**US Army Corps
of Engineers**
Hydrologic Engineering Center

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

Appendix M - Sensitivity Analyses for the Stochastic Model of Extreme Floods for the American River at Folsom Dam

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14. ABSTRACT

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

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SENSITIVITY ANALYSES
FOR THE STOCHASTIC MODEL OF EXTREME FLOODS
FOR THE AMERICAN RIVER AT FOLSOM DAM

March 18, 2004

OVERVIEW

This report presents the results of sensitivity analyses that were conducted for the stochastic flood model (SEFM[37]) that was developed for the American River at Folsom Dam[36]. Sensitivity analyses were conducted for two purposes. First, sensitivity analyses provide the reader with additional insight and understanding of the watershed and reservoir responses to the various hydrometeorological inputs to the stochastic model. Second, the findings from these analyses will provide information for decision-making for use in selecting those hydrometeorological inputs that have the greatest effect on the flood outputs and should be included in uncertainty analyses.

Uncertainty analyses are to be conducted as a future task for this project and the findings of those analyses will be used to develop uncertainty bounds for flood-frequency relationships for flood peak discharge, maximum 24-hour discharge, maximum 72-hour discharge, maximum reservoir release, runoff volume, and maximum reservoir level.

The following sections provide descriptions of the procedures and the results from conducting sensitivity analyses for watershed and reservoir responses to changes in the various hydrometeorological inputs to the stochastic flood model.

BACKGROUND

The stochastic flood model for the American River is comprised of: a series of modules for selecting the hydrometeorological inputs; computational routines for modeling the rainfall-snowmelt-runoff processes; and a modified HEC-1 watershed model (USCOE[42]) for computing flood hydrographs, combining hydrographs from subbasins, and routing of flood flows through the stream network and reservoirs. Each of these separate elements and modules have been described in prior reports (Schaefer[23-36]). Excerpts have been taken from these prior reports and are presented below to provide background and easy reference for the reader in reviewing the results of the sensitivity analyses. Readers are referred to the original reports for more detailed information about the various subjects and the models used to simulate the hydrometeorological inputs.

A general description of the American River watershed is shown in Figure 1a and the layout of the 33 subbasin HEC-1 watershed model is shown in Figure 1b. Antecedent precipitation and snowpack were allocated using zones of mean annual precipitation (Table 1a) and elevation (Table 1b) and those zones are depicted in Figures 2a,b, respectively. Eight soil zones (Figure 2c) were used to characterize the soils in the watershed. Soil moisture accounting, snowmelt, surface runoff and interflow runoff were computed on a distributed basis using Hydrologic Runoff Units (HRUs). HRUs are defined as unique combinations of zones of mean annual precipitation, elevation and soil characteristics (SEFM[37]). The Holtan infiltration model[10] was modified to include computation of interflow runoff and the modified Holtan procedure utilizes four soil properties in computing runoff (SEFM[37]). The parameter set for the modified Holtan procedure with the highest likelihood was obtained through calibration to four historical floods using GLUE methodology (Beven et al[1,2], Calibration report[35]) and is listed in Table 2.

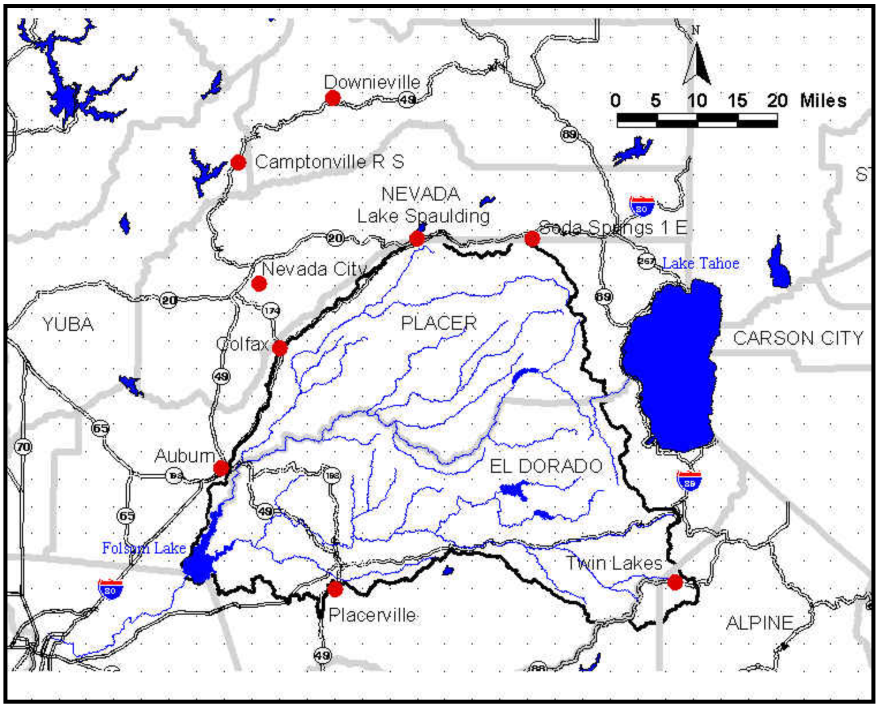

Figure 1a – American River Watershed above Folsom Dam and Surrounding Area

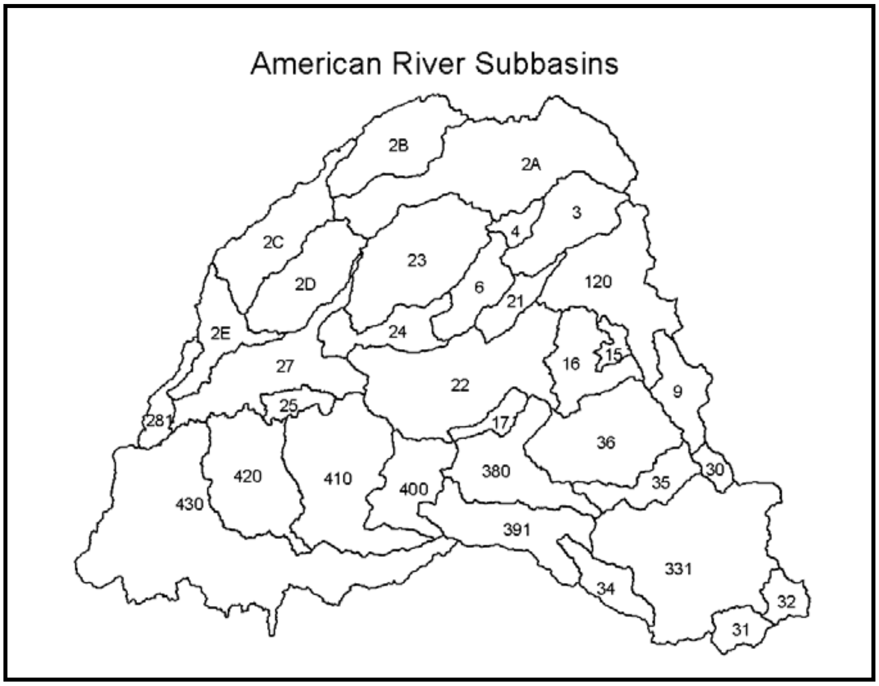

Figure 1b – Layout of 33-Subbasins for American River Watershed

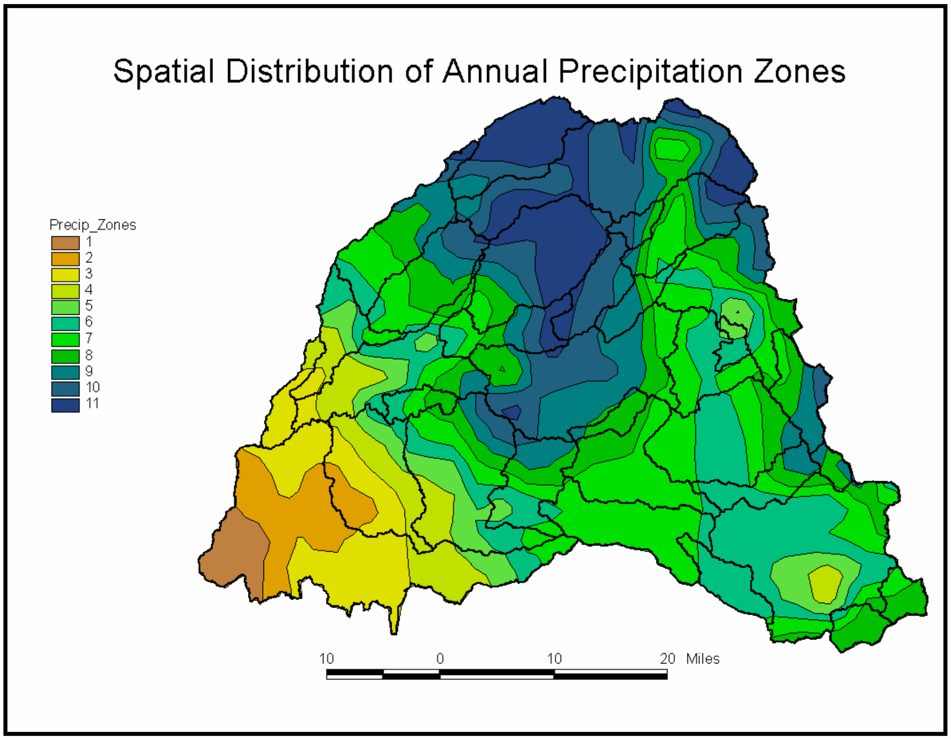

Figure 2a – Zones of Mean Annual Precipitation for the American River Watershed

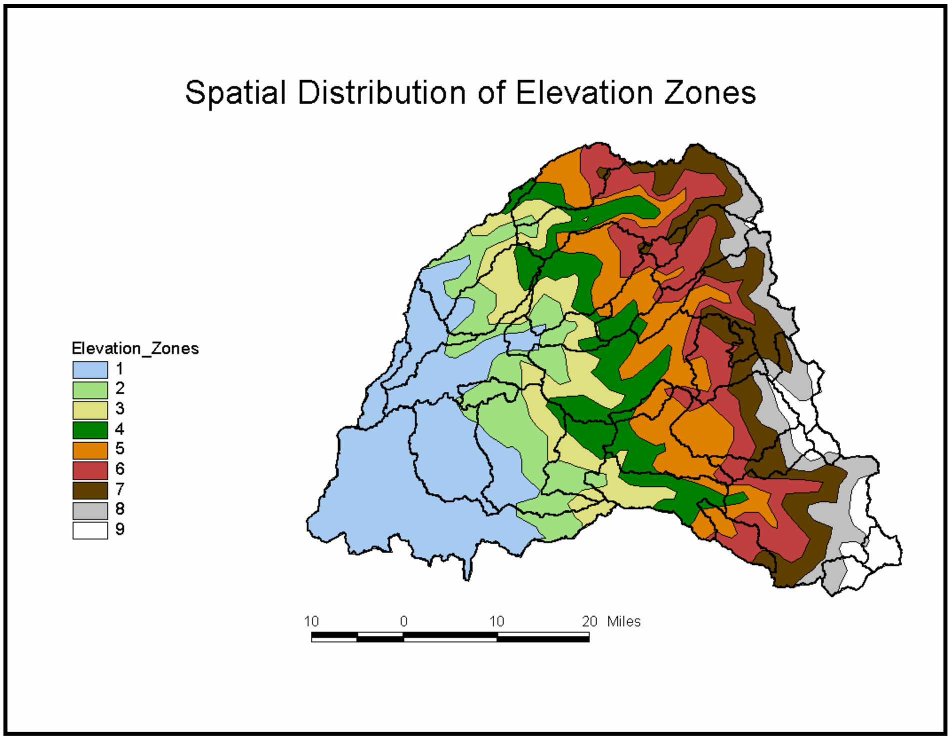

Figure 2b – Elevation Zones for the American River Watershed

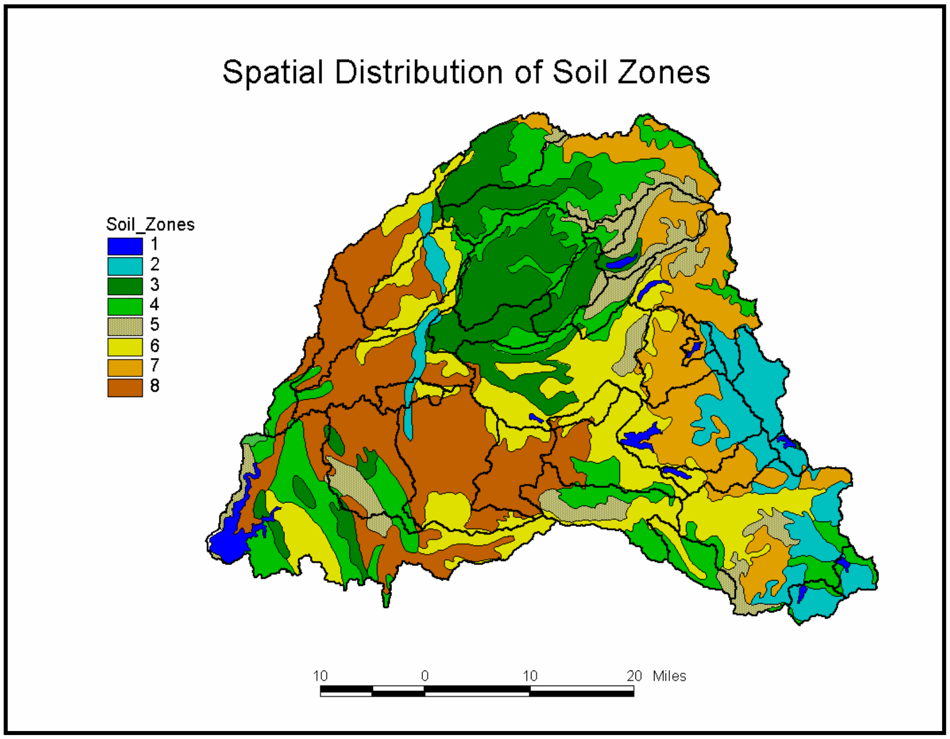

Figure 2c – Soil Zones for the American River Watershed

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%

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%

Table 2 – Final Calibrated Parameter Set of Soil Characteristics based on GLUE[1,2,35] 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

METHODS USED FOR SENSITIVITY ANALYSIS

One-At-A-Time (OAT) sensitivity analysis has a long history in engineering practice. OAT analyses are accomplished by examining the magnitude of model outputs while varying the magnitude of one input parameter at a time while keeping all other input parameters at pre-selected control values. This approach is best suited to situations where all, or a majority of the inputs are independent of each other. Hydrologic models of complex systems are often ill-suited to OAT analysis because many of the hydrometeorological inputs are correlated. In addition, the outputs from hydrologic models are often non-linear and the results from OAT analysis may be confounded by the selected control values and operational rules.

