9	3.26	1.99	0.95	0.69	0.61	0.87	1.50	2.28

Storage in Upstream Reservoirs

There are five major reservoirs in the upper watershed that have an effect on the magnitude of floods on the American River. These reservoirs include: Union Valley; Hell Hole; French Meadows; Ice House; and Loon Lake. End-of-month storage was analyzed at these reservoirs to characterize normal operations and the relationship between storage levels at the five reservoirs (Figure 14a,b). The storage available for floodwaters at the three largest reservoirs, Union Valley, Hell Hole and French Meadows, are also used in the operations at Folsom Dam for setting maximum allowable reservoir levels (Figure 16). Table 9 lists the summary statistics for end-of-month storage available at these three reservoirs.

Analyses were conducted to establish the relationship between antecedent precipitation at the Lake Spaulding station and storage levels at the five reservoirs (Figure 14c). Specifically, in wet climatic years, storage levels tend to be above normal for a given time of year. In dry climatic years, storage levels tend to be below normal. Thus, relationships exist between storage levels and antecedent precipitation and there is a high level of cross-correlation between the storage levels at some of the reservoirs.

A multivariate stochastic model was developed that preserved: the correlation structure with antecedent precipitation for each reservoir; the cross-correlation structure of reservoir storage volume between the five reservoirs; and the unexplained variance in the relationships. Additional information on the analyses of the five reservoirs and the multivariate stochastic model is contained in the report on the upstream reservoirs[24] (Appendix I).

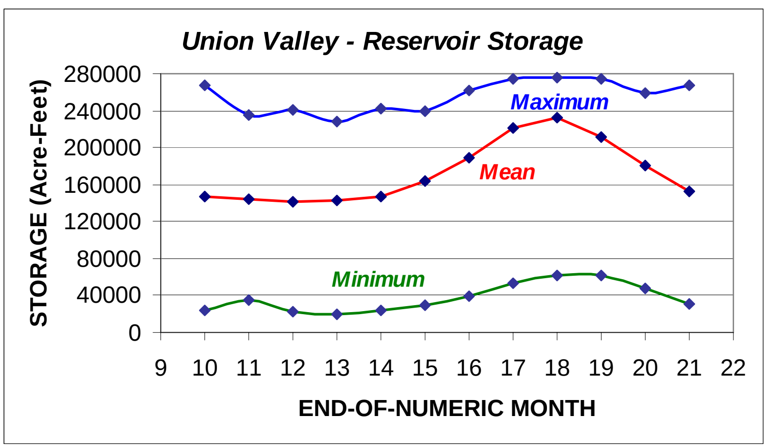

Figure 14a – Seasonal Values of Reservoir Storage for Union Valley Reservoir, 1962-2000

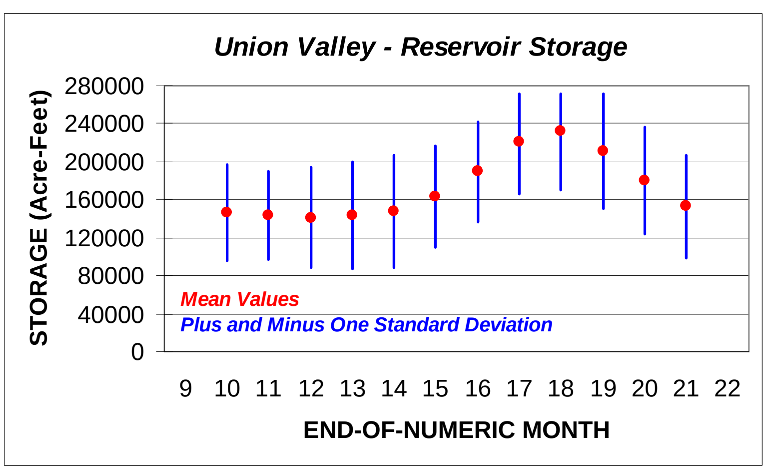

Figure 14b – Seasonal Variability of Reservoir Storage at Union Valley Reservoir

Table 9 – Summary Statistics for End-of-Month Combined Floodwater Storage Availability for Hell Hole, Union Valley, and French Meadows Reservoirs for 1967-2002 Water-Years where Maximum Available Storage for Folsom Rule Curve Usage is Limited to 200,000-acre-feet

SUMMARY STATISTICS	HELL-HOLE , UNION VALLEY, AND FRENCH MEADOWS RESERVOIRS END-OF-MONTH UPSTREAM STORAGE AVAILABLE (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
Maximum	200000	200000	200000	200000	200000	200000	200000
Minimum	103900	10900	3500	12800	3900	2700	34500
Mean	179400	179200	177100	167200	160900	152100	155600
Std Dev	24290	35780	44830	51950	60020	56670	52710
Skewness	-1.50	-3.26	-2.69	-1.70	-1.51	-1.23	-1.07

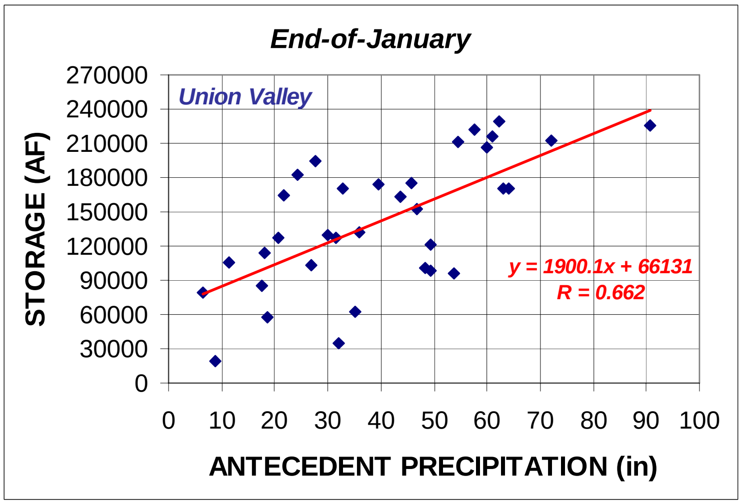

Figure 14c – Relationship Between Reservoir Storage at Union Valley Reservoir and Antecedent Precipitation at Lake Spaulding for End-of-January

Initial Streamflow

A review of historical floods revealed that the magnitude of streamflow antecedent to the storm event was not a significant contributor to the magnitude of floods and maximum reservoir levels. Historical streamflows were analyzed and mean values of end-of-month streamflow were deemed adequate for setting initial baseflows (Table 10). The selection of the magnitude of initial streamflow is related to the subject of antecedent storms and floods, which is discussed in the next section. Additional information on the analyses of initial streamflow is contained in the report on antecedent streamflow[28].

Table 10 – Adopted End-of-Month Mean Values of Antecedent Streamflow Inflow to Folsom Reservoir

ANTECEDENT STREAMFLOW FOR END-OF-MONTH DATES							
	OCT	NOV	DEC	JAN	FEB	MAR	APR
Mean Value	1350 cfs	2225 cfs	3025 cfs	4000 cfs	5250 cfs	6125 cfs	6025 cfs

Antecedent Storms/Floods

Analyses of storms antecedent and posterior to historical extreme storms were analyzed and found to be independent of the magnitude of the extreme storm (see report on antecedent/posterior storms[22], Appendix J). The possibility of antecedent and posterior storms was accommodated in the stochastic modeling of extreme storms/floods by assembling prototype storms (Figures 6a,b,c) that contained periods of precipitation surrounding the most severe period of storm activity. This approach allowed storm duration to be treated as a variable rather than a fixed duration such as the conventional 72-hour duration. It also allowed the incorporation of antecedent/posterior precipitation in a historically accurate manner.

Initial Storage Level in Folsom Lake

Four different reservoir rule curves have been in effect since 1956 when Folsom Lake was first filled. Each evolution of the rule curve came in response to the occurrence of a flood or drought that highlighted shortcomings in the previous rule curve. The existence of multiple rule curves required that a common system of measuring initial reservoir storage be employed. A system of departures was utilized to place operations on a common scale. A departure was defined as the difference between the actual reservoir storage value and the target maximum allowable storage computed using the rule curve in existence at the time of observation for a given end-of-month. Positive departures represent reservoir storage (water levels) above the target maximum allowable storage. Negative departures represent reservoir storage below the maximum allowable storage for a given end-of-month. The concept was that the target maximum reservoir level for each rule curve may be different, but the behavior of the departures about that target should be reasonably similar for the various rule curves. Figure 15 depicts storage departures for the four rule curves for the period from 1966 through 2002.