Global sensitivity analysis is an alternative to OAT analysis. The global approach differs from the OAT approach in that sampling techniques are used for selection of each of the hydrometeorological inputs for each execution of the stochastic flood model. Numerous simulations are conducted to allow mapping of the variability of the model outputs for each of the inputs. The global approach is particularly useful when some of the model inputs are correlated, or where there are interactions between some inputs. This is the case for the stochastic flood model where, for example, many of the hydrometeorological inputs are correlated to some degree with antecedent precipitation. Table 3 lists the dependencies that exist between the various hydrometeorological inputs.

Global sensitivity analysis has been used in this study and the results are presented below. The results of the OAT analysis are presented in Appendix A to provide those readers familiar with OAT analysis a frame of reference for comparison with the results of the global sensitivity analysis. Again, the reader is cautioned that interpretation of the results from OAT analysis can be difficult or misleading when there are correlated inputs and interactions between model inputs and parameters.

Table 3 – 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 on Day of Maximum 24-hour Precipitation
5	Sea-Level Temperature	Storm Magnitude	For Day of Maximum 24-hr Precipitation in storm
6	Freezing-Level	Sea-Level Temperature and Storm Magnitude	For Day of Maximum 24-hr 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 Folsom Operating Rules	Utilizes Folsom Rule Curves and Storage in 5 Upstream Reservoirs

SCREENING LEVEL GLOBAL SENSITIVITY ANALYSIS

A screening level global sensitivity analysis was conducted (Saltelli[21,22]), to provide a quantitative measure of the relative sensitivity of the flood and reservoir responses to each of the hydrometeorological inputs. The procedure adopted here was to generate 5000 sample sets of the hydrometeorological inputs for the end-of-January and compute flood and reservoir responses for each sample set. The end-of-January was chosen as a general case representative of the mid-winter months of December, January and February because extreme floods are predominately produced in the mid-winter months.

The 72-hour basin-average precipitation was expected to be a dominant input for generation of floods. Therefore, sampling of 72-hour precipitation focused on the more extreme events and was conducted in the range of annual exceedance probabilities from 0.10 (1:10) to 0.00002 (1:50,000). Sampling of the other hydrometeorological inputs was conducted over a wide range of possible values. Latin-hypercube sampling (McKay etal[14], Wyss et al [52]) was utilized for 72-hour basin-average precipitation and Monte Carlo procedures (Jain[11]) were used for all other hydrometeorological inputs. This approach allowed use of the previously coded stochastic computer routines that incorporated the various correlation relationships (SEFM[37]).

The sensitivity of flood and reservoir responses was evaluated for each input using scatterplots and partial correlation coefficients. Specifically, a sensitivity index (S_i) was computed as the square of the partial correlation coefficient (Ezekial et al[54]) for each input. The sensitivity index is a measure of the variance of the flood or reservoir response explained by a specific hydrometeorological input, and:

$$S_i = 1 - \left(\frac{1 - R^2_{all}}{1 - R^2_{all-1}} \right) \tag{1}$$

where: S_i is a sensitivity index, the square of the partial correlation coefficient; R^2_{all} is the coefficient of determination for multiple linear regression using all of the hydrometeorological inputs; and R^2_{all-1} is the coefficient of determination of multiple linear regression using all of the hydrometeorological inputs except the input of interest.

Measure of Flood Response

Sensitivities of the stochastic flood model were determined by examining the flood response to changes in values of the hydrometeorological inputs. The term *flood response,* as used in the global sensitivity analysis, refers to flood outputs from the stochastic flood model for the American River watershed. Specifically, the maximum 24-hour inflow to Folsom Dam was used to characterize the flood response for the global sensitivity analyses. This measure was chosen because it is an indicator of both flood response from the watershed and is a good indicator of Folsom reservoir response to extreme and very extreme floods (Figure 3).

Scatterplots of the flood response versus each of the hydrometeorological inputs are shown in Figures 4-9. Sensitivity indices have been computed for each input and are listed in rank order in Table 4. A short discussion is provided about the behavior of the flood response for each of the hydrometeorological inputs.

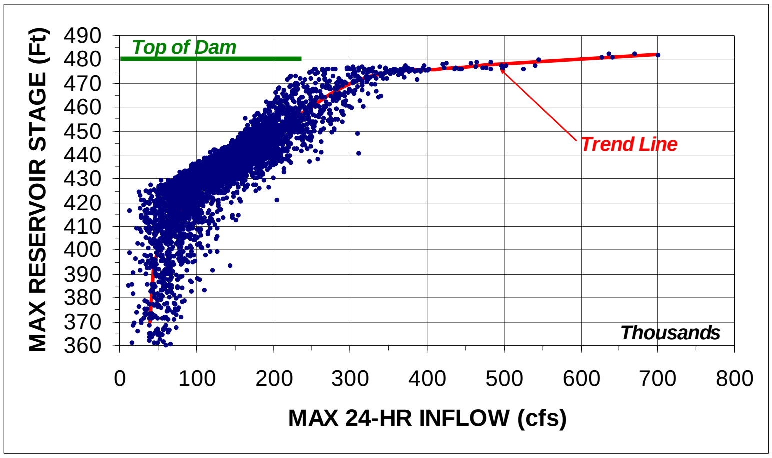

Figure 3 – Scatterplot of Folsom Reservoir Response to Changes in Maximum 24-Hour Inflow to Folsom Reservoir for the End-of-January

Table 4 – 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

72-Hour Basin-Average Precipitation

The magnitude of 72-hour basin-average precipitation was found to be the dominant input for explaining the variance in the flood response (Figure 4, Table 4). This finding was not unexpected, given the large magnitude of precipitation events that occur over the watershed.

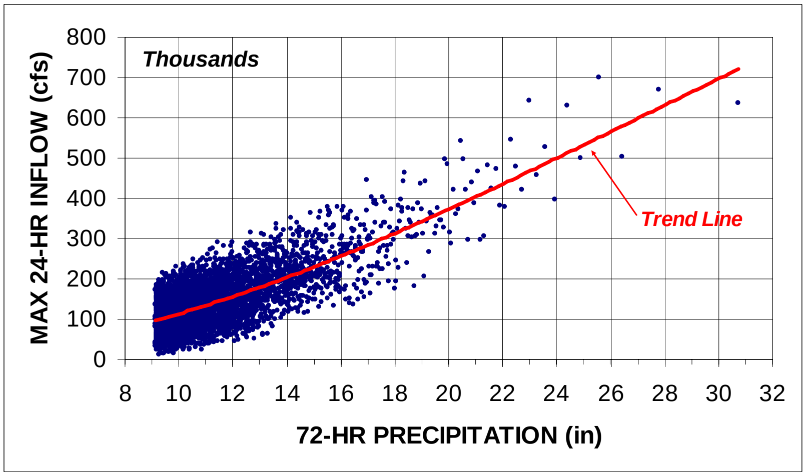

Figure 4 – Sensitivity of Flood Response to Changes in 72-Hour Basin-Average Precipitation for Global Sensitivity Analysis for the End-of-January

Freezing Level During Storm Event

The magnitude of the freezing level was found to be the second most important factor in explaining the variance in the flood response (Figure 5, Table 4). Freezing level during a storm event is an important factor because it affects the flood response in a non-linear manner over the range of possible freezing levels. When the freezing level is low, precipitation falls as snow throughout much of the watershed and affected areas do not contribute to the flood response. Conversely, when the freezing level exceeds the maximum elevation in the watershed, all precipitation occurs in the liquid phase and increased temperatures result in increased snowmelt. Thus, freezing level has a negative effect on flood response at low values and a positive effect on flood response at high values.

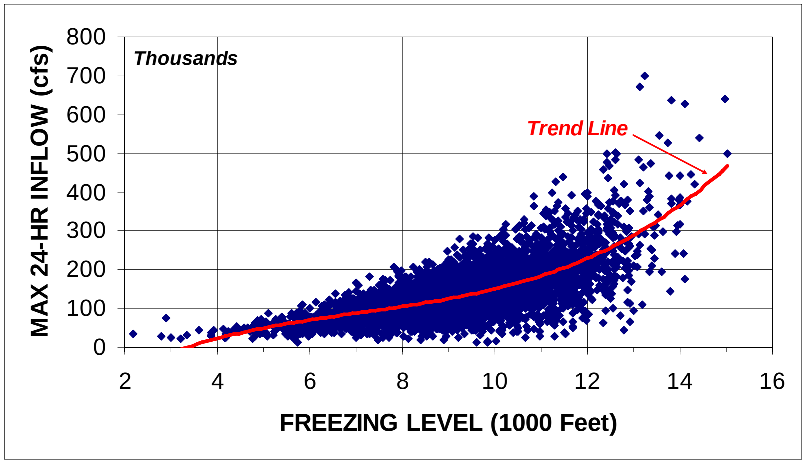

Figure 5 – Sensitivity of Flood Response to Changes in Freezing Level for Global Sensitivity Analysis for the End-of-January

Antecedent Precipitation

The magnitude of antecedent precipitation affects the flood response in several ways. The primary effect is by changing antecedent soil moisture conditions. When the antecedent precipitation is below-average, soils tend to be in a drier condition and reduce the flood response. In typical and wet water-years, there is usually adequate precipitation to bring the soil moisture conditions to field capacity throughout much of the watershed.

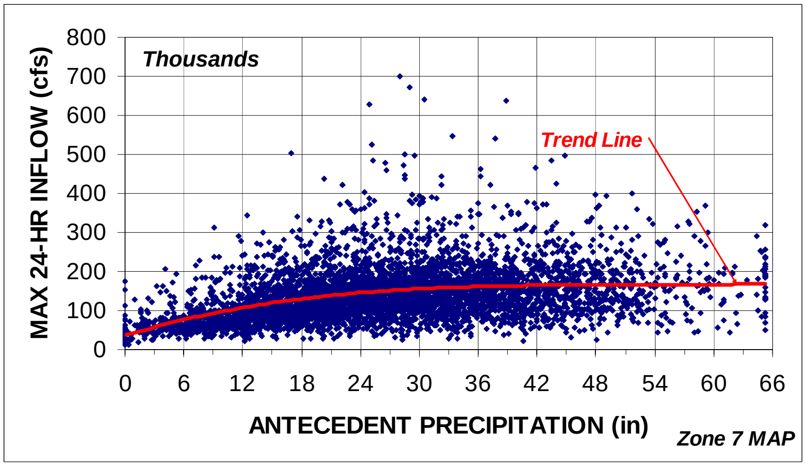

Figure 6 – Sensitivity of Flood Response to Changes in Antecedent Precipitation for Global Sensitivity Analysis for the End-of-January

Snowpack

Snowpack magnitude was not found to have a significant effect on the flood response. This result seems to be counter intuitive. This appears to be due to several compensating situations. Typically, there is more snow available in the upper watershed than can be melted during the storm event. Thus, increases in snowpack in excess of that which can be melted have limited effect, with the primary effect being to reduce the flood response as melt-water is retained in the snowpack as part of the snow compaction process (USBR[40]). This condition is offset by situations where there is snow at the lower elevations in the watershed and greater snowmelt contribution occurs from the lower elevations. There are also interactions with antecedent precipitation. In warmer winters, antecedent precipitation occurs primarily in the liquid phase and snowpacks tend to be smaller but soil moisture conditions are wetter. In colder winters, much of the antecedent precipitation occurs in the form of snow and results in drier antecedent soil moisture conditions. All of these factors combine to yield the relatively flat response depicted in Figure 7.

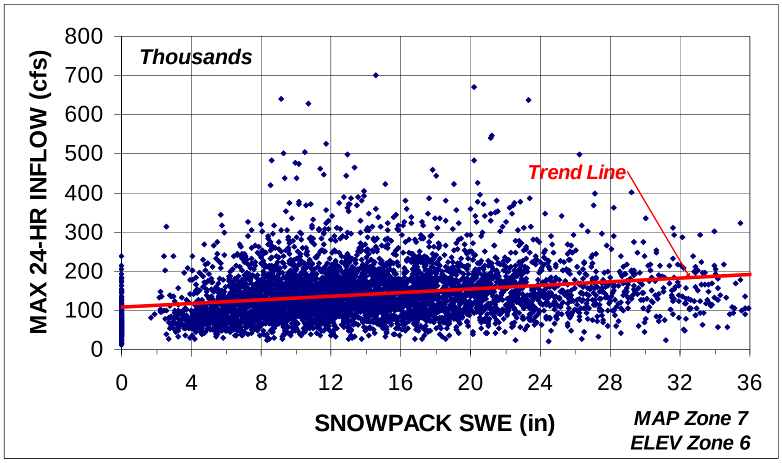

Figure 7 – Sensitivity of Flood Response to Changes in Snowpack Magnitude for Global Sensitivity Analysis for the End-of-January

Sea-Level Dewpoint Temperature

Temperatures for snowmelt production are set by the combination of sea-level temperatures and freezing levels during the storm. Comparing results shown in Figures 5, 8 and Table 4 indicate that freezing level rather than sea-level dewpoint temperature is the more important factor for snowmelt production and flood response.

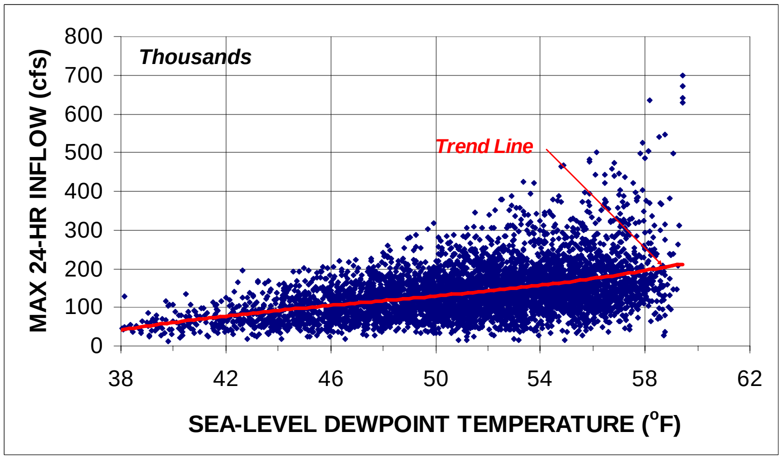

Figure 8 – Sensitivity of Flood Response to Changes in Sea-Level Dewpoint Temperature for Global Sensitivity Analysis for the End-of-January

Storage Available in Five Major Upstream Reservoirs

The storage available for floodwaters in the five major upstream reservoirs (Hell Hole, Union Valley, French Meadows, Loon Lake and Ice House) had a minor effect on the flood response. Typically, there is ample storage in the upstream reservoirs to either capture the flood runoff or significantly attenuate the incoming flood flows. In addition, the attenuating effect of reservoir routing acts to delay the flood peak from these reservoirs. As a result, the flood releases from these reservoirs generally add to the recession limb rather than the flood peak of the inflow hydrograph at Folsom Dam. Figure 9 indicates reduced flood attenuation when the upstream reservoirs are nearly full, and larger flood attenuation when the upstream reservoirs are drawn down.

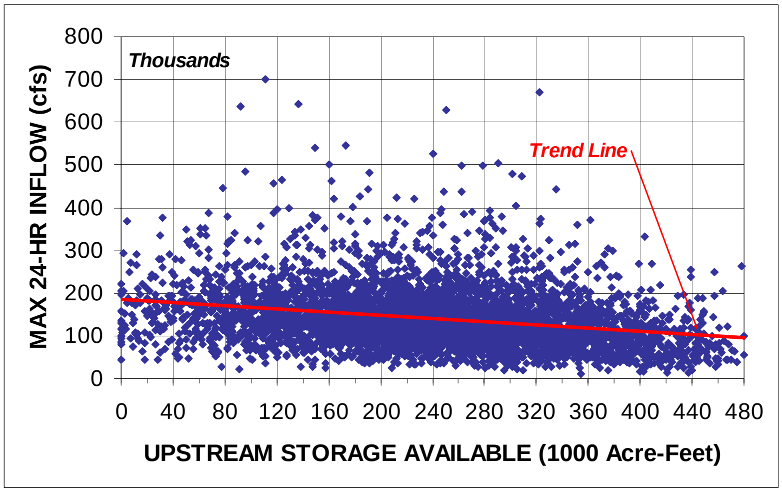

Figure 9 – Sensitivity of Flood Response to Changes in Storage Available in Five Major Upstream Reservoirs for Global Sensitivity Analysis for the End-of-January

Spatial and Temporal Distribution of Prototype Storms

The spatial and temporal distribution of precipitation in the 24 prototype storms does have a significant effect on flood response for peak inflows and maximum 24-hour inflows into Folsom Reservoir (Figures 10a,b,c). The scatterplot depicted in Figure 10a provides a qualitative measure of the variability in flood responses to the various spatial and temporal precipitation patterns.

Additional insight into the effect of the 24 prototype storms can be seen in the results from the One-At-A-Time analyses excerpted from Appendix A. A review of Figures 10b,c shows high variability in the magnitudes of flood peak inflow and maximum 24-hour inflow for the prototype storms. Further, there is diversity within the prototype storms in that a given storm may rank in the upper quartile in peak response and rank in the middle or lower quartile at the 24-hour flood response, and vice-versa. This reflects good diversity in the spatial and temporal storm patterns for the 24 prototype storms.

Each prototype storm is comprised of one spatial template (spatial distribution of precipitation) and 33 temporal templates (one temporal pattern per subbasin). This complexity obstructed the development of a suitable numeric measure for the spatial and temporal character of the 24 prototype storms. Therefore, a quantitative measure of the sensitivity of flood response to the prototype storms was not computed. Nonetheless, the variation in flood response seen in Figures 10a,b,c indicates that the flood response is sensitive to the spatial and temporal distribution of precipitation over the watershed.

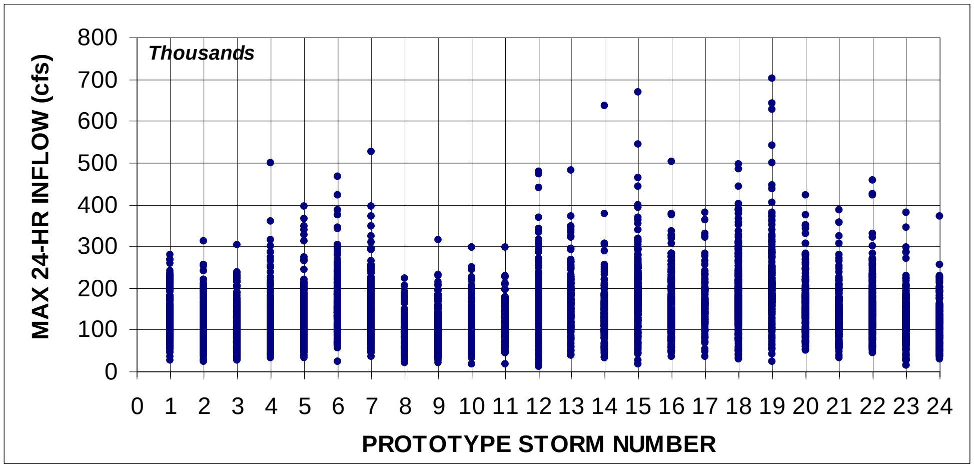

Figure 10a – Sensitivity of Maximum 24-Hour Inflow to the Spatial and Temporal Distribution of Precipitation for the 24 Prototype Storms for Global Sensitivity Analysis for the End-of-January

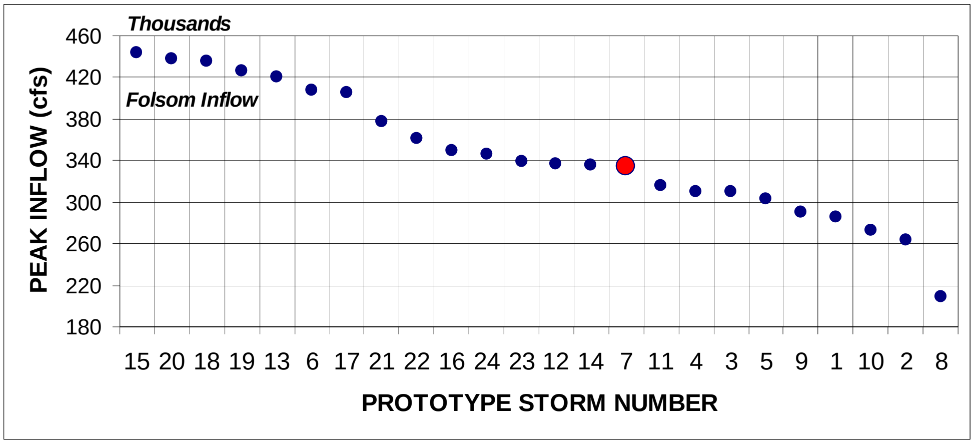

Figure 10b – Sensitivity of Flood Peak Inflow to the Spatial and Temporal Distribution of Precipitation for the 24 Prototype Storms for One-At-A-Time Analysis (from Appendix A)

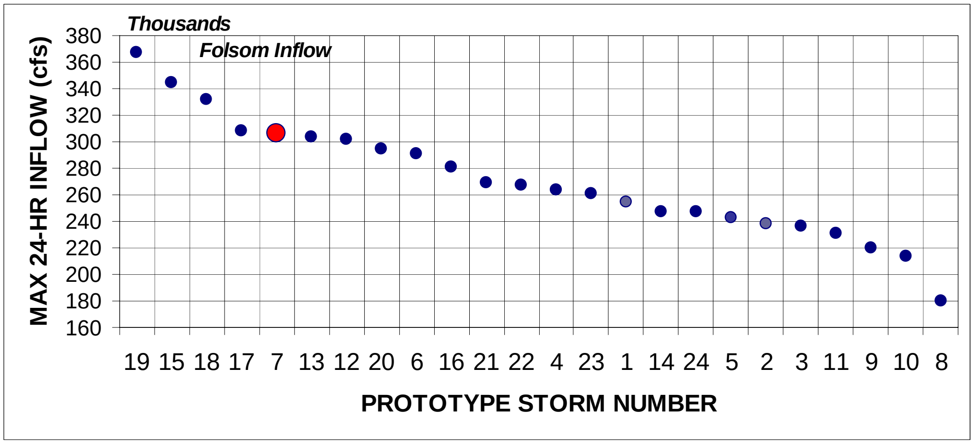

Figure 10c – Sensitivity of Maximum 24-Hour Inflow to the Spatial and Temporal Distribution of Precipitation for the 24 Prototype Storms for One-At-A-Time Analysis (from Appendix A)

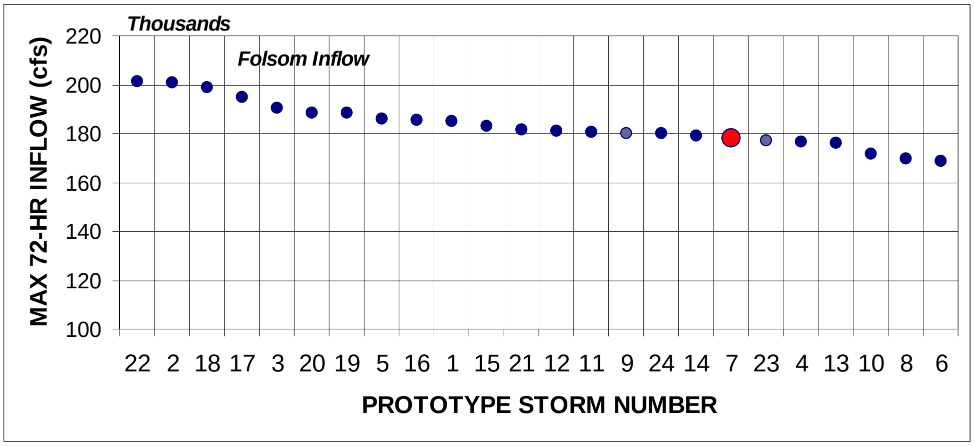

Figure 10d – Sensitivity of Maximum 72-Hour Inflow to the Spatial and Temporal Distribution of Precipitation for the 24 Prototype Storms for One-At-A-Time Analysis (from Appendix A)

Measure of Folsom Reservoir Response

The term *reservoir response* refers to model outputs from reservoir routing at Folsom reservoir. This specifically includes maximum reservoir stages and maximum reservoir releases, where reservoir releases measures discharge from the outlets and spillways. Scatterplots of reservoir response versus various hydrometeorological inputs are shown in Figures 12-18. Sensitivity indices have been computed for each input and are listed in ranked order in Table 5. Comparison of the ranked order of sensitivity indices in Table 5 with values in Table 4 shows the same order for the most important hydrometeorological inputs. A short discussion is provided about the sensitivity of the reservoir response to changes in the initial storage in Folsom Reservoir. All other hydrometeorological inputs were discussed previously.