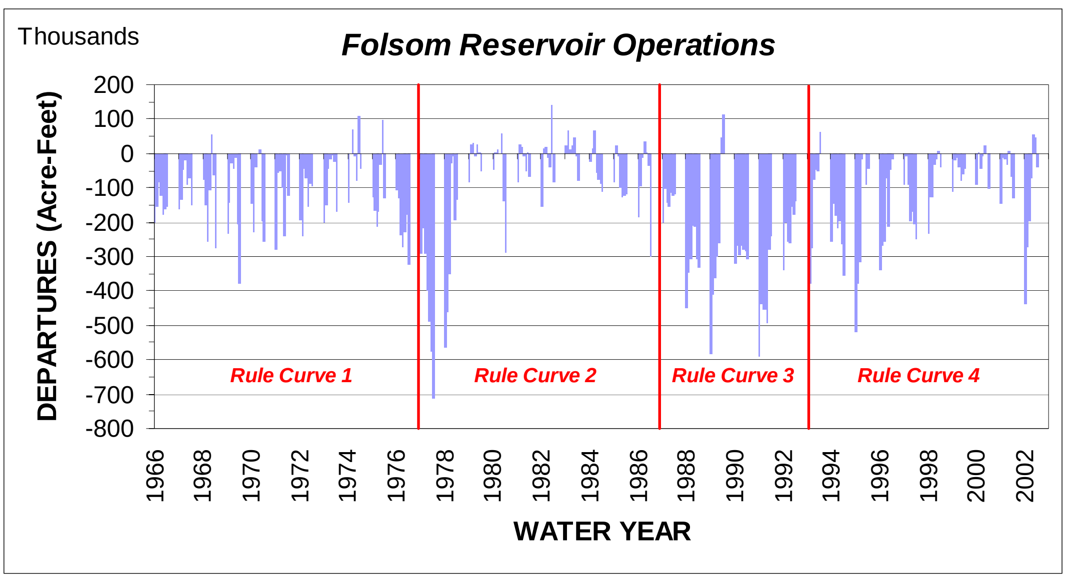

Figure 15 – Departures from Target Maximum Allowable Reservoir Operating Levels at Folsom Lake

The statistical characteristics of the departures were examined to determine which years from Rule Curves 1, 2 and 3 could be combined with data from Rule Curve 4 (Figure 16) to be representative of current operations. In general, operations for all very wet and very dry water years were combined with data from the 1992-2002 Rule Curve 4 period. Both these conditions represent cases where the storage levels are largely determined by natural climatic events rather than by human intervention and manipulation by reservoir operation rules.

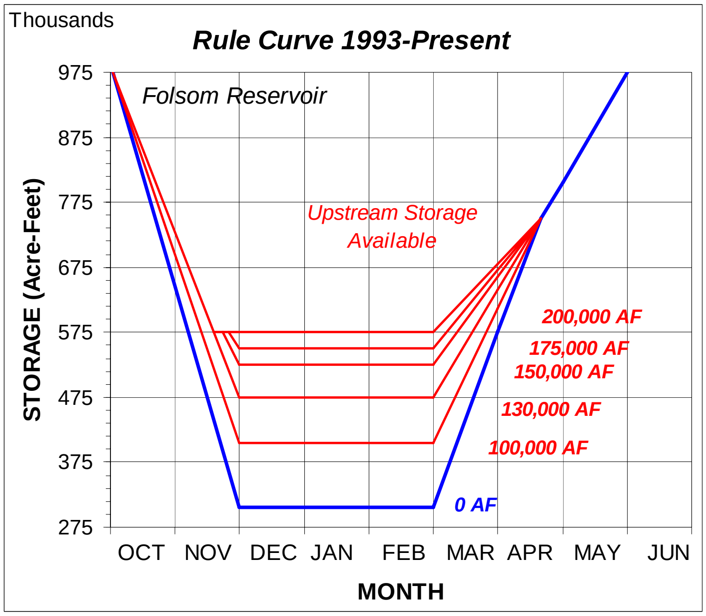

Figure 16 – Reservoir Rule Curve 4 for Setting Maximum Allowable Reservoir Levels for Operation of Folsom Reservoir

A stochastic model was developed to simulate reservoir operations that utilized correlation with antecedent precipitation. Table 11 lists summary statistics from that model which reflect historical operations for end-of-month conditions. A review of the summary statistics shows that Folsom reservoir is typically below the maximum allowable storage level (negative departures). There are few encroachments on the maximum storage levels (positive departures) for the early portion of the water-year. The frequency of encroachments increases as the water-year progresses. Additional information on the procedures used to analyze Folsom storage and the details of the stochastic model are contained in the report on Folsom reservoir operations[29] (Appendix K).

Table 11 – Summary Statistics from Stochastic Simulation of Storage Departures for Folsom Reservoir

MEASURE	SUMMARY STATISTICS FOR SIMULATED STORAGE DEPARTURES (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
Mean	-263,900	-162,850	-136,750	-101,600	-93,200	-99,100	-117,900
Standard Deviation	159,000	126,200	133,300	108,100	103,900	120,300	152,800
Skewness	-0.2	-0.6	-0.8	-1.2	-1.2	-1.3	-1.2
Positive Departures	2.4%	6.4%	15.0%	15.9%	17.7%	21.7%	25.4%

Folsom Reservoir Operations During Floods
Reservoir routing of inflow floods to Folsom Lake was conducted in accordance with the current Flood Control Diagram (FCD) for reservoir levels below 448.0 feet NGVD. Procedures contained within the Emergency Spillway Release Diagram (ESRD) were used when the reservoir level exceeded 448.0 feet NGVD. Changes in reservoir releases were made according to the ramping rate schedule shown in Table 12. Initial reservoir levels were set via a stochastic model[29] based on the procedures discussed in the prior section on initial reservoir levels at Folsom Dam.

Table 12 – Maximum Ramping Rates Used in Outlet and Spillway Operations for Folsom Dam

RESERVOIR STAGE (Feet)	RESERVOIR CONDITION	CURRENT RESERVOIR RELEASE RANGE OF RELEASES FROM (cfs)	CURRENT RESERVOIR RELEASE RANGE OF RELEASES TO (cfs)	MAXIMUM ALLOWABLE RAMPING RATE (cfs/hr)
Below 470 Feet	Increasing Inflow Reservoir Rising	0	25,000	+5,000 cfs/hr
		25,000	115,000	+15,000 cfs/hr
		115,000	160,000	+7,500 cfs/hr
Above 470 Feet	Increasing Inflow Reservoir Rising	160,000	up	Emergency Spillway Release Diagram
ALL	Decreasing Inflow Reservoir Falling	inflow flood peak	160,000	Emergency Spillway Release Diagram
		160,000	115,000	Emergency Spillway Release Diagram
		115,000	down	-5,000 cfs/hr

SIMULATION PROCEDURE

One of the key features of the stochastic model is the use of Monte Carlo sampling methods for selecting the magnitude and combination of hydrometeorological input parameters for computation of floods. All hydrometeorological input parameters that are dependent upon other parameters (Table 4) are selected based on correlation relationships that preserve both the deterministic portion of the relationship and the unexplained variance. This approach preserves the natural variability exhibited in the historical records.

All simulations were conducted for end-of-month watershed conditions. This approach was adopted to reduce the amount of data analyses required for the hydrometeorological parameters and to simplify the simulation procedures. A flowchart for the stochastic simulation procedure is shown in Figure 17 and the basic concepts of the simulation procedure are described below.

The stochastic simulation procedure can be grouped into five steps.

Step 1: *Select date of occurrence of extreme storm*

- Select end-of-month for occurrence of extreme storm based on historical seasonality of extreme storms

Step 2: *Select all parameters associated with the occurrence of the extreme storm event*

- Select magnitude of 72-hour precipitation based on 72-hour basin-average precipitation-frequency relationship
- Select one of twenty-four prototype storms for describing the temporal and spatial distribution of the storm, and scale prototype storm to have the selected 72-hour basin-average precipitation amount
- Select sea-level temperature from physically-based probability temperature model for day of maximum 24-hour precipitation in selected prototype storm
- Select freezing level based on sea-level temperature and 24-hour precipitation on day of maximum precipitation for selected prototype storm
- Scale temporal temperature pattern for selected prototype storm for all elevation zones using selected values for sea-level and freezing level

Step 3: *Establish antecedent watershed and reservoir conditions at onset of extreme storm*

- Select antecedent precipitation at Lake Spaulding for end-of-month that was selected for occurrence of extreme storm, allocate antecedent precipitation to all zones of mean annual precipitation
- Allocate snowpack SWE for all zones of elevation and mean annual precipitation based on correlation with antecedent precipitation at Lake Spaulding
- Determine initial soil moisture for all HRUs using selected values of antecedent precipitation, snowpack, and applicable values of evapotranspiration
- Select storage values in five upstream reservoirs based on correlation with antecedent precipitation at Lake Spaulding and preserving cross-correlation of storage values between the five reservoirs
- Select initial streamflow inflow to Folsom Lake prior to onset of storm
- Select initial storage at Folsom Lake based on correlation with antecedent precipitation at Lake Spaulding, storage available in three largest upstream reservoirs, and utilizing reservoir operation procedures

Step 4: *Conduct Watershed Modeling*

- Conduct rainfall-runoff and snowmelt modeling for all HRUs and aggregate results to subbasin level for surface runoff and interflow
- Execute HEC-1 watershed model for selected hydrometeorological inputs and determine inflow flood tributary to Folsom Lake

Step 5: *Conduct Reservoir Routing of Inflow Flood*

- Execute reservoir routing that implements current reservoir operational procedures

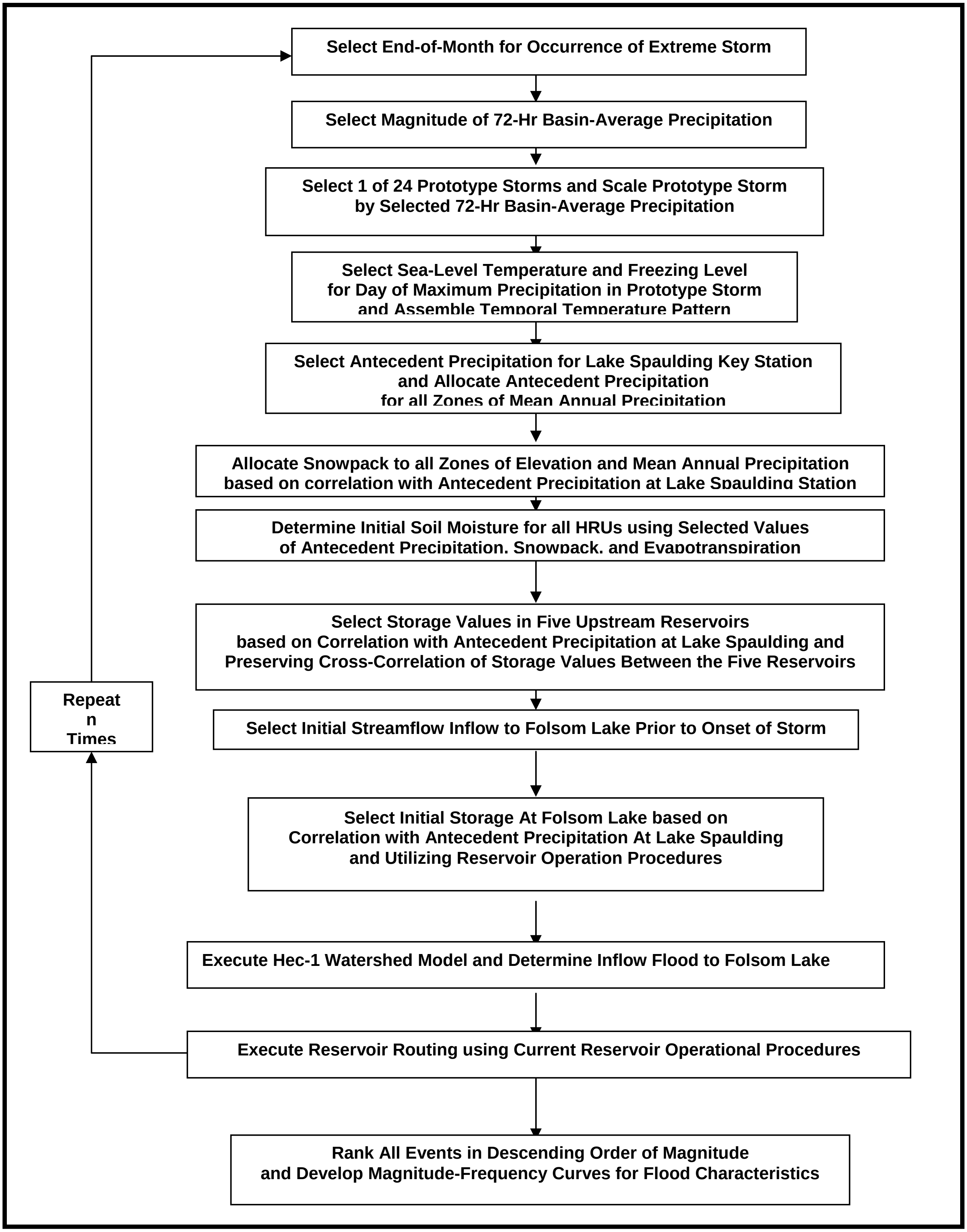

Figure 17 – Flow Chart for Stochastic Simulation Procedure for American River Watershed

CALIBRATION OF THE WATERSHED MODEL TO HISTORICAL FLOODS

Four historical floods were used for calibration of the HEC-1 watershed model that included the November 1950, October 1962, February 1986, and January 1997 floods. Calibration of the HEC-1 watershed model was accomplished using concepts from the Generalized Likelihood Uncertainty Estimation (GLUE) method developed by Beven and Binley[1] (see report on calibration[30], Appendix L). The GLUE method seeks to identify sets of model parameter values (parameter sets) that are capable of simulating the observed flood hydrographs to an acceptable level of similarity. Goodness-of-fit measures are used to determine the level to which a simulated hydrograph is similar to the observed hydrograph and to compute a likelihood value for each parameter set.

This approach resulted in identification of 30 parameter sets that were suitable for replicating ten hydrographs recorded at various watershed locations for the four historical floods. The "calibrated parameter set" used in computing the flood-frequency relationships for this report was selected as being the parameter set with the highest likelihood of the 30 parameter sets (Table 3 repeated from earlier in report). Figure 18 shows a comparison of observed and simulated hydrographs for the January 1997 flood using the final calibrated parameter set and Table 13 lists comparisons of flood characteristics for the three largest floods used in calibration. The full suite of 30 parameters sets would be used in conducting an uncertainty analysis for the flood-frequency relationships, which is a recommended future task for this project.

Table 3 – Final Calibrated Parameter Set of Soil Characteristics based on GLUE[1] Procedures

SOIL ZONE	MEDIAN SOIL DEPTH (in)	(f_d) DEEP PERCOLATION (in/hr)	(f_c) MINIMUM SURFACE INFILTRATION (in/hr)	(f_{max}) MAXIMUM SURFACE INFILTRATION (in/hr)	(S_{max}) EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (in)	COMMENTS
1	0	0.000	0.000	0.0	0.0	water bodies
2	5	0.022	0.071	3.2	3.8	very shallow soils over bedrock
3	15	0.016	0.071	3.2	11.3	
4	25	0.048	0.100	3.2	9.1	
5	35	0.023	0.065	3.2	13.7	
6	50	0.035	0.094	3.2	20.4	
7	36	0.023	0.060	3.2	12.6	underlain by deep outwash soils
8	40	0.078	0.136	3.2	17.1	fractured and/or tilted bedrock

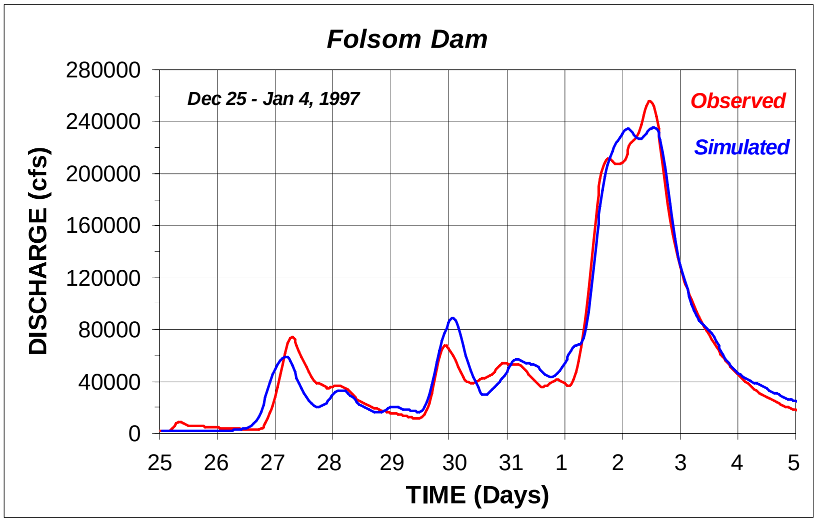

Figure 18 – Comparison of Simulated and Observed Flood Hydrographs for Inflow to Folsom Dam on the American River for January 1997 Flood Event for Final Calibrated Parameter Set

Table 13 – Comparison of Observed and Simulated Flood Peak Discharges for Inflow to Folsom Dam for Final Calibrated Parameter Set

FLOOD MEASURE	FLOOD PEAK DISCHARGES					
	1950 FLOOD EVENT		1986 FLOOD EVENT		1997 FLOOD EVENT	
	1-Hr Peak	3-Day Peak	1-Hr Peak	3-Day Peak	1-Hr Peak	3-Day Peak
OBSERVED DISCHARGE	180,000	107,500	207,500	144,700	255,600	142,200
SIMULATED DISCHARGE	179,300	104,800	194,000	140,800	235,000	143,200
PERCENT OF OBSERVED	99.6%	97.5%	93.5%	97.3%	91.9%	100.7%

FLOOD-FREQUENCY CURVE EXTENSION

ADJUSTMENT OF THE STOCHASTIC FLOOD MODEL TO MATCH THE SYSTEMATIC FLOOD-FREQUENCY CURVE FOR AMERICAN RIVER

A second-level adjustment was made to the stochastic flood model to replicate the 3-day flood-frequency curve developed by the Sacramento District Corps of Engineers (SDC)[40]. Adjustments were made to match the 100-year 3-day discharge from the Sacramento District flood-frequency curve and to generally match the shape of the remainder of the 3-day flood-frequency relationship as closely as possible. The basic construct behind this approach was to accept the Log-Pearson III fit to the observed data as a matter of USCOE policy and to use the stochastic model to extend the frequency curve for estimating the annual exceedance probabilities of extreme floods.

As background, the maximum 3-day flood-frequency relationship[40] was developed by the Sacramento District COE for the unregulated systematic record at Fair Oaks, CA (USGS gage 11446500) for the period from 1905-2004. The term *unregulated*, as used here, means that the storage effects due to Folsom Dam and the five large upstream reservoirs were removed to replicate natural conditions. Specifically, adjustments were made to the recorded post-Folsom Dam streamflow records (1956-present) to remove the effects of regulation by Folsom Dam and the five large upstream reservoirs.

The second-level adjustment can be expressed as:

$$SFM_{CurveExtensionFF} = \phi \, SFM_{originalFF} \qquad (2)$$

where: $SFM_{CurveExtensionFF}$ is the maximum 3-day unregulated flood-frequency relationship generated by the stochastic flood model as adjusted to match the SDC maximum 3-day unregulated flood-frequency curve; ϕ is a function used for curve-matching; and $SFM_{originalFF}$ is the maximum 3-day unregulated flood-frequency relationship (Figure 19) generated by the stochastic flood model as originally formulated by the first-level calibration to large historical floods.

The second-level adjustment was accomplished in several steps. First, the stochastic flood model was executed in an unregulated mode using a HEC-1 watershed model configuration where the five large upstream reservoirs were removed. This provided a baseline comparison between the results of the stochastic flood model and the SDC systematic flood-frequency curve for unregulated conditions. Figure 19 depicts a comparison between the SDC flood-frequency curve for unregulated maximum 3-day discharges at Fair Oaks and the flood-frequency curve generated by the stochastic flood model. A review of Figure 19 shows the flood-frequency curve generated by the stochastic flood model resides slightly below the SDC curve.