Table 5 – Sensitivity Indices for Folsom Reservoir Response for Various Hydrometeorological Inputs

HYDROMETEOROLOGICAL INPUTS	FOLSOM RESERVOIR RESPONSE SENSITIVITY INDEX (S_i)	RELATIVE SENSITIVITY OF RESERVOIR RESPONSE
Initial Storage in Folsom Reservoir	0.574	High
Basin-Average 72-Hour Precipitation	0.433	High
Freezing Level during Storm Event	0.131	Moderate
Antecedent Precipitation	0.098	Moderate
Storage Available in 5 Major Upstream Reservoirs	0.044	Low
Snowpack Magnitude	0.012	Low
Sea-Level Temperature during Storm Event	0.003	Low

Influence of Spillway Operation on Reservoir Response

Flood control operations at Folsom Dam are governed by operational rules described in the Flood Control Diagram (FCD)[45] and Emergency Spillway Release Diagram (ESRD)[45]. In particular, emergency spillway releases are based on the magnitude of an inflow flood and the rate of change of the reservoir inflow. Maximum allowable storage in Folsom Reservoir is based on seasonality and on the storage available in the 5 major upstream reservoirs (Figure 11). These operational procedures should be kept in mind when reviewing the sensitivity results for reservoir response.

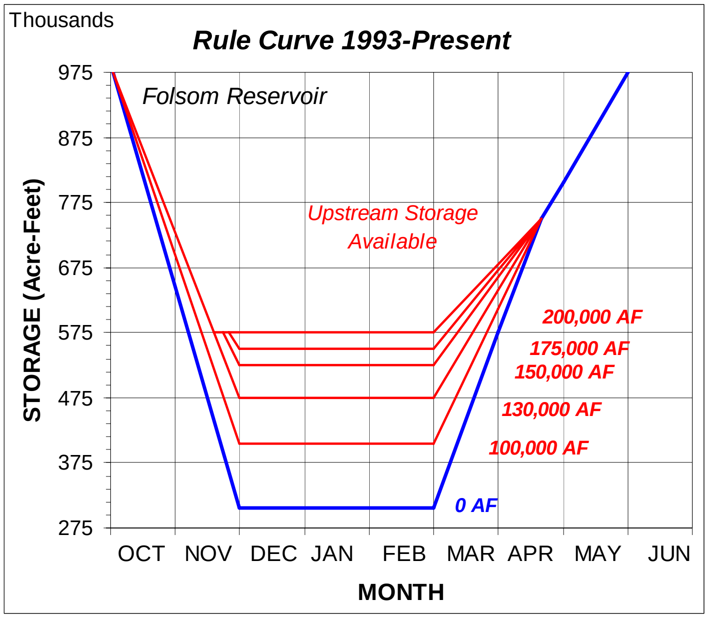

Figure 11 – Current Reservoir Rule Curve for Setting Maximum Allowable Storage for Folsom Reservoir

Initial Storage in Folsom Reservoir

The initial storage in Folsom Reservoir at the onset of a flood event was found to be an important factor in explaining the variance in the maximum reservoir stage produced by floods. Lower maximum reservoir stages are associated with smaller initial storage values and higher maximum reservoir stages are associated with larger initial storage values (Figure 12). These outcomes are also affected by the magnitude of antecedent precipitation, which affects flood magnitudes. Smaller values of antecedent precipitation are associated with lower initial storage values and drier initial soil moisture conditions. Conversely, larger values of antecedent precipitation are associated with higher initial storage values and wetter initial soil moisture conditions.

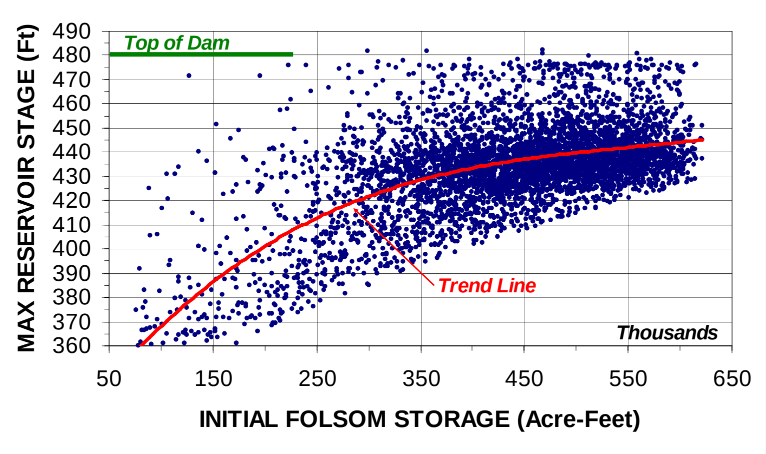

Figure 12 – Sensitivity of Folsom Reservoir Response to Changes in Initial Folsom Storage for Global Sensitivity Analysis for End-of-January

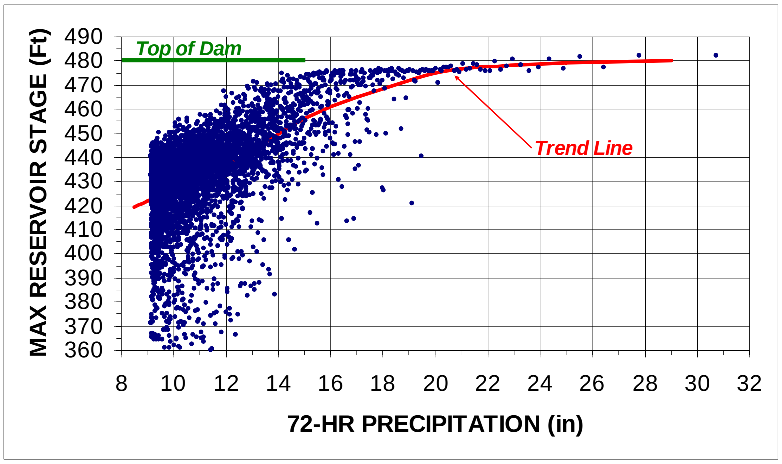

Figure 13 – Sensitivity of Folsom Reservoir Response to Changes in 72-Hour Basin-Average Precipitation for Global Sensitivity Analysis for End-of-January

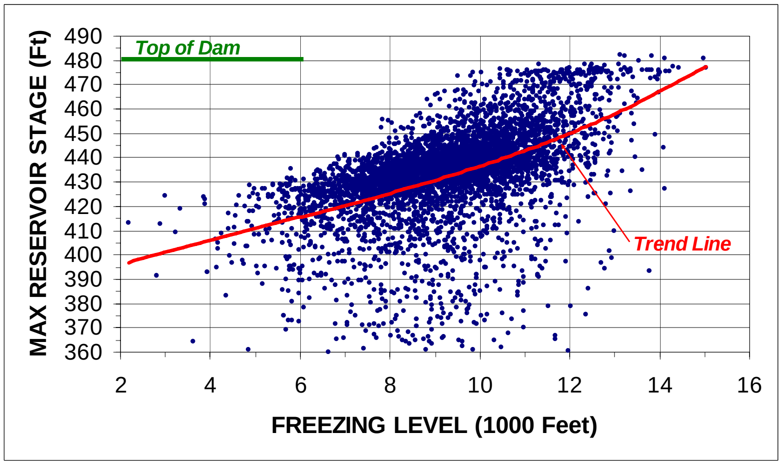

Figure 14 – Sensitivity of Folsom Reservoir Response to Changes in Freezing Level for Global Sensitivity Analysis for End-of-January

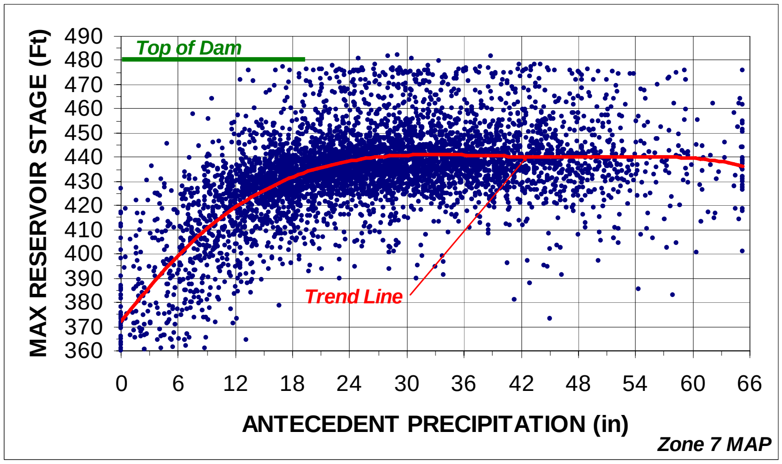

Figure 15 – Sensitivity of Folsom Reservoir Response to Changes in Antecedent Precipitation for Global Sensitivity Analysis for End-of-January

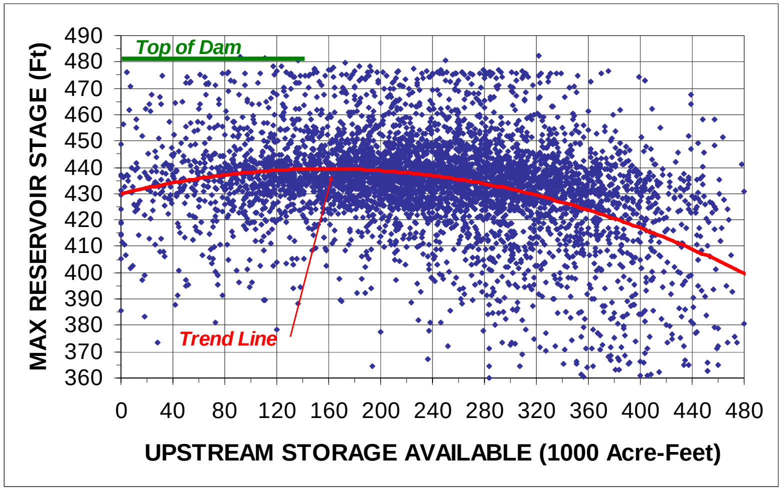

Figure 16 – Sensitivity of Folsom Reservoir Response to Changes in Storage Available in Five Major Upstream Reservoirs for Global Sensitivity Analysis for End-of-January

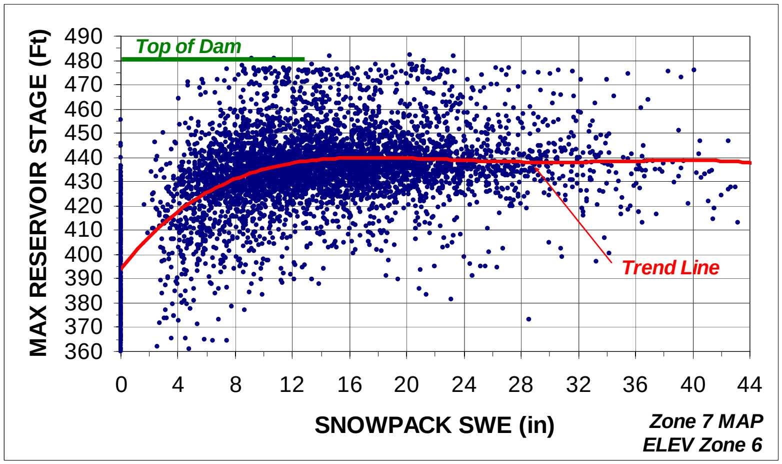

Figure 17 – Sensitivity of Folsom Reservoir Response to Changes in Snowpack Magnitude for Global Sensitivity Analysis for End-of-January

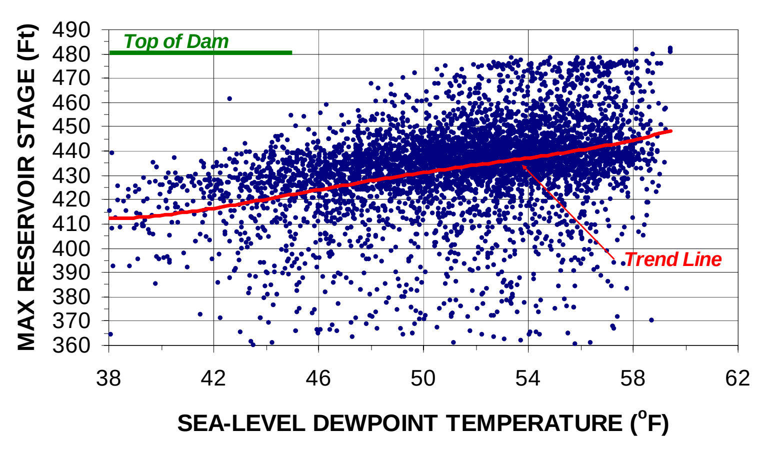

Figure 18 – Sensitivity of Folsom Reservoir Response to Changes in Sea-Level Dewpoint Temperature for Global Sensitivity Analysis for End-of-January

RECOMMENDATIONS FOR CONDUCTING UNCERTAINTY ANALYSIS

The primary goal in conducting the uncertainty analysis is to develop uncertainty bounds for the flood-frequency relationships for flood peak discharge, maximum 24-hour discharge, maximum 72-hour discharge, maximum reservoir release, runoff volume and maximum reservoir level. The largest contributions to the total uncertainty will be from those hydrometeorological inputs and watershed parameters that significantly affect the flood and reservoir responses and, and for which, there is notable uncertainty in characterizing the inputs or parameters.

For example, if the flood response is sensitive to a given input and there is considerable uncertainty in the formulation of the model and/or model parameters that describe that input, those uncertainties will propagate through the stochastic flood model and be primary contributors to the total uncertainty for the flood response. Conversely, if the flood response is not sensitive to a given input, then uncertainties in the model or model parameters for that input will not be significant contributors to the total uncertainty for the flood response.