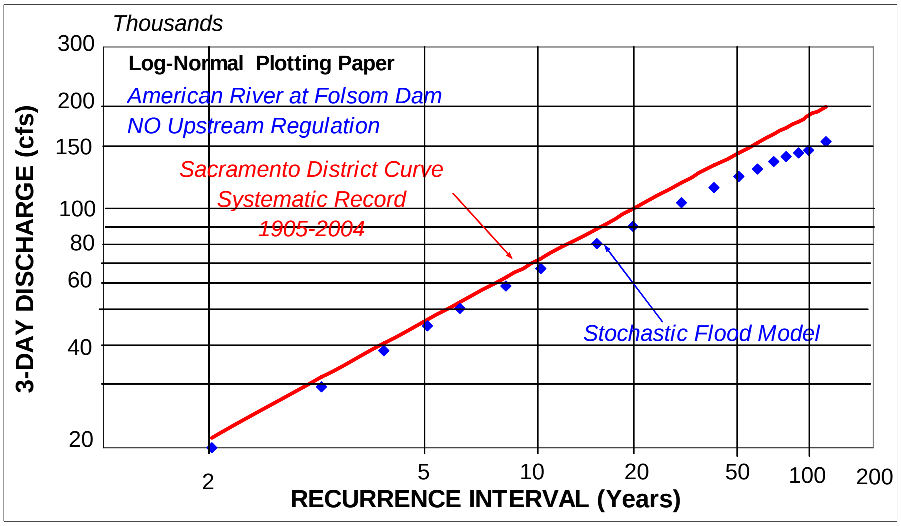

Figure 19 – Comparison of SDC Maximum 3-Day Flood-Frequency Relationship with Maximum 3-Day Flood-Frequency Relationship Produced by the Stochastic Flood Model after Calibration of HEC-1 Watershed Model to Largest Historical Floods for Floods Unregulated by Upstream Reservoirs

Next, a determination was made of the appropriate form of the function ϕ for adjustment. A comparison of the two flood-frequency curves in Figure 19 suggests an increase in the slope of the stochastically generated frequency relationship would result in matching of the two curves and allow an explicit match at the 100-year recurrence interval for the systematic record.

Numerically, ϕ is simply a function for curve-matching. However, application of the ϕ function has hydrologic implications with regard to the magnitude and relationship between flood peak discharges, hydrograph shapes, maximum *n*-day discharges, runoff volumes and related flood characteristics. Therefore, it is desirable to implement the ϕ function via application of the hydrometeorological inputs and/or watershed model parameters in order to preserve the physical and statistical relationships that were built into the stochastic flood model.

Accordingly, the list of parameter inputs for the HEC-1 watershed model and the list of hydrometeorological parameters were examined to identify those parameters that would be logical/practical choices for adjusting the outputs from the stochastic flood model to match the SDC systematic flood-frequency curve. These assessments were made in-light of the results of the GLUE analysis for calibration[30] of the HEC-1 watershed model and the results of the sensitivity analyses[31] of the stochastic flood model (Appendix M). These considerations eliminated the soil parameters from consideration (Table 3) since they had been determined through calibration. Likewise, surface unit-hydrographs and channel routing parameters for the stream network had been determined through a separate detailed calibration to numerous floods by Mr. Robert Collins of the Sacramento District[4,38]. This narrowed the choices to the hydrometeorological inputs that were found to have moderate to high sensitivity in the sensitivity analyses[31] as shown in Table 14 (excerpted from report on sensitivity analyses[27]).

A review of Table 14 shows the flood response of the watershed to have the highest sensitivity to the magnitude of the 72-hour basin-average precipitation. Considering the nearness of the flood-frequency curve for the stochastic flood model to common floods on the SDC curve suggests that an adjustment of the 72-hour basin-average precipitation-frequency relationship would be adequate to match the two flood-frequency curves. The 72-hour precipitation-frequency relationship is governed by the basin-average at-site mean, and L-moment ratios L-Cv and L-skewness (Tables 5a,b) that were found through regional frequency analysis[9,20]. Adjustment of the L-Cv value and the resultant variance was determined to be the appropriate parameter/mechanism for producing the desired increases in flood characteristics.

Table 14 – Sensitivity Indices for Flood Response for Various Hydrometeorological Inputs

HYDROMETEOROLOGICAL INPUTS	FLOOD RESPONSE SENSITIVITY INDEX (S_i)	RELATIVE SENSITIVITY OF FLOOD RESPONSE
Basin-Average 72-Hour Precipitation	0.526	High
Freezing Level during Storm Event	0.266	Moderate
Antecedent Precipitation	0.170	Moderate
Snowpack Magnitude	0.014	Low
Sea-Level Temperature during Storm Event	0.002	Low
Storage Available in 5 Major Upstream Reservoirs	0.001	Low

The final step was accomplished by trial-and-error through execution of the stochastic flood model using trial values of L-Cv. Repeated trials were made until the generated maximum 3-day flood-frequency curve reasonably matched the SDC flood-frequency curve while explicitly matching at the 100-year recurrence interval. It was found that increasing the L-Cv value by 30% provided the desired match in flood-frequency curves (Figure 20a,b). This adjustment equates to about a 30% increase in the population estimate of the standard deviation (Table 15b). Computation of the distribution parameters for the four-parameter Kappa distribution yielded the parameter values shown in Table 15b.

Table 15a – Population L-Moments for Basin-Average 72-Hour 1862-mi^2 Precipitation for American River Watershed Obtained through Curve-Matching Procedure

REGIONAL L-MOMENTS			
At-Site Mean	L-Cv	L-Skewness	L-Kurtosis
6.20-inches	0.2550	0.1992	0.1636

Table 15b – Distribution Parameters and Product-Moments for Four-Parameter Kappa Distribution for Basin-Average 72-Hour 1862-mi^2 Precipitation for American River Watershed Obtained through Curve-Matching Procedure

KAPPA DISTRIBUTION PARAMETERS			
Xi (ξ)	***Alpha (α)***	***Kappa (κ)***	***h***
4.8560	2.1660	-0.0487	-0.0146
PRODUCT MOMENTS			
At-Site Mean	**Standard Deviation**	**Coefficient Skewness**	**Coefficient Kurtosis**
6.20-inches	2.99-inches	1.45	7.21

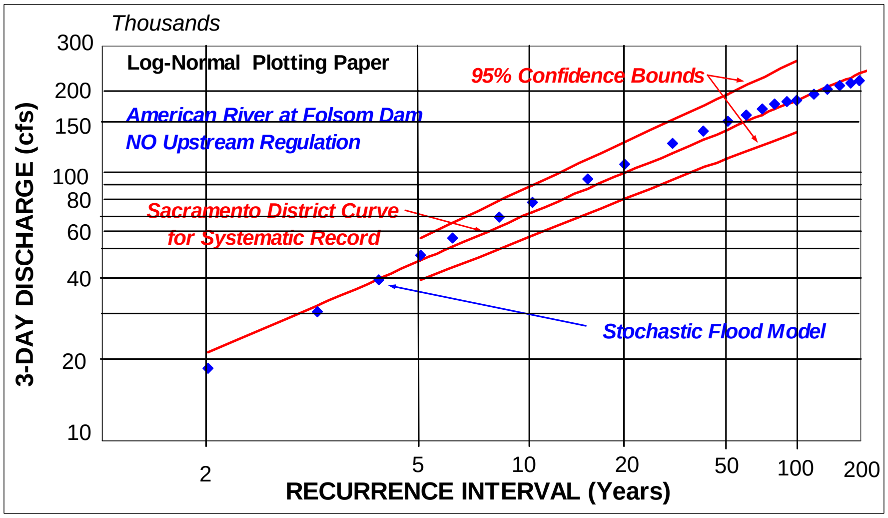

Figure 20a – Comparison of Sacramento District Maximum 3-Day Flood-Frequency Relationship and Maximum 3-Day Flood-Frequency Relationship from Adjusted Stochastic Flood Model for Floods Unregulated by Upstream Reservoirs

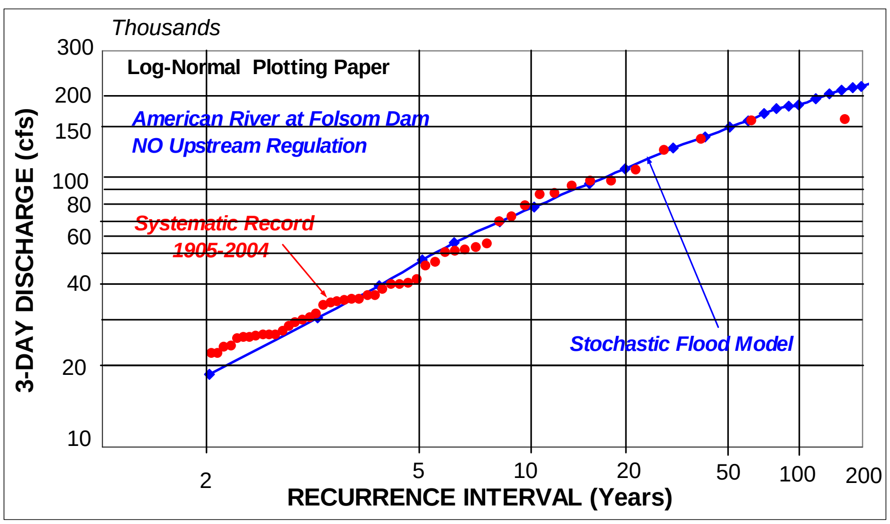

Figure 20b – Comparison of Maximum Observed 3-Day Discharges for Period from 1905-2004 and Maximum 3-Day Flood-Frequency Relationship from Adjusted Stochastic Flood Model for Floods Unregulated by Upstream Reservoirs

Comparison with Findings from NRC Committee on American River Flood Frequencies

In 1998, a National Research Council Committee (NRC)[12] was formed to examine flooding issues on the American River and to independently develop a flood-frequency relationship for maximum 3-day discharge. The flood-frequency relationship developed by the NRC was very similar to the SDC flood-frequency curve, essentially matching the SDC relationship for common floods and residing just below the SDC curve for floods in the range of recurrence intervals from 20-years to 200-years. As part of their study, the NRC Committee examined numerous climate, meteorological, and flood related issues. They concluded that the "true" flood-frequency curve for maximum 3-day unregulated discharge likely resides below their adopted curve for flood events more rare than about the 200-year flood.

One of the NRC Committee recommendations was to conduct additional studies and to examine other methods for estimating the frequency characteristics of extreme floods. The stochastic flood model represents one-such method for developing flood-frequency estimates for extreme floods. In particular, the behavior of the flood-frequency relationship seen in Figure 20 for the calibrated stochastic model is consistent with the flood behavior expected by the *NRC Committee on American River Flood Frequencies*[12]. A review of Figure 20 and the NRC report indicates that the flood outputs from the stochastic model are consistent with the findings and conclusions of the NRC Committee regarding the flood-characteristics of extreme floods on the American River.

The flood-frequency relationships generated by the stochastic flood model can now be viewed as an extension of the conventional Log Pearson III flood-frequency relationships developed from observed floods in the watershed. The stochastic flood model provides improved estimates of the flood-frequency characteristics for the more extreme floods.

Interpretation of Calibration Function ϕ

There are alternative interpretations possible for the physical meaning of the adjustment function ϕ. One interpretation is that it is simply a convenient and practical method for matching the flood-frequency curves. In this interpretation, the 30% change in L-Cv represents an amalgamation of effects from multiple hydrometeorological and watershed model sources, including some contribution from the 72-hour precipitation-frequency relationship.

A second interpretation relates to the representativeness of the maximum 3-day flood-frequency relationship relative to the 72-hour basin-average precipitation-frequency relationship. Both relationships have uncertainties due to sampling variability associated with the length of available record. In addition, there is uncertainty arising from measurement of flood discharges. The recorded discharges in the systematic record are estimates, which can only be measured within perhaps 5% to 10% by volumetric, flow-meter and indirect methods.

In general, greater confidence can be placed in the precipitation-frequency relationship because it is based on a regional analysis that incorporates a much larger sample size both in terms of number of stations and geographic coverage (Schaefer[20]). The SDC flood-frequency relationship includes flood data from the “dust-bowl” era in the 1930’s, which contained no significant flood events. The systematic flood record also includes periods with increased frequency of large floods and includes the two very large flood events of February 1986 and January 1997 (NRC[12]). This combination of very small floods and very large floods has likely increased the variance in the flood sample data over that expected in the long-term.

Thus, the 30% increase in L-Cv of the 72-hour precipitation-frequency relationship likely reflects the adjustment needed to compensate for sampling variability associated with both the flood-frequency and precipitation-frequency relationships and uncertainties associated with the hydrometeorological inputs and watershed model parameters of SEFM.

This discussion is presented here as a reminder to the reader of some of the uncertainties inherent in working with environmental data, and the resultant uncertainties that propagate through the hydrologic modeling schemes.

MAGNITUDE-FREQUENCY CHARACTERISTICS OF EXTREME FLOODS FOR REGULATED CONDITIONS

Computer simulations of the calibrated stochastic flood model were conducted for *regulated* conditions. Regulated conditions refer to inclusion of the flood attenuating effects due to existence of the five major reservoirs in the upper American River watershed. Stochastic simulation of the operation of these reservoirs was discussed in the prior section on *Storage in Upstream Reservoirs*.

The results from the Monte Carlo computer simulations were used to develop magnitude-frequency relationships for flood peak discharge, maximum 24-hour and 72-hour discharge inflow to Folsom Lake, runoff volume, maximum release from Folsom Dam, and maximum reservoir level (Figures 22, 23, 24, 25, 26, 27, 28, respectively). These relationships were based on 75,000 computer simulations using a variation of latin-hypercube[11,47] censored sampling for the precipitation input that allowed the flood-frequency curves to be developed in a piecewise manner[32]. This greatly reduced the number of simulations that would otherwise have been required to develop the frequency relationships. A graphical depiction of the piecewise approach is shown in Figure 21 and the details of the sampling approach are listed in Table 12. Additional information about this procedure is presented in the SEFM Technical Support Manual[32].

Three sets of computer simulations were conducted for each of the three segments of the frequency curve (Figure 21). For example, three sets of 10,000 simulations each were conducted for the upper segment of each frequency curve to yield the 30,000 simulations listed in Table 16. Quantile estimates were made for each of the sets using plotting position methods[5,34] (Equation 3). The final quantile estimates for a given AEP were obtained as the average of the quantile estimates for the given AEP. These values are represented by the data points shown on the various magnitude-frequency relationships. Averaging of the results from the multiple sets of simulations helped to reduce the sampling variability inherent in Monte Carlo simulation.

The results of the simulations are presented as probability-plots using standard plotting position methods[5,34]. This approach avoids the problems often encountered in selecting and fitting a probability distribution to the model outputs. Third-order polynomials have been fit to the magnitude-frequency relationships to provide numerical estimates for selected quantiles. Outputs from the stochastic flood model were ranked in descending order of magnitude and the estimate of the annual exceedance probability (P_{ex}) for each ranked flood output was obtained from the Cunane[5] plotting position formula using a Gringorten[7] weighting factor of 0.44. Specifically:

$$P_{ex} = \frac{i - 0.44}{N + 0.12} \qquad (3)$$

where: N is equal to the record length of the annual maxima series being simulated (years) and equals the number of subdivisions for latin-hypercube sampling of 72-hour basin-average precipitation; and i is the rank of the flood output. A description of this procedure is contained in the SEFM Technical Support Manual[32].

Table 16 – Sample Sizes and Ranges of Annual Exceedance Probabilities for Various Segments of Piecewise Approach used in Developing Flood-Frequency Relationships

CURVE SEGMENT	RANGE OF ANNUAL EXCEEDANCE PROBABILITY		NUMBER OF SIMULATIONS
	FROM	TO	
Lower Segment	0.5	3×10^{-4}	27,000
Middle Segment	10^{-2}	10^{-4}	18,000
Upper Segment	2×10^{-4}	10^{-6}	30,000

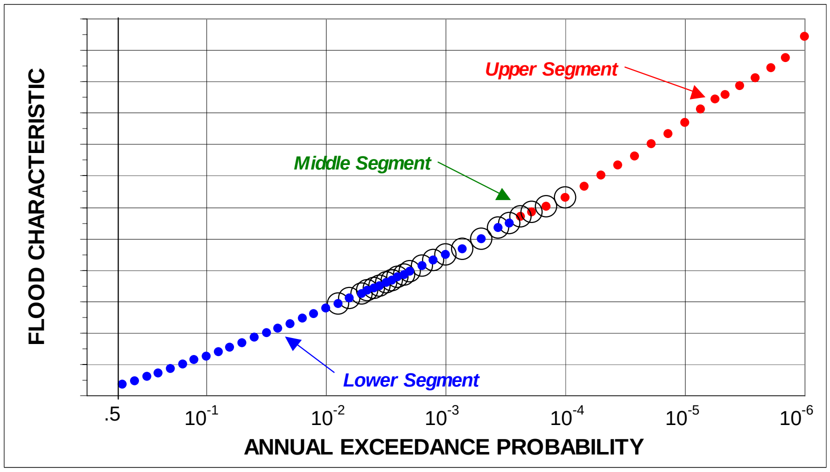

Figure 21 – Depiction of Piecewise Approach with Three Segments
for Developing Flood Magnitude-Frequency Relationships

Reservoir Inflow – Flood Peak Discharge

The reservoir inflow magnitude-frequency curve for flood peak discharge obtained from the stochastic flood model is shown in Figure 22. A review of the flood outputs revealed that the magnitude of 72-hour basin-average precipitation and the temporal distribution of the prototype storm were dominant contributors to the magnitude of flood peak discharge. A comparison of stochastic flood outputs to recorded and historical floods was made. The stochastically generated 100-year recurrence interval flood peak was estimated to be 338,900 cfs, which compares with 265,000 cfs for the 1862 flood (unregulated), 255,600 cfs for the 1997 flood and 207,400 cfs for the 1986 flood.

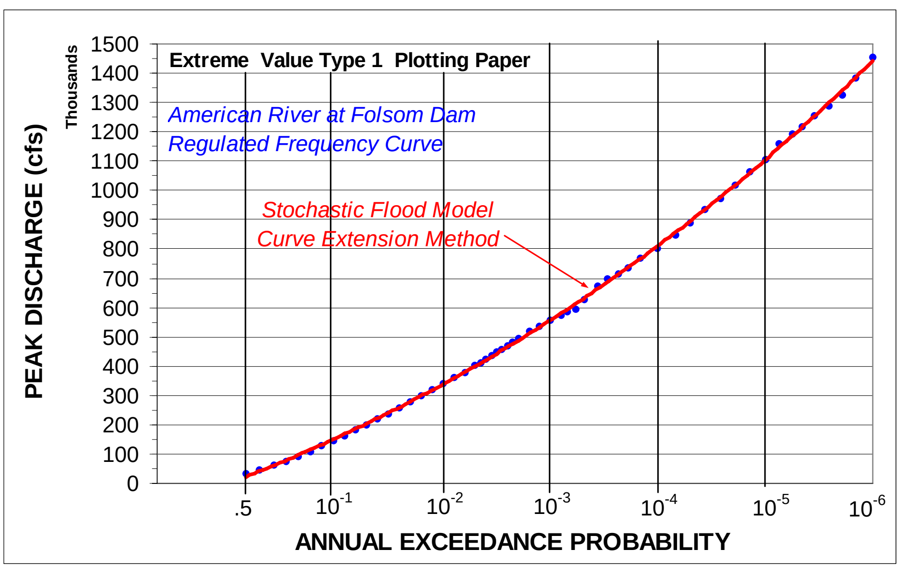

Figure 22 – Magnitude-Frequency Relationship for Flood Peak Discharge
Inflow to Folsom Dam on the American River, CA

A third-order polynomial was fit to the peak discharges obtained from the stochastic flood model (Figure 22) using annual exceedance probability as the explanatory variable. Quantile estimates for flood peak discharge can be obtained from Equations 4a,b:

$$Q_p = 1061x^3 + 7514x^2 + 161000x - 21625 \quad (4a)$$

$$x = Log_{10}(1/P_{ex}) \quad (4b)$$

where: Q_p is flood peak discharge (cfs); and P_{ex} is annual exceedance probability.