The complexity and computational time/effort required to conduct the uncertainty analysis increases markedly with the number of inputs and parameters that are included. Thus, there is a practical need to limit the number of inputs and parameters to those that will be the primary contributors to the total uncertainty. Table 6 lists the recommendations for inclusion of those hydrometeorological inputs to be included in the uncertainty analysis.

Table 6 – Recommendations for Selection of Hydrometeorological Inputs and Watershed Model Parameters for Inclusion in Uncertainty Analysis

HYDROMETEOROLOGICAL INPUTS WATERSHED PARAMETERS	FLOOD OR RESERVOIR RESPONSE SENSITIVITY	RELATIVE MAGNITUDE OF UNCERTAINTIES		INCLUDE IN UNCERTAINTY ANALYSIS
		MODEL OF PHENOMENON	MODEL PARAMETERS	
72-Hour Basin-Average Precipitation-Frequency	High	Low	Moderate	X
Spatial and Temporal Distribution of Storms 24 Prototype Storms	High	Low	Moderate	N/A
Initial Storage in Folsom Reservoir	High	Low	High	X
Freezing Level during Storm	Moderate	Low	Moderate	X
Antecedent Precipitation	Moderate	Low	Moderate	X
Seasonality	Moderate	Low	Low	
Snowpack Magnitude	Low	Low	Moderate	
Sea-Level Temperature during Storm Event	Low	Low	Low	
Storage Available in 5 Major Upstream Reservoirs	Low	Low	Moderate	
Modified Holtan Rainfall-Runoff Modeling Parameters	Low	Low	Moderate	X

The recommendation for inclusion of a given hydrometeorological input was based on consideration of several factors including: the flood and reservoir response sensitivity; the relative uncertainty in the chosen model for describing an input; and the relative uncertainty in determining the parameters for the chosen model. The flood response sensitivity was obtained directly from the sensitivity indices computed previously (Tables 4,5). A qualitative assessment of the uncertainty in model selection was obtained by consideration of the current state of knowledge and experience in computer modeling of a given phenomenon. Lastly, an assessment of the relative magnitude of uncertainties in parameter estimation for a chosen model was based on consideration of the sample size used to estimate the parameters and the general knowledge and experience of the expected parameter behavior for the given phenomenon. Each of these assessments is listed in qualitative terms in Table 6. A brief discussion of each of the hydrometeorological inputs is contained in the following sections to provide some background on the chosen uncertainty ratings.

72-Hour Basin-Average Precipitation-Frequency Relationship

Uncertainties associated with the 72-hour basin-average precipitation (Figure 19) have been analyzed and presented in a separate report[30]. Recognizing that flood response was found to be sensitive to the magnitude of the 72-hour precipitation, uncertainty in the 72-hour precipitation-frequency relationship will be a primary contributor to the total uncertainty in the flood-frequency relationships.

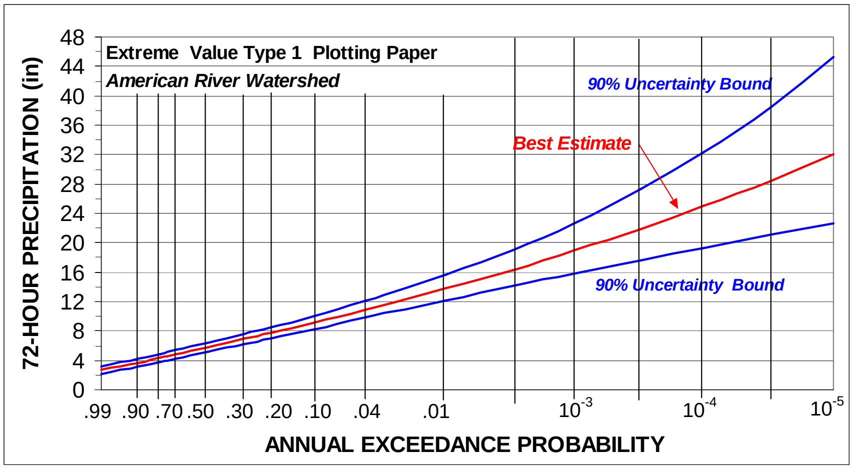

Figure 19 – 72-Hour Basin-Average Precipitation-Frequency Relationship and 90% Uncertainty Bounds for American River Watershed above Folsom Dam

Spatial and Temporal Distribution of Storms – 24 Prototype Storms

Assessment of uncertainties associated with the prototype storms will not be included in the uncertainty analysis. There is a high diversity in the temporal and spatial patterns[32] (Table 4) and the temporal characteristics are well-behaved across the sample set (Figures 10b,c,d). It is believed that these 24 patterns constitute a representative sample of possible storm patterns and should be adequate for characterizing the spatial and temporal distribution of precipitation in extreme storms. It is unlikely that a larger sample of storm patterns would significantly alter the outcomes of the flood simulations or the resultant uncertainty bounds.

Further, the 24 prototype storms were developed from historical storms. The complexity inherent in the spatial and temporal storm templates makes it impractical, in terms of time and budget, to attempt the creation of alternative synthetic storm templates.

Initial Storage in Folsom Reservoir

Initial storage in Folsom Reservoir is stochastically modeled on an end-of-month basis with a linear regression model using antecedent precipitation as an explanatory variable. Experience has shown this to be a practical approach to modeling initial storage (SEFM[37]). Four reservoir rule curves have been in use over the 48-years of project operation[29]. Thus, there are relatively large uncertainties in the model parameters given the small samples of historical data and the difficulty in comparing operations between the four rule curves. It is expected that uncertainties in the initial storage in Folsom Reservoir will be a major contributor to uncertainties in the frequency relationships for maximum reservoir stage and reservoir releases, particularly for moderate sized floods.

Freezing Level During Storm

Freezing level on the day of maximum 24-hour precipitation was stochastically modeled using a multiple linear regression relationship with sea-level temperature and maximum 24-hour precipitation as explanatory variables. In addition, the relationship was modified to provide an upper-limit freezing level asymptote for very extreme storm magnitudes. There are uncertainties in the parameters for this model given the small sample size of available data. There are also uncertainties associated with setting the upper-limit asymptote for freezing level conditions that have not yet been observed in extreme storms. This level of uncertainties, coupled with the moderate sensitivity for this input, indicates that it should be included in the uncertainty analysis.

Antecedent Precipitation

Antecedent precipitation (multi-month precipitation) has been shown to be well described by the 3-parameter Gamma distribution (Stedinger[39]) in a variety of studies (SEFM[37]). In addition, numerous precipitation measurement stations and a large sample set were used in estimating the distribution parameters. Thus, the uncertainties associated with simulation of antecedent precipitation are low relative to that for other inputs. However, antecedent precipitation is used as an explanatory variable for several other hydrometeorological inputs and is used in the determination of initial soil moisture conditions. Thus, uncertainties in antecedent precipitation will propagate through several other inputs. This consideration, in addition to the flood response having moderate sensitivity to antecedent precipitation, suggests that it be included in the uncertainty analysis.

Seasonality

The seasonality of storms (seasonality report[23]) was found to be well-described by the normal distribution, which is consistent with the findings of other seasonality analyses conducted for locations along the west coast of the US (SEFM[37]). The sample size of the dates of extreme storms was sufficiently large to reduce the uncertainty in parameter estimation to a magnitude that would only result in the possibility of small changes to the frequencies of the end-of-month storm occurrences. In addition, the majority of extreme floods occur in the winter period (December through February) when there is low sensitivity in the flood response due to seasonality of storm occurrence (Figure A10a). For these reasons, seasonality of storm occurrences was considered to be a minor contributor to the total uncertainty for extreme floods and not recommended for inclusion in the uncertainty analysis.

Snowpack

The low sensitivity of the flood response to changes in snowpack snow-water-equivalent indicates that snowpack would be a minor contributor to the total uncertainty in the flood-frequency relationships. In addition, snowpack is highly correlated with antecedent precipitation and inclusion of antecedent precipitation in the uncertainty analysis will result in increased variability in snowpack magnitudes. For these reasons, it was not considered necessary to include snowpack in the uncertainty analysis.

Sea-Level Temperature

Flood response was found to have very low sensitivity to changes in sea-level temperature. Accordingly, sea-level temperature would be a minor contributor to the total uncertainty in the flood-frequency relationships and is not recommended for inclusion in the uncertainty analysis.

Storage Available in Five Major Upstream Reservoirs

There is usually ample storage in the five major upstream reservoirs to greatly attenuate inflow floods. As a result, there is generally low sensitivity of flood and reservoir response to changes in available floodwater storage in the upstream reservoirs. While upstream storage is an item of importance in implementation of the reservoir rule curve (USCOE[45]) for regulation of flood storage in Folsom Reservoir, it would be a minor contributor to the total uncertainty in the flood-frequency relationships and is not recommended for inclusion in the uncertainty analysis.

Modified Holtan Rainfall-Runoff Modeling Parameters

All of the previous considerations have addressed uncertainty in the hydrometeorological inputs. Uncertainty in the watershed model will be addressed by including the uncertainty contribution from the 30 soil parameter sets for rainfall-runoff modeling. These uncertainties were discussed previously and analyzed as part of the GLUE procedures (Beven et al[1]) in calibration of the watershed model[35].

Summary

Four hydrometeorological inputs and one set of watershed parameters are recommended for inclusion in the uncertainty analysis (Table 6). These are factors where there was high or moderate sensitivity of the flood response, and where there was moderate or high uncertainty in the determination of model parameters for the phenomenon. These factors are expected to address the primary contributors to the total uncertainty in the flood-frequency relationships from the hydrometeorological inputs and watershed model.

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. Campolongo F, Kleinjen J and Andres J, Screening Methods, Chapter 4, *Sensitivity Analysis*, John Wiley and Sons LTD, Saltelli A, Chan K and Scott EM Editors, 2000.
4. CDEC, *California Data Exchange Center,* California Water Resources Department, Flood Management Division, Sacramento, CA.
5. Collins RF, 29-Subbasin HEC-1 Watershed Model of American River, version of Feb 2001, US Army Corps of Engineers Sacramento District.
6. Cunnane C, Unbiased Plotting Positions – A Review, Journal of Hydrology, volume 37, no. 3, pp205-222, 1978.
7. 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.
8. Gringorten II, A Plotting Rule for Extreme Probability Paper, Journal Geophysical Research, vol 68, no. 3, pp813-814, 1963.
9. Helsel DR and Hirsch RM, Statistical Methods in Water Resources, Elsevier Studies in Environmental Science 49, NY, 1992.
10. 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.
11. Jain R, The Art of Computer Systems Performance Analysis, John Wiley and Sons, 1991.
12. 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.
13. Johnson NL and Kotz S, Distributions in Statistics - Three Volume Set, John Wiley and Sons, 1970.
14. 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.
15. National Research Council, Improving American River Flood Frequency Analysis, National Academy Press, Washington DC, 1999.
16. 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.
17. NRC, Improving American River Flood Frequency Analyses, Committee on American River Flood Frequencies, Water Science and Technology Board, National Research Council, 1999.
18. NRCS, *Snotel Data Network*, Water and Climate Center, National Resource Conservation Service, US Department of Agriculture, Washington DC.

19. 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.
20. Oregon Climate Service, Mean Annual Precipitation Maps for Western United States, PRISM Model, Corvallis Oregon, 1997.
21. Saltelli A, Chan K and Scott EM, Sensitivity Analysis, John Wiley and Sons LTD, 2000.
22. Saltelli A, Global Sensitivity Analysis, An Introduction, International Conference on Sensitivity Analysis, Sante Fe New Mexico, March 2004.
23. 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.
24. 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.
25. 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.
26. 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.
27. 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.
28. 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.
29. 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.
30. 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.
31. 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.
32. 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.
33. 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.
34. 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.

35. Schaefer MG, 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.
36. Schaefer MG and Barker BL, Stochastic Modeling of Extreme Floods on The American River at Folsom Dam, Interim Report of Findings, MGS Engineering Consultants, Inc, prepared for US Army Corps of Engineers Hydrologic Engineering Center, December 2003.
37. SEFM, Stochastic Event Flood Model – Users Manual, MGS Engineering Consultants, Inc, Schaefer MG and Barker BL, March 2001.
38. STATSGO, State Soil Geographic Database for the Conterminous United States, US Department of Agriculture, Natural Resource Conservation Service, Washington DC.
39. Stedinger JR, Vogel RM, and Foufoula-Georgiou, E, Frequency Analysis of Extreme Events, Chapter 18, *Handbook of Hydrology*, McGraw Hill, 1992.
40. USBR, Effect of Snow Compaction on Runoff from Rain on Snow, Engineering Monograph 35, US Bureau of Reclamation, Bertle FA author, 1966.
41. USBR, Work Products for Calibration of HEC-1 Watershed Model for American River to February 1986 Flood, US Bureau of Reclamation Flood Hydrology Group.
42. USCOE, HEC-1 Flood Hydrograph Package Version 4.1 – Users Manual, Hydrologic Engineering Center, US Army Corps of Engineers 1996.
43. USCOE, Work Products for Calibration of HEC-1 Watershed Model for American River to January 1997 Flood, US Army Corps of Engineers Sacramento District.
44. USCOE, American River Basin, California, Folsom Dam and Lake Revised PMF Study, US Army Corps of Engineers Sacramento District, October 2001.
45. USCOE, Flood Control Diagram and Emergency Spillway Release Diagram for Folsom Dam on the American River, US Army Corps of Engineers Sacramento District.
46. USDA, Soil Survey Eldorado National Forest California, Natural Resource Conservation Service, 1985.
47. USDA, Soil Survey Eldorado Area California, Natural Resource Conservation Service, 1974.
48. USDA, Soil Survey Tahoe National Forest Area California, Natural Resource Conservation Service, 1982.
49. USDA, Soil Survey Placer County California, Western Part, Natural Resource Conservation Service, 1980.
50. Viessman W, Knapp JE, Lewis GL and Harbaugh TE, *Introduction to Hydrology*, Intext Harper and Row, Second Edition, 1977.
51. Weiss LL, Ratio of True to Fixed Interval Maximum Rainfall, Journal Hydraulics, ASCE, 90(HY1), pp77-82, 1964.
52. Wyss GD and Jorgenson KH, A Users Guide to LHS: Sandia’s Latin Hypercube Sampling Software, Sandia National Laboratories, report SAND98-0210, February 1998.
53. Yevdjevich VM, Statistical and Probability Analysis of Hydrological Data, Part II Regression and Correlation Analysis, *Handbook of Hydrology*, Vent Te Chow Editor, Section 8, McGraw-Hill, 1964.