One of the topics of interest for this study was the estimation of the AEP of the flood peak discharge for the Probable Maximum Flood (PMF). The Folsom reservoir inflow PMF peak has been computed by the USCOE[39] to be 906,000 cfs. Application of the flood-frequency relationship for the PMF peak discharge provides an estimated AEP of 4.5 x 10^{-5} (1:22,000). Estimates of flood peak discharge were computed in a similar manner for selected quantiles, and are listed in Table 17.

Table 17 – Flood Peak Discharge Estimates for Folsom Dam for Selected Quantiles for Regulated Conditions on the American River Watershed

ANNUAL EXCEEDANCE PROBABILITY	FLOOD PEAK DISCHARGE
10^{-6}	1,444,000 cfs
10^{-5}	1,104,000 cfs
4.5 x 10^{-5}	906,100 cfs PMF
10^{-4}	810,500 cfs
10^{-3}	557,600 cfs
10^{-2}	339,000 cfs

Reservoir Inflow – Maximum 24-Hour Discharge

The reservoir inflow magnitude-frequency curve for maximum 24-hour discharge obtained from the stochastic flood model is shown in Figure 23. The magnitude of the maximum 24-hour discharge has been used in the past by the SDC as an indicator of the likely reservoir response to floods considering the flood response time of the watershed, the storage capacity of Folsom Lake, and the spillway operating procedures. The February 1986 and January 1997 floods are the two largest 24-hour discharges in the record and are of particular interest. Both floods occurred under regulated conditions. Figure 23 depicts the range of annual exceedance probabilities possible for these floods depending upon on the length of the representative period assigned by the analyst. The green circles in Figure 23 are associated with a sampling period of 100-years (1905-2004) and the green horizontal lines represent the range of AEPs that result depending upon the choice of representative periods, such as 1966-2004 (most recent period) and 1862-2004 (complete historical record).

Quantile estimates for maximum 24-hour discharge (Q_{24}) can be obtained from Equations 5, 4b:

$$Q_{24} = 761x^3 + 8025x^2 + 120850x - 17820 \quad (5)$$

Estimates of maximum 24-hour discharge (cfs) were computed from Equations 5 and 4b for selected quantiles, and are listed in Table 18.

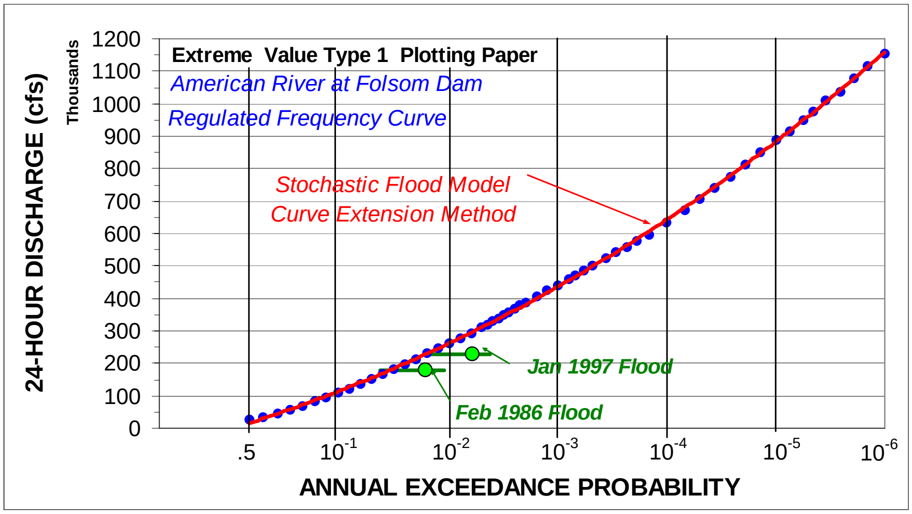

Figure 23 – Magnitude-Frequency Relationship for Maximum 24-Hour Discharge Inflow to Folsom Dam on the American River, CA

Table 18 – Estimates of Maximum 24-Hour Discharge for Folsom Dam for Selected Quantiles for Regulated Conditions on the American River Watershed

ANNUAL EXCEEDANCE PROBABILITY	MAXIMUM 24-HOUR DISCHARGE
10^{-6}	1,161,100 cfs
10^{-5}	882,200 cfs
10^{-4}	642,700 cfs
10^{-3}	437,500 cfs
10^{-2}	262,100 cfs

Reservoir Inflow – Maximum 72-Hour Discharge

The reservoir inflow magnitude-frequency curve for maximum 72-hour discharge obtained from the stochastic flood model for regulated conditions is shown in Figure 24. The February 1986 and January 1997 floods are also depicted in Figure 24 showing the range of annual exceedance probabilities possible for these floods events depending on the choice of the length of the representative period that contained these floods. As before, the green and yellow circles in Figure 24 are associated with a sampling period of 100-years (1905-2004). The green and yellow horizontal lines represent the range of AEPs possible depending upon selection of the representative periods, such as 1966-2004 and 1862-2004.

Quantile estimates for maximum 72-hour discharge (Q_{72}) can be obtained from Equations 6, 4b:

$$Q_{72} = -629x^3 + 13140x^2 + 61695x - 2525 \qquad (6)$$

The maximum 72-hour discharge for the PMF computed by the USCOE[39] is 472,200 cfs. Application of the flood-frequency relationship for the maximum 72-hour discharge in the PMF (Equations 5, 4b) provides an estimated AEP of $4x10^{-5}$ (1: 25,000). Estimates of maximum 72-hour discharge were computed from Equations 6 and 4b for selected quantiles, and are listed in Table 19.

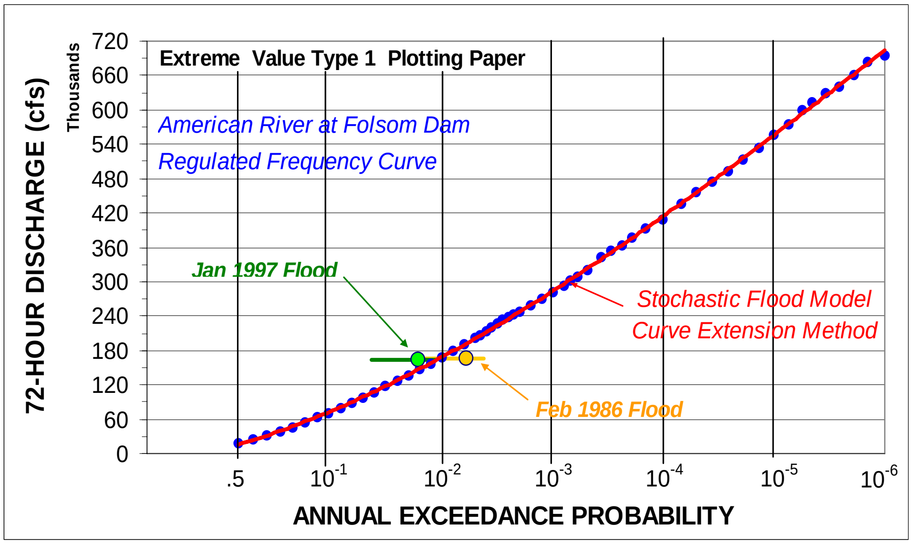

Figure 24 – Magnitude-Frequency Relationship for Maximum 72-Hour Discharge Inflow to Folsom Dam on the American River, CA

Table 19 – Estimates of Maximum 72-Hour Discharge for Folsom Dam for Selected Quantiles for Regulated Conditions on the American River Watershed

ANNUAL EXCEEDANCE PROBABILITY	MAXIMUM 72-HOUR DISCHARGE
10^{-6}	704,800 cfs
10^{-5}	555,800 cfs
4×10^{-5}	472,200 cfs PMF
10^{-4}	414,200 cfs
10^{-3}	283,800 cfs
10^{-2}	168,400 cfs

Flood Runoff Volume

The magnitude-frequency curve for runoff volume obtained from the stochastic flood model is shown in Figure 25. The values of runoff volume (Table 10) include baseflow, which represents a very small fraction of the total volume for all but the most common flood events. The duration of the period of runoff for any given flood event varies with the duration of the selected prototype storm. Therefore, the runoff volume is not associated with any specific duration, such as an *n*-day volume. Prototype storms vary from 3-days to 8-days in duration with most storms having durations in the 6-day to 7-day range. Considering the range in storm durations and adding the response time of the watershed, a nominal 10-day duration may be used as a rough basis of comparison for the frequency characteristics of runoff volumes generated by the stochastic flood model.

Quantile estimates for runoff volume (V_{runoff}) in acre-feet can be obtained from Equations 7, 4b:

$$V_{runoff} = -3455x^3 + 97110x^2 + 591780x - 19500 \qquad (7)$$

Estimates of flood runoff volume were computed from Equations 7 and 4b for selected quantiles, and are listed in Table 20.