54. Ezekiel, Mordecai and Fox KA, Methods of Correlation and Regression Analysis, Linear and Curvilinear, John Wiley and Sons, 3rd Edition, New York, pp 193, 1959.

APPENDIX A

ONE-AT-A-TIME SENSITIVITY ANALYSiS

ONE-AT-A-TIME SENSITIVITY ANALYSIS

One-at-a-time (OAT) sensitivity analysis was used as a screening level approach for examining the effect of various hydrometeorological inputs on the flood outputs from the stochastic model (Campolongo et al[3]). This analysis was intended primarily to provide the reader with a qualitative depiction of the sensitivity of the watershed and reservoir responses to the various hydrometeorological inputs. This was accomplished by varying one hydrometeorological input at a time while holding all other inputs at fixed control values. Mean or median values were used as the control values (Table A1) for all of the hydrometeorological inputs except for 72-hour basin-average precipitation. The control value for 72-hour basin-average precipitation was set at an annual exceedance probability (AEP) of 0.004 (1:250) rather than a mean value because the focus of this study is on extreme storm/flood events. This control value represents a precipitation magnitude in the general range where reservoir response to floods is of particular interest.

Many of the hydrometeorological inputs are correlated with other hydrometeorological inputs (Table A2, repeated from main report). In the case of antecedent precipitation, snowpack and antecedent soil moisture, values of correlated hydrometeorological inputs were set at expected values based on the correlation relationship and the selected value of the explanatory hydrometeorological input. This approach was taken in order to examine reasonable combinations, and avoid combinations of conditions that were either implausible or impossible. Specific procedures for conducting a one-at-a-time sensitivity analysis for a given hydrometeorological input are described in the section that contains the findings of the sensitivity analysis for that input.

Table A1 – Control Values for One-at-a Time (OAT) Sensitivity Analyses

HYDROMETEOROLOGICAL INPUTS	CONTROL VALUE	COMMENTS
Seasonality of Storms	End-of-January	
Basin-Average 72-Hour Precipitation	15.8-inches	AEP (1:250)
Spatial and Temporal Distribution of Precipitation over watershed during storms	Prototype Storm #7 Dec 1996-Jan 1997	Middling value in terms of flood response
Antecedent Precipitation	39.0-inches 27.0-inches	Lake Spaulding key precipitation station Mean Annual Precipitation Zone 7
Snowpack Magnitude and Allocation	22.6-inches 13.6-inches	Alpha key snowpack station Mean Annual Precipitation Zone 7 and Elevation Zone 6
Sea-Level Temperature during Storm Event	56.3 °F	
Freezing Level during Storm Event	12,200 feet	
Initial Storage in 5 Major Upstream Reservoirs	109,000 acre-feet, Hell Hole 143,000 acre-feet, Union Valley 67,700 acre-feet, French Meadows 34,600 acre-feet, Loon Lake 21,300 acre-feet, Ice House	Mean end-of-January values
Initial Storage in Folsom Reservoir	473,400 acre-feet	Mean end-of-January value
Antecedent Soil Moisture	Based on control values of antecedent precipitation and snowpack	Varies with antecedent precipitation and snowpack
Soil Characteristics	Calibrated Parameter Set	See Table 3 and Calibration Report[35]

Table A2 – 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 on Day of Maximum 24-hour Precipitation
5	Sea-Level Temperature	Storm Magnitude	For Day of Maximum 24-hr Precipitation in storm
6	Freezing-Level	Sea-Level Temperature and Storm Magnitude	For Day of Maximum 24-hr 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 Folsom Operating Rules	Utilizes Folsom Rule Curves and Storage in 5 Upstream Reservoirs

Measures of Flood Response and Reservoir Response

Maximum 24-hour discharge (inflow to Folsom Reservoir) was used for assessing the sensitivity of flood responses from the watershed. Maximum reservoir stage and/or maximum reservoir release were used to assess the sensitivity of reservoir response to changes in the hydrometeorological inputs.

Influence of Spillway Operation on Reservoir Response

Flood control operations at Folsom Dam are governed by operational rules described in the Flood Control Diagram (FCD)[45] and Emergency Spillway Release Diagram (ESRD)[45]. In particular, emergency spillway releases are based on the magnitude of an inflow flood and the rate of change of the reservoir inflow. There are numerous thresholds in the ESRD that require increases in spillway releases. These operational thresholds result in dips and other anomalous behavior in the sensitivity curves for reservoir response. This situation should be kept in mind when reviewing the shapes of sensitivity curves for reservoir response.

72-Hour Basin-Average Precipitation

The sensitivity of flood and reservoir responses to 72-hour basin-average precipitation is depicted in Figures A1a,b,c. The large red circle in Figures A1a,b,c references the control value of 72-hour precipitation for this sensitivity analysis. Control values for all other hydrometeorological inputs for this sensitivity analysis are listed in Table A1. A review of Figure A1a shows a nearly linear flood response over a range of two standard deviations of the 72-hour precipitation frequency relationship. This is the strongest flood response of all of the hydrometeorological inputs.

There is a similar strong reservoir response to 72-hour basin-average precipitation. The reservoir response is also affected by implementation of protocols in the Emergency Spillway Release Diagram[45] (ESRD). In particular, the apparent anomaly in Figures A1b,c near 15.5-inches of 72-hour precipitation is due to increased spillway releases at certain thresholds in the ESRD[45].

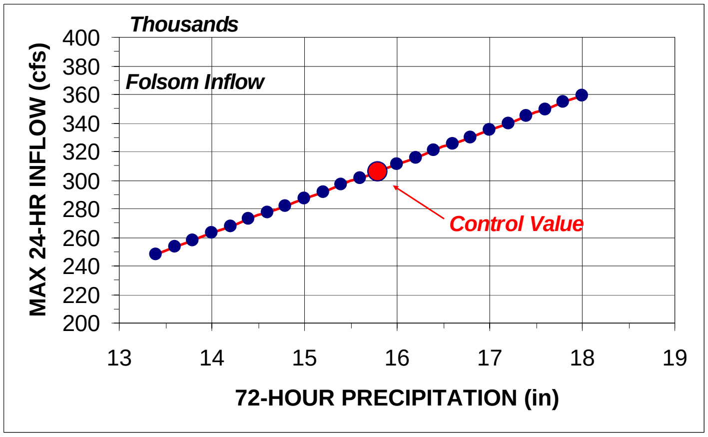

Figure A1a – Sensitivity of Flood Response to Changes in 72-Hour Basin-Average Precipitation for One-at-a-Time Sensitivity Analysis for End-of-January

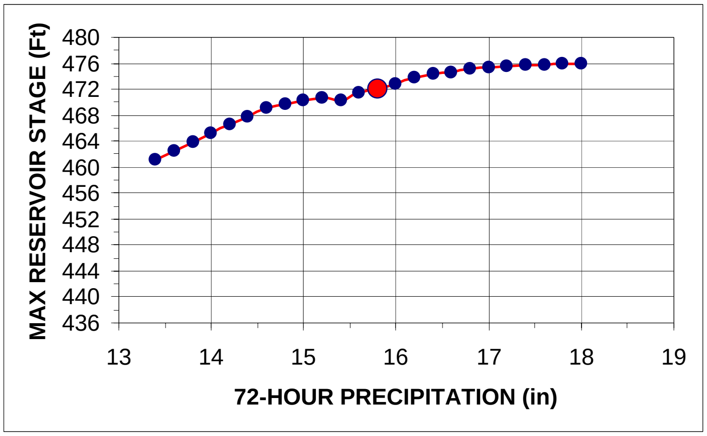

Figure A1b – Sensitivity of Folsom Reservoir Response to Changes in 72-Hour Basin-Average Precipitation for One-at-a-Time Sensitivity Analysis for End-of-January

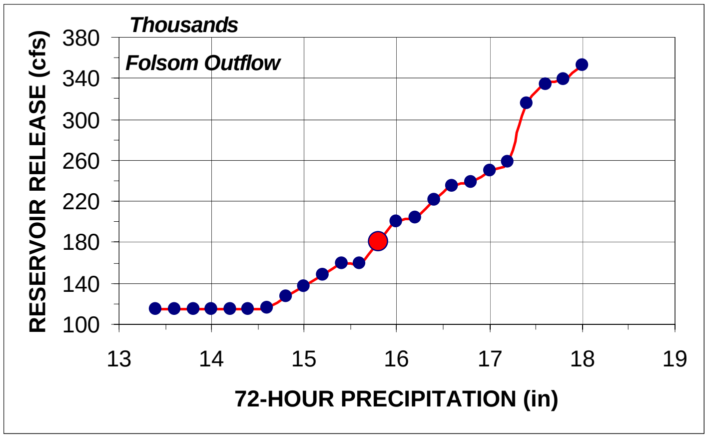

Figure A1c – Sensitivity of Maximum Folsom Reservoir Release to Changes in 72-Hour Basin-Average Precipitation for One-at-a-Time Sensitivity Analysis for End-of-January

Spatial and Temporal Distribution of Precipitation - 24 Prototype Storms

The sensitivity of watershed and reservoir responses to the spatial and temporal distributions of the 24 prototype storms is shown in Figures A2a,b,c,d. Prototype storm 7 was chosen as the control because the Jan 1997 storm/flood (large red circle) was an event of importance. It is also an event with which many readers would have familiarity, and resides in the middle of the flood responses for a range of durations of discharge. Control values for all other hydrometeorological inputs for this sensitivity analysis are listed in Table A1.

A review of Figures A2a,b shows that the spatial and temporal distribution of precipitation over the watershed has a strong influence on the magnitude of the flood response. Close inspection indicates that the temporal patterns of the various prototype storms result in high diversity of flood responses for peak discharge (Figure A2a), maximum 24-hour discharge (Figure A2b), and maximum 72-hour discharge (Figure A2c). Specifically, prototype storms that have flood responses ranking in the upper quartile for one duration, may rank near the middle or lower quartiles at other durations.

This diversity in flood responses is suggestive that the 24 prototype storms[26,32] (Table A3) provide a representative sample of storm characteristics for the American River watershed. The reservoir response for maximum reservoir stage and maximum reservoir release are shown in Figures A2d,e, respectively. A high level of variability in reservoir response is seen in both figures due to the variability in the spatial and temporal distributions in the 24 prototype storms.

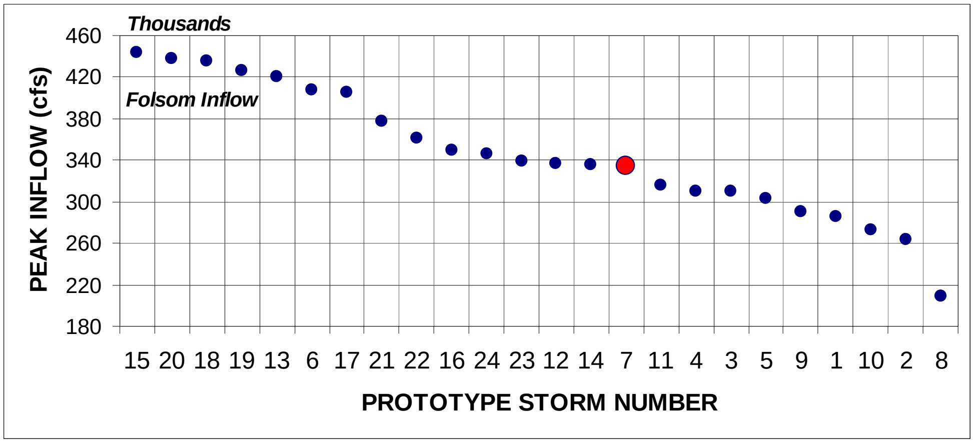

Figure A2a – Sensitivity of Peak Inflow to the Various 24 Prototype Storms
for One-at-a-Time Sensitivity Analysis for End-of-January