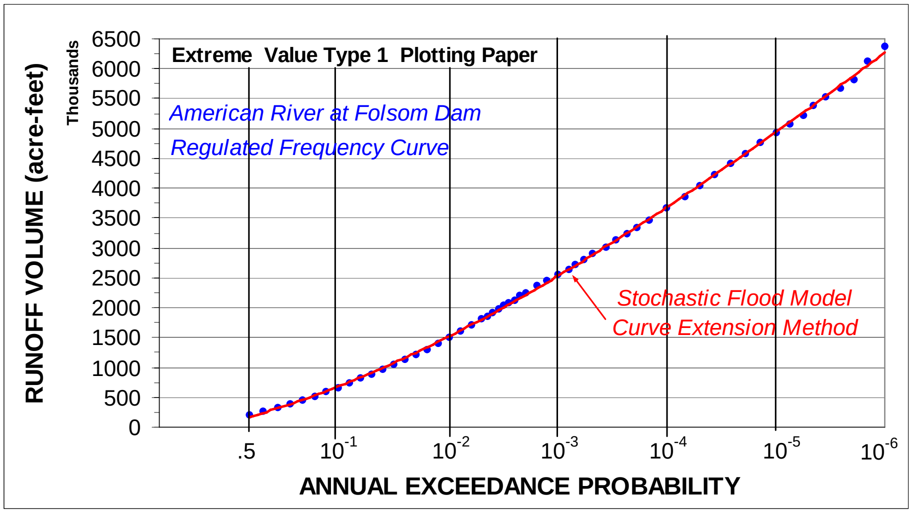

Figure 25 – Magnitude-Frequency Relationship for Runoff Volume Inflow to Folsom Dam on the American River, CA

Table 20 – Estimates of Flood Runoff Volume into Folsom Lake Dam for Selected Quantiles for Regulated Conditions on the American River Watershed

ANNUAL EXCEEDANCE PROBABILITY	FLOOD RUNOFF VOLUME
10^{-6}	6,281,000 acre-feet
10^{-5}	4,935,000 acre-feet
10^{-4}	3,680,000 acre-feet
10^{-3}	2,537,000 acre-feet
10^{-2}	1,525,000 acre-feet

Reservoir Outflow Peak Discharge

The magnitude-frequency curve for reservoir outflow peak discharge obtained from the stochastic flood model is shown in Figure 26. The irregular shape of the curve reflects the discharge characteristics of the low-level outlets and spillways, and operational procedures for flood control.

As discussed previously, the current procedures contained in the flood control diagram (FCD) and Emergency Spillway Release Diagram (ESRD) were used to conduct reservoir routing of the inflow floods. Releases in excess of 115,000 cfs, the safe capacity of the downstream channel and levee system, were found to have an estimated annual exceedance probability of 0.0095 (1:105). The initial storage volume at Folsom Lake and the storage available in the five upstream reservoirs were important factors in addition to the magnitude of the inflow flood in determining the maximum release from Folsom Dam.

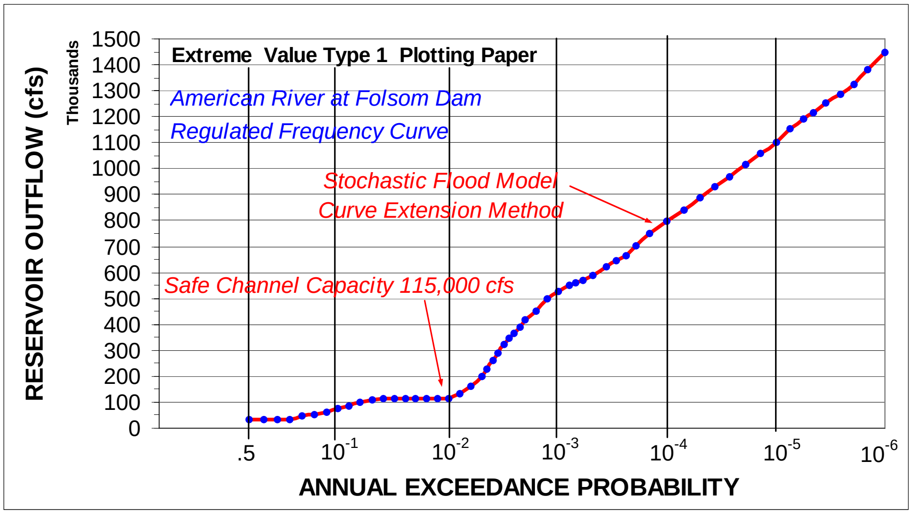

Figure 26 – Magnitude-Frequency Relationship for Reservoir Outflow Peak Discharge from Folsom Dam on the American River, CA

Maximum Reservoir Level

The magnitude-frequency curve for maximum reservoir level obtained from the stochastic flood model is shown in Figure 27. As was the case for reservoir outflow, the initial storage volume at Folsom Lake and the storage available in the five upstream reservoirs were important factors in determining the maximum reservoir level attained during passage of an extreme flood.

The annual exceedance probability (AEP) for floodwaters reaching the top of flood control pool (466.0 feet) was estimated to be 0.0095 (1:105). The estimated AEP for floodwaters reaching the top of dam elevation (480.5 feet) was $2x10^{-5}$ (1:5,000).

The 1997 and 1986 floods are the largest floods that occurred during the 1905-2004 systematic record. The February 1986 flood occurred while Reservoir Rule Curve 3 was in place and the maximum reservoir level reached near 466.0 feet. The current Rule Curve 4 (Figure 16) provides significant increases in storage available for floodwaters relative to that from Rule Curve 3. To provide a common measure of reservoir performance, the February 1986 flood hydrograph was routed through Folsom Lake using the current reservoir operating procedures and typical February conditions for setting the initial reservoir level at the start of the storm. Reservoir routing for this situation produced a maximum stage of 448.7 feet for the 1986 flood event for current operating procedures.

The January 1997 occurred under the current operating procedures (Rule Curve 4) and the maximum stage recorded was 456.0 feet. Both floods have been plotted on Figure 26 based on a systematic record length of 100-years (1905-2004) and the Cunnane-Gringorton[5,7,34] plotting position formula (Equation 3). As was done previously, the horizontal green lines through the 1986 and 1997 floods represent the range of AEPs possible based on the representative period that is chosen for analysis.

Table 21 lists the results of the computer simulations for combinations of annual exceedance probability and reservoir levels that are of general interest. The marked change in slope above the top of flood control pool (Figure 27) reflects the shift in reservoir operations to significantly increased spillway releases in transferring from flood control operation to protection of the dam from overtopping.

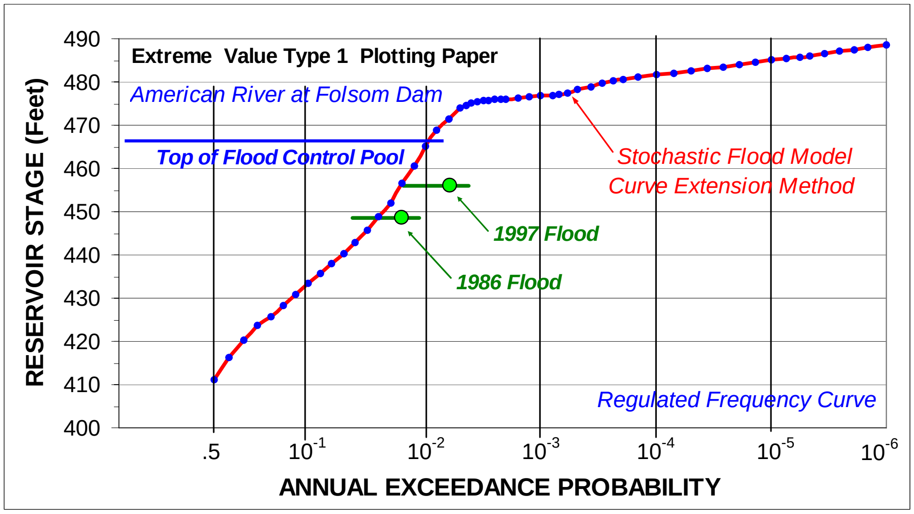

Figure 27 – Magnitude-Frequency Relationship for Maximum Reservoir Level for Folsom Dam on the American River, CA

Table 21 – Estimates of Annual Exceedance Probabilities for Selected Reservoir Levels for Folsom Dam for Regulated Conditions on the American River

ANNUAL EXCEEDANCE PROBABILITY	MAXIMUM FOLSOM RESERVOIR LEVEL	RESERVOIR ZONE
10^{-6}	488.5 ft	
10^{-5}	485.1 ft	
10^{-4}	481.6 ft	
2.0×10^{-4}	480.5 ft	Top of Dam
10^{-3}	476.8 ft	
3.5×10^{-3}	475.4 ft	Top of Surcharge Pool
9.5×10^{-3}	466.0 ft	Top of Flood Control Pool
10^{-2}	465.3 ft	

UNCERTAINTIES IN COMPUTED FLOOD-FREQUENCY RELATIONSHIPS

Uncertainties are inherent in the development of the flood-frequency relationships depicted in Figures 22-27. Uncertainties arise from a variety of sources that include: the usual problems encountered in data measurement, recording and quality control; difficulty in accurate measurement of some hydrometeorological inputs, particularly in mountainous settings; sampling variability from the limited length of record available; spatial and temporal variability of the phenomenon; complexity of interaction with other hydrometeorological parameters; as well as other contributors. In a similar manner, there are uncertainties with regard to the ability of the various computer algorithms in the watershed model to mimic the complex rainfall-runoff processes, subbasin flood response, and streamflow routing processes for the stream network in the watershed.

These uncertainties are mitigated to some extent by calibration of the HEC-1 watershed model to historical floods. Nonetheless, the combined effect of the various contributors of uncertainty is to create uncertainty about how closely the computed flood-frequency relationships approach reality.

Recommendation for Conducting Uncertainty Analysis

Estimation of the magnitude of uncertainty in the flood-frequency relationships (Figures 22-27) can be attained by conducting an uncertainty analysis and developing uncertainty bounds for the flood-frequency curves. An uncertainty analysis is recommended as a final element of this project. The results of that analysis would be used to improve the flood-frequency estimates and provide uncertainty bounds about those estimates for each of the flood characteristics.

SUMMARY

A stochastic flood model was developed for the American River watershed tributary to Folsom Dam for use in developing flood-frequency estimates for extreme floods. The stochastic flood model utilized a deterministic flood computation model (HEC-1) and treated the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures were used to allow the climatic and storm related input parameters to vary in accordance with that observed in nature. Hydrometeorological inputs that were treated as variables included: seasonality of storm occurrence; magnitude of extreme storm, temporal and spatial distribution of storms; temporal temperature pattern during the storm; sea-level and freezing level temperatures; antecedent precipitation; antecedent snowpack; antecedent soil moisture; initial storage in major upstream reservoirs; and initial storage in Folsom Lake.

Flood-frequency estimates of extreme floods were made utilizing the stochastic flood model to extend the existing 3-day flood-frequency relationship. This was accomplished in two stages. The first stage utilized four historical floods to calibrate the HEC-1 watershed model. The second-stage was accomplished by adjusting the stochastic flood model to match the 100-year discharge that was computed from the systematic record while reproducing the flood-frequency characteristics of the observed 3-day record to the maximum extent possible.

75,000 computer simulations were conducted to develop magnitude-frequency relationships for the flood characteristics of peak discharge, maximum 24-hour discharge, maximum 72-hour discharge, maximum reservoir release, runoff volume, and maximum reservoir level. Each simulation contained a set of climatic and storm parameters that were selected through Monte Carlo procedures based on the historical record and collectively preserved dependencies between the hydrometeorological input parameters. Execution of the watershed hydrologic model HEC-1 and reservoir routing of the inflow floods yielded the annual maxima flood characteristics of interest.

The flood-frequency relationships generated by the flood model were used to estimate the Annual Exceedance Probability (AEP) of selected flood characteristics. The AEP for floodwaters reaching the top of flood control pool (466.0 feet) was estimated to be 0.0095 (1:105). The AEP for floodwaters reaching the top of dam elevation (480.5 feet) was estimated to be $2x10^{-5}$ (1:5,000). The maximum 72-hour discharge in the US Corps of Engineers Probable Maximum Flood (PMF) is 472,200 cfs and was estimated to have an AEP of $4x10^{-5}$ (1:25,000).

REFERENCES

1. Beven KJ and Binley A, The Future of Distributed Models: Model Calibration and Uncertainty Prediction, Hydrological Processes, Volume 6, pp272-298, 1992.
2. Cameron DS, Beven KJ, Tawn J, Blazkova S and Naden P, Flood Frequency Estimation by Continuous Simulation for a Gaged Upland Catchment (with Uncertainty), Journal of Hydrology, Vol 219 pp169-187, 1999.
3. CDEC, *California Data Exchange Center*, California Water Resources Department, Flood Management Division, Sacramento, CA.
4. Collins RF, 29-Subbasin HEC-1 Watershed Model of American River, version of Feb 2001, US Army Corps of Engineers Sacramento District.
5. Cunnane C, Unbiased Plotting Positions – A Review, Journal of Hydrology, volume 37, no. 3, pp205-222, 1978.
6. Daly C, Neilson RP, and Phillips DL, A Statistical-Topographic Model for Mapping of Climatological Precipitation over Mountainous Terrain (PRISM Parameter-Elevation Regression on Independent Slopes Model), Journal of Applied Meteorology, Volume 33, pp140-158, 1994.
7. Gringorten II, A Plotting Rule for Extreme Probability Paper, Journal Geophysical Research, vol 68, no. 3, pp813-814, 1963.
8. Holtan HN, Stitner GJ, Henson WH and Lopez NC, USDAHL-74, Revised Model of Watershed Hydrology, Technical Bulletin No. 1518, Agricultural Research Service, US Department of Agriculture, 1975.
9. Hosking JRM and Wallis JR, Regional Frequency Analysis – An Approach Based on L-Moments, Cambridge Press, 1997.
10. Jensen ME and Haise HR, Estimating Evapotranspiration from Solar Radiation, Proceedings of the ASCE, Journal of Irrigation and Drainage, Volume 89, No IR4, pp15-41, 1963.
11. McKay MD, Conover WJ, and Beckman RJ, A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code, Technometrics, 221, pp239-245, 1979.
12. National Research Council (NRC), Improving American River Flood Frequency Analyses, Water Science and Technology Board, National Academy Press, Washington DC, 1999.
13. NCDC, Climatological Data for California, Summary of the Day Data, National Climatic Data Center (NCDC) Asheville NC, available through HydroSphere Data Products, Boulder CO, 1999.
14. NRCS, *Snotel Data Network*, Water and Climate Center, National Resource Conservation Service, US Department of Agriculture, Washington DC.
15. NWS, National Weather Service, Hydrometeorological Report 58, Probable Maximum Precipitation for California, Calculation Procedures, U.S. Department of Commerce, NOAA, US Weather Bureau, Washington DC, October 1998.
16. 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.

17. Oregon Climate Service, Mean Annual Precipitation Maps for Western United States, PRISM Model, Corvallis Oregon, 1997.
18. Schaefer MG, Seasonality Analysis of Extreme Storms for the American River Watershed, MGS Engineering Consultants Inc, prepared for Hydrologic Engineering Center, US Army Corps of Engineers, November 1999.
19. Schaefer MG, Antecedent Precipitation Characteristics for the American River Watershed, MGS Engineering Consultants Inc, prepared for Hydrologic Engineering Center, US Army Corps of Engineers, December 2000.
20. 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.
21. Schaefer MG, Catalog of Storms for the Spatial Analysis of Storms for the American River Watershed, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, February 2000.
22. Schaefer MG, Analysis of Storms Antecedent and Posterior to Extreme Storms for the American River Watershed, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, February 2000.
23. Schaefer MG, Snowpack Characteristics and Relationship with Antecedent Precipitation for the American River Watershed, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, January 2001.
24. Schaefer MG, Analysis of Seasonal Reservoir Storage for Reservoirs in the Upper American River Watershed, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, February 2001, revised December 2003.
25. Schaefer MG, 72-Hour Precipitation-Frequency Relationship and Uncertainty Analysis for the 1890-mi^2 American River Watershed, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, July 2002.
26. Schaefer MG, Analysis of Air Temperature Profiles and Air Temperature Lapse Rates During Storms for the American River Watershed, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, October 2002.
27. Schaefer MG, Description of Stochastic Storm Resampling Approach and Selection of Prototype Storms For Resampling, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, October 2002.
28. Schaefer MG, Analysis of Antecedent Streamflow Tributary to Folsom Reservoir, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, October 2002.
29. Schaefer MG, Analysis of Historical Reservoir Operations at Folsom Dam and Development of a Stochastic Model for Simulation of Initial Reservoir Storage, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, December 2002, revised December 2003.
30. Schaefer MG and Barker BL, Calibration of American River Watershed Model to Historical Floods, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, June 2003, revised October 2003.

31. Schaefer MG and Barker BL, Sensitivity Analyses for the Stochastic Model of Extreme Floods on the American River at Folsom Dam, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, March 2004.

32. SEFM, Stochastic Event Flood Model – Users Manual, MGS Engineering Consultants, Inc, Schaefer MG and Barker BL, March 2001.

33. STATSGO, State Soil Geographic Database for the Conterminous United States, US Department of Agriculture, Natural Resource Conservation Service, Washington DC.

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

35. USBR, Effect of Snow Compaction on Runoff from Rain on Snow, Engineering Monograph 35, US Bureau of Reclamation, Bertle FA author, 1966.

36. USBR, Work Products for Calibration of HEC-1 Watershed Model for American River to February 1986 Flood, US Bureau of Reclamation Flood Hydrology Group.

37. USCOE, HEC-1 Flood Hydrograph Package Version 4.1 – Users Manual, Hydrologic Engineering Center, US Army Corps of Engineers 1996.

38. USCOE, Work Products for Calibration of HEC-1 Watershed Model for American River to January 1997 Flood, US Army Corps of Engineers Sacramento District.

39. USCOE, American River Basin, California, Folsom Dam and Lake Revised PMF Study, US Army Corps of Engineers Sacramento District, October 2001.

40. USCOE, Adopted Rain Flood Flow Frequency Analysis, American River, California, U.S. Army Corps of Engineers Sacramento District, April 1999.

41. USDA, Soil Survey Eldorado National Forest California, Natural Resource Conservation Service, 1985.

42. USDA, Soil Survey Eldorado Area California, Natural Resource Conservation Service, 1974.

43. USDA, Soil Survey Tahoe National Forest Area California, Natural Resource Conservation Service, 1982.

44. USDA, Soil Survey Placer County California, Western Part, Natural Resource Conservation Service, 1980.

45. Viessman W, Knapp JE, Lewis GL and Harbaugh TE, *Introduction to Hydrology*, Intext Harper and Row, Second Edition, 1977.

46. Weiss LL, Ratio of True to Fixed Interval Maximum Rainfall, Journal Hydraulics, ASCE, 90(HY1), pp77-82, 1964.

47. Wyss GD and Jorgenson KH, A Users Guide to LHS: Sandia's Latin Hypercube Sampling Software, Sandia National Laboratories, report SAND98-0210, February 1998.