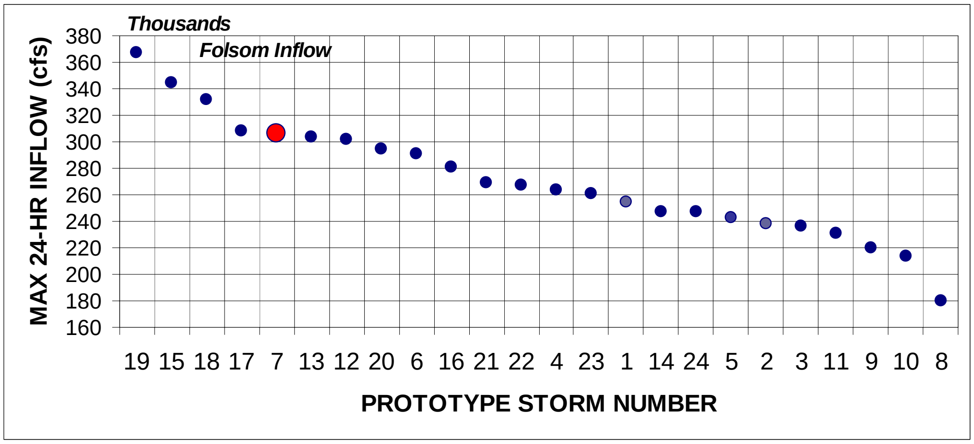

Figure A2b – Sensitivity of Maximum 24-Hour Discharge to the Various 24 Prototype Storms for One-at-a-Time Sensitivity Analysis for End-of-January

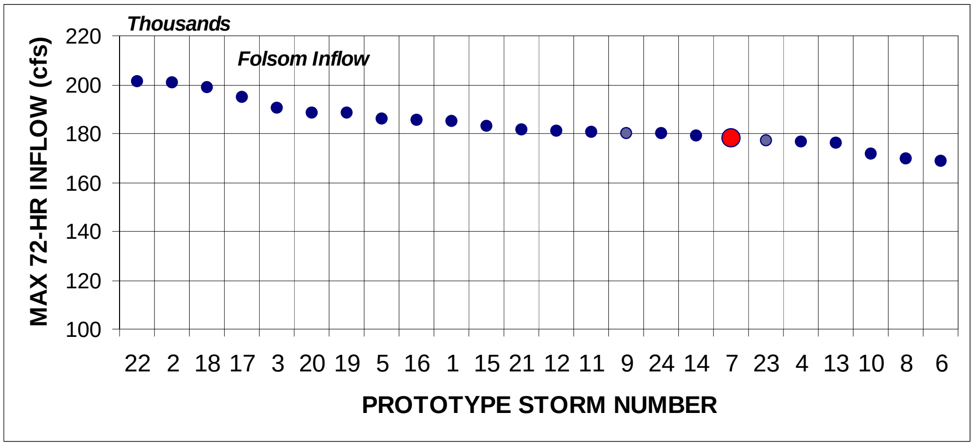

Figure A2c – Sensitivity of Maximum 72-Hour Inflow to the Various 24 Prototype Storms for One-at-a-Time Sensitivity Analysis for End-of-January

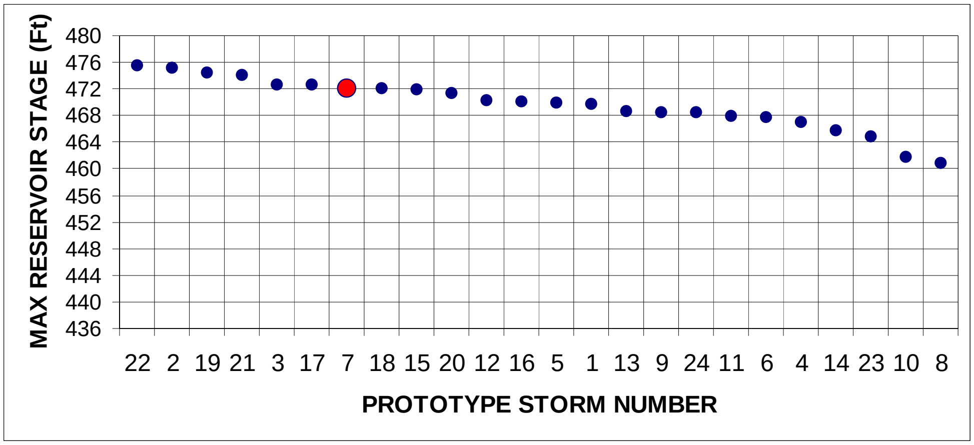

Figure A2d – Sensitivity of Maximum Folsom Reservoir Stage to the Various 24 Prototype Storms for One-at-a-Time Sensitivity Analysis for End-of-January

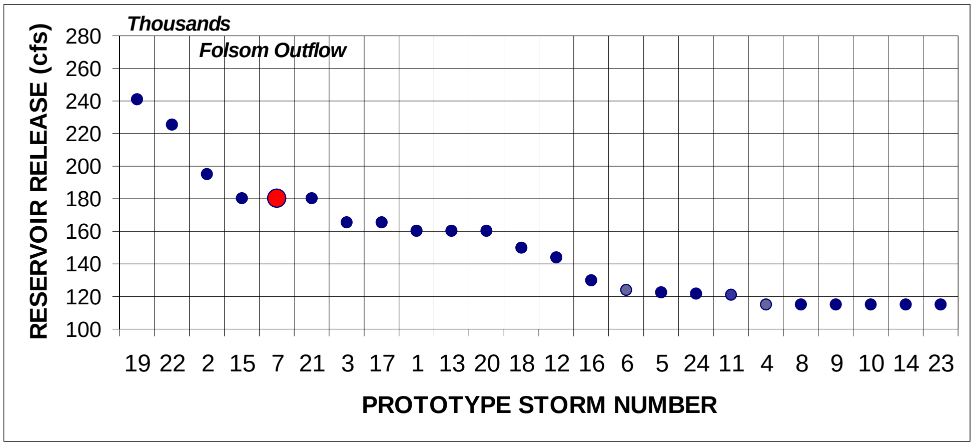

Figure A2e – Sensitivity of Maximum Folsom Reservoir Release to the Various 24 Prototype Storms for One-at-a-Time Sensitivity Analysis for End-of-January

Table A3 – Dates and Storm Characteristics for 24 Prototype Storms

PROTOTYPE NUMBER	STORM DATE	RATIO 24-HR / 72-HR PRECIP	RATIO TOTAL / 72-HR PRECIP
1	Oct 9-15, 1962	0.488	1.127
2	Feb 12-21,1986	0.417	1.703
3	Dec 17-24, 1955	0.436	1.511
4	Dec 19-25, 1964	0.486	1.468
5	Nov 16-22, 1950	0.500	1.329
6	Jan 29-Feb 3, 1963	0.524	1.025
7	Dec 28-Jan 3, 1997	0.584	1.311
8	Jan 17-23,1969	0.379	1.155
9	Jan 9-16, 1980	0.433	1.569
10	Feb 5-10, 1999	0.460	1.078
11	Dec 19-24, 1982	0.471	1.020
12	Dec 17-23, 1981	0.550	1.029
13	Feb 13-17, 1982	0.560	1.001
14	Mar 8-14, 1995	0.450	1.318
15	Dec 10-14,1995	0.643	1.016
16	Feb 7-14, 1962	0.495	1.584
17	Jan 6-12, 1995	0.574	1.467
18	Dec 6-12, 1992	0.633	1.356
19	Jan 18-26, 1967	0.683	1.469
20	Nov 11-17, 1981	0.561	1.398
21	Jan 13-18, 1970	0.492	1.360
22	Feb 16-21, 1980	0.447	1.542
23	Jan 26-30, 1981	0.542	1.124
24	Nov 9-16, 1973	0.468	1.476

Antecedent Precipitation and Snowpack

Antecedent Precipitation is defined as cumulative precipitation from October 1st through the end-of-month of storm occurrence. The precipitation station at Lake Spaulding (Figure 1a) was used in the stochastic model as a key station for determining the correlation relationship between antecedent precipitation and other hydrometeorological inputs. In particular, snowpack magnitudes are highly correlated with antecedent precipitation (Snowpack report[28]) and it was impractical to conduct separate sensitivity analyses for antecedent precipitation and snowpack. Accordingly, expected values of snowpack were used to allocate snow-water equivalent to the various zones of mean annual precipitation and elevation (Figures 2a,b) based on the correlation relationship with antecedent precipitation.

In this sensitivity analysis, values of antecedent precipitation at Lake Spaulding were varied over the range of exceedance probabilities from 0.99 to 0.01 for the end-of-January. The mean value of antecedent precipitation in zone 7 is marked by the large red circle in Figures A3a,b. The value of antecedent precipitation at Lake Spaulding was then used to set the values of antecedent precipitation in the zones of mean annual precipitation for the watershed (Figure 2a). Likewise, it was used to allocate snowpack snow-water equivalent to zones of mean annual precipitation and elevation. Soil moisture accounting was conducted for each hydrologic runoff unit (HRU) to set the initial soil moisture conditions. All other hydrometeorological inputs were set at the control values listed in Table A1.

Variation of the flood response with antecedent precipitation is shown in Figure A3a and the reservoir response is depicted in Figure A3b. Antecedent precipitation in zone 7 of mean annual precipitation (Table 1a, Figure 2a) was selected for depicting the sensitivity because it is representative of the typical antecedent precipitation in the upper-central portion of the watershed and is a value that would be more meaningful to readers familiar with the American River. Similar shaped response curves would be obtained using any of the other zones as a reference for antecedent precipitation.

Review of Figures A3a,b shows the greatest effect at low values of antecedent precipitation. This is the situation where drier soil conditions and small snowpack limit the flood response. The flattening at the upper portion of the curves reflects wet soil moisture conditions and the situation where more snowpack is present than can be melted during the storm event. Thus, an increase in antecedent precipitation and snowpack at these already high levels does not result in a marked increase in either the flood response or reservoir response.

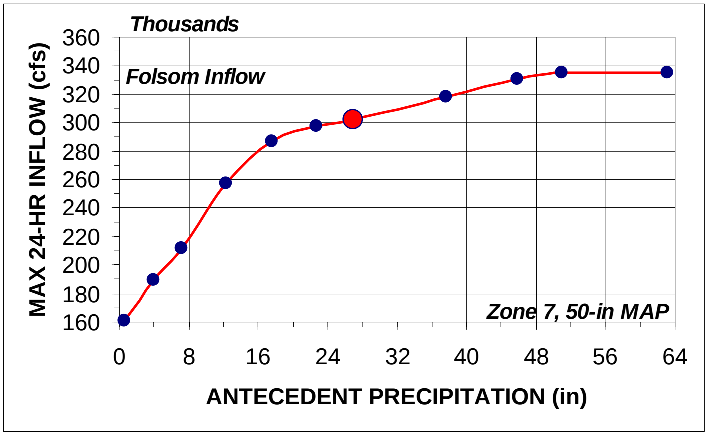

Figure A3a – Sensitivity of Flood Response to Changes in Antecedent Precipitation for One-at-a-Time Sensitivity Analysis for End-of-January

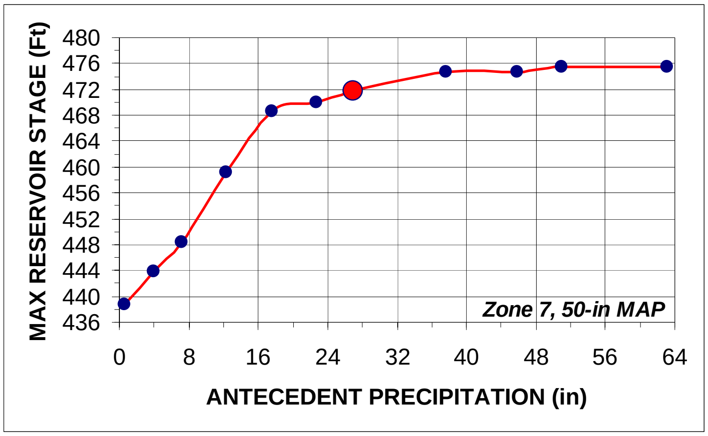

Figure A3b – Sensitivity of Folsom Reservoir Response to Changes in Antecedent Precipitation for One-at-a-Time Sensitivity Analysis for End-of-January

Sea-Level Temperature During Storm Event

High levels of atmospheric moisture are a necessary ingredient to fuel extreme storms. Atmospheric moisture, measured as precipitable water, is a function of dewpoint temperature, where increased levels of atmospheric moisture are associated with higher dewpoints. Sea-level dewpoint temperature for the day of maximum precipitation during a storm event is determined in the stochastic flood model from a physics-based model of dewpoint temperatures (SEFM[37]). Sea-level temperatures for all other days are based on temporal temperature patterns for the 24 prototype storms that are indexed to the day of maximum precipitation. The temporal temperature pattern at sea-level is then determined by scaling temporal patterns to the selected air temperature for the day of maximum precipitation during the storm (Figure A4).

The OAT sensitivity analysis for sea-level temperature was conducted by allowing the sea-level temperature to vary over the full range possible based on the physics-based model of dewpoint temperatures. All other hydrometeorological inputs were set at the control values listed in Table A1.

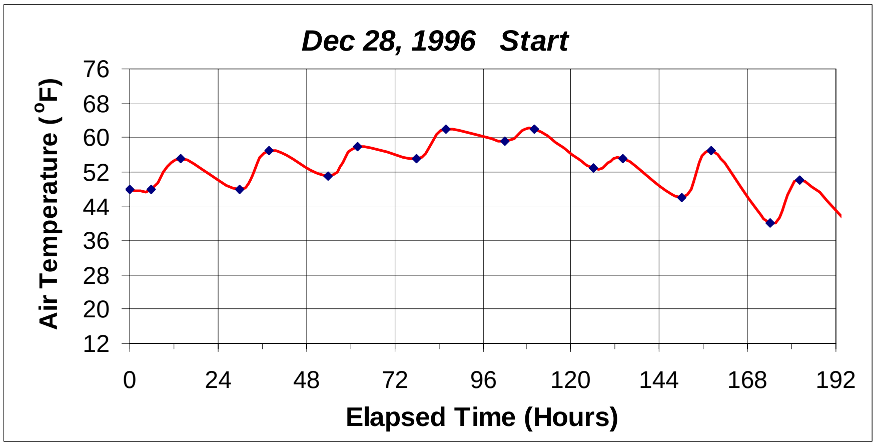

Figure A4 – Example Air Temperature Temporal Pattern for Storm of Dec 28, 1996-Jan 2, 1997 At Sea-Level

The results of the sensitivity analysis for sea-level temperature are depicted in Figures A5a,b for flood response and reservoir response, respectively. It is seen that sea-level temperature has a very minor effect on both the flood response and reservoir response, relative to the magnitude of responses for other hydrometeorological inputs. With regard to snowmelt generation, sea-level temperatures have the greatest effect in the lower elevation zones of the watered and the freezing level has the greater effect at higher elevation zones. Since the vast majority of snowpack is at the higher elevations, sea-level temperature has a minor effect on snowmelt runoff generation.

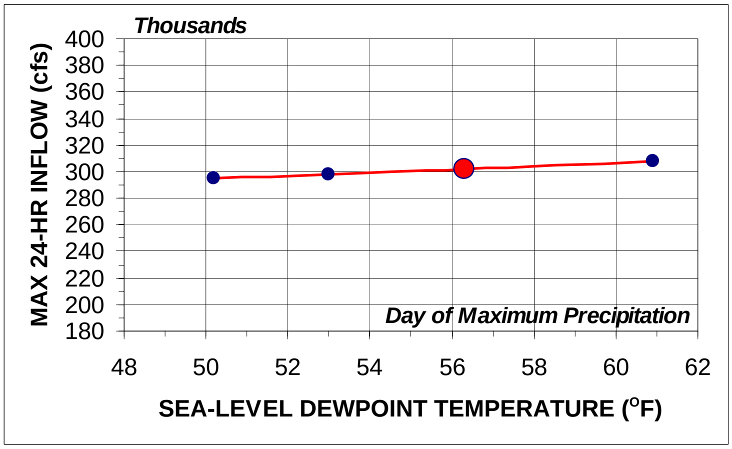

Figure A5a – Sensitivity of Flood Response to Changes in Sea-Level Dewpoint Temperature for One-at-a-Time Sensitivity Analysis for End-of-January

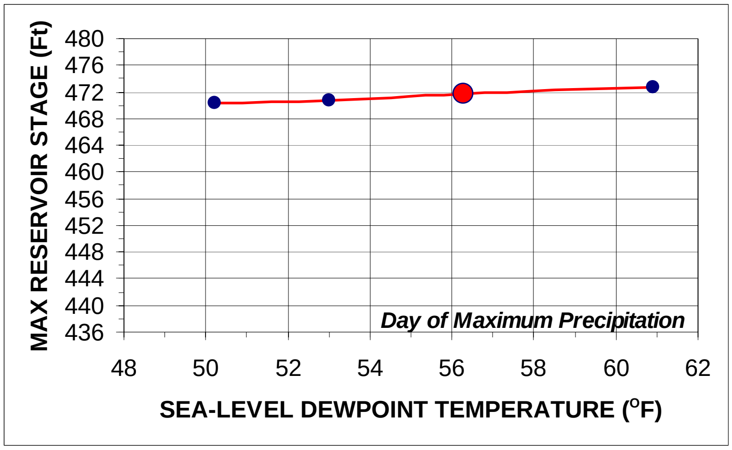

Figure A5b – Sensitivity of Folsom Reservoir Response to Changes in Sea-Level Dewpoint Temperature for One-at-a-Time Sensitivity Analysis for End-of-January

Freezing Level During Storm Event

Analyses of historical data found that freezing level on the day of the maximum 24-hour precipitation during a storm event varies with the magnitude of the maximum 24-hour precipitation and the sea-level temperature[31]. In the sensitivity analysis, values of the freezing level were varied over the range of values for exceedance probabilities from 0.99 to 0.01, conditioned on the occurrence of the control values for precipitation (15.8-inches in 72-hours) and sea-level dewpoint temperature of 56.3°F on the day of maximum 24-hour precipitation. Freezing levels for all other days were based on temporal patterns for the 24 prototype storms that are indexed to the day of maximum precipitation. The temporal pattern for freezing level was then determined by scaling the indexing temporal pattern to the selected freezing level for the day of maximum precipitation during the storm (Figure A6). All other hydrometeorological inputs were set at the control values listed in Table A1.

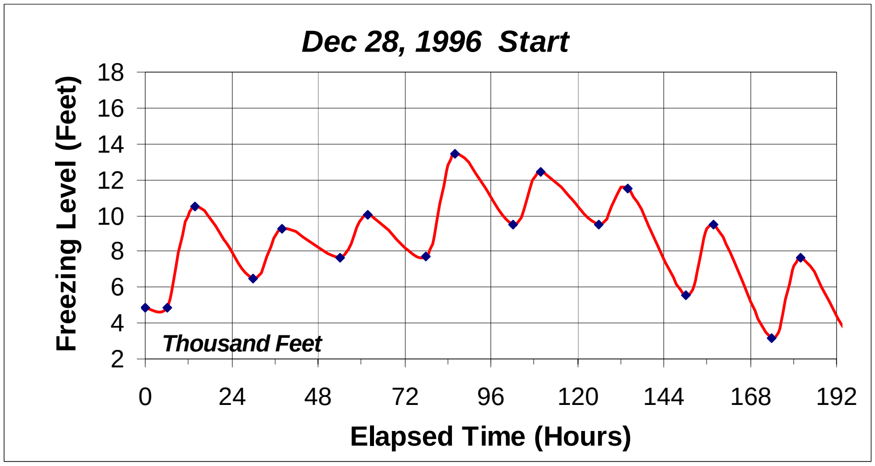

Figure A6 – Example Freezing Levels Temporal Pattern for Storm of Dec 28, 1996-Jan 2, 1997

The results of the sensitivity analysis for freezing level are shown in Figures A7a,b for watershed/flood response and reservoir response, respectively. A review of the sensitivity results indicates that freezing level has a moderate effect on both the flood response and reservoir response, relative to the magnitude of responses for other hydrometeorological inputs.

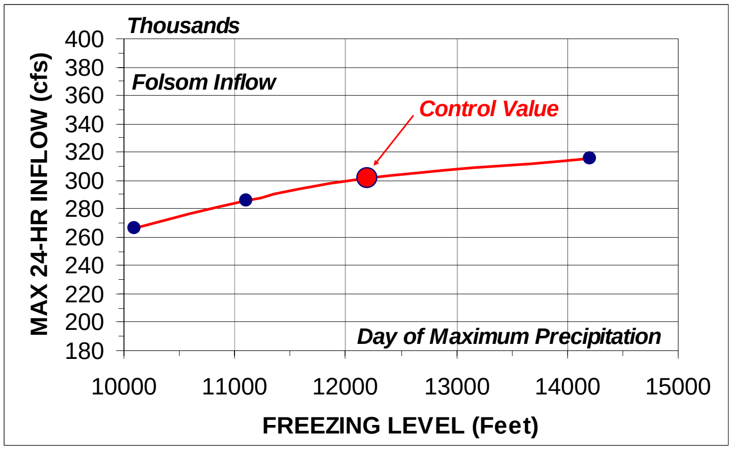

Figure A7a – Sensitivity of Flood Response to Changes in Freezing-Level
for One-at-a-Time Sensitivity Analysis for End-of-January

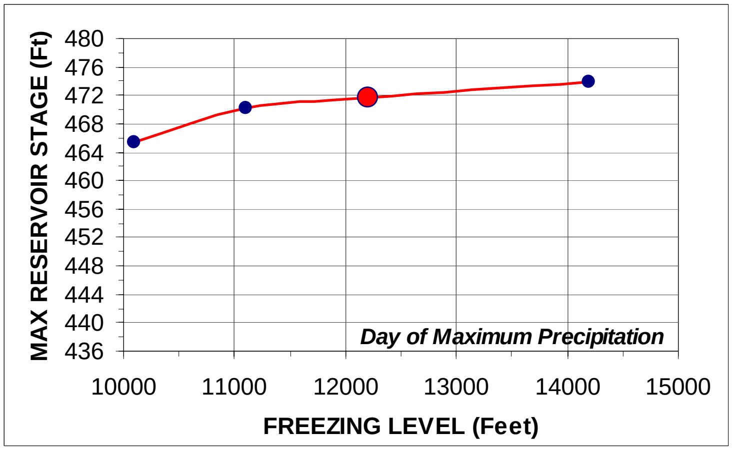

Figure A7b – Sensitivity of Folsom Reservoir Response to Changes in Freezing-Level for One-at-a-Time Sensitivity Analysis for End-of-January

Storage in Five Major Upstream Reservoirs

Storage availability in the five major upstream reservoirs (Hell Hole, Union Valley, French Meadows, Loon Lake and Ice House) can reduce both the runoff volume and flood peak discharge tributary to Folsom Dam. Storage levels in the upstream reservoirs were varied by 1.5 standard deviations above, and one standard deviation below the end-of-January mean storage value. This provided variation from zero storage available (all reservoirs at spillway crest elevation) to 436,000 acre-feet of storage available in the five reservoirs (near historical minimum storage). All other hydrometeorological inputs were set at the control values listed in Table A1. In particular, the initial storage in Folsom Reservoir was fixed at the control value of 473,400 acre-feet to isolate the effect of changes in upstream storage availability on the reservoir response.

The results of the sensitivity analysis for flood response to changes in upstream storage are shown in Figure A8a. A modest increase in flood response is seen in the upper portion of Figure A8a when the upstream reservoirs are nearly full. Conversely, there is no change in the flood response in the lower portion of Figure A8a when the upstream reservoirs are sufficiently drawn down to essentially contain the flood runoff from tributary areas.

It should be noted that flood response is also sensitive to the magnitude of the control values that are chosen. For smaller inflow flood magnitudes, tributary runoff may be completely stored within the upstream reservoirs. Conversely for extreme floods, the magnitude of upstream storage will only have a modest effect on attenuating tributary inflow to the upstream reservoirs.

The results of Folsom reservoir response are shown in Figures A8b,c. The Folsom Reservoir response shown in Figure A8c reflects the sensitivity of the reservoir response when flood magnitudes are just over the threshold required to initiate operation of the emergency spillway gates. The sensitivity of the reservoir response would not be as dramatic if the control values (and resultant floods) were markedly smaller or larger than that chosen here. These results point out the variability in reservoir releases as flood magnitudes just reach the threshold for operation of the emergency spillways.

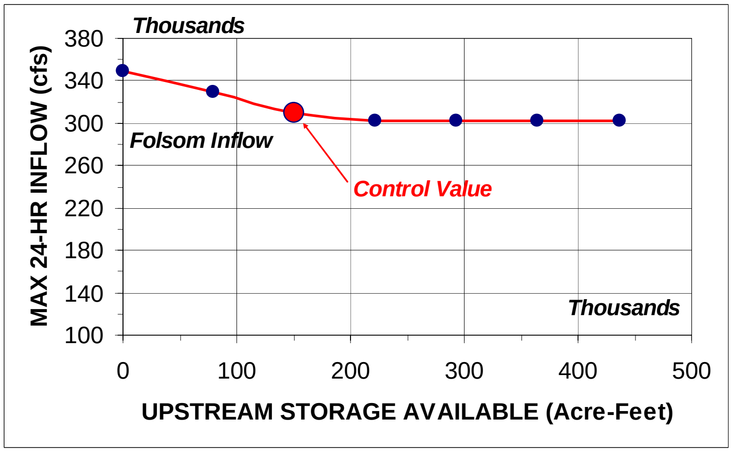

Figure A8a – Sensitivity of Flood Response to Changes in Upstream Reservoir Storage Availability for One-at-a-Time Sensitivity Analysis for End-of-January

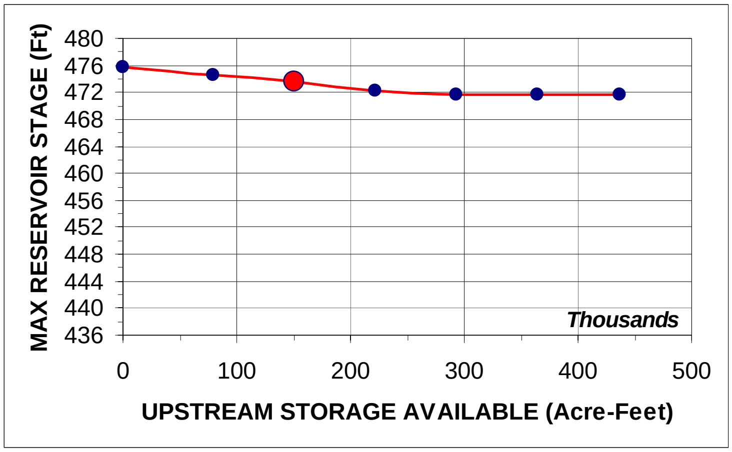

Figure A8b – Sensitivity of Folsom Reservoir Response to Changes in Upstream Reservoir Storage Availability for One-at-a-Time Sensitivity Analysis for End-of-January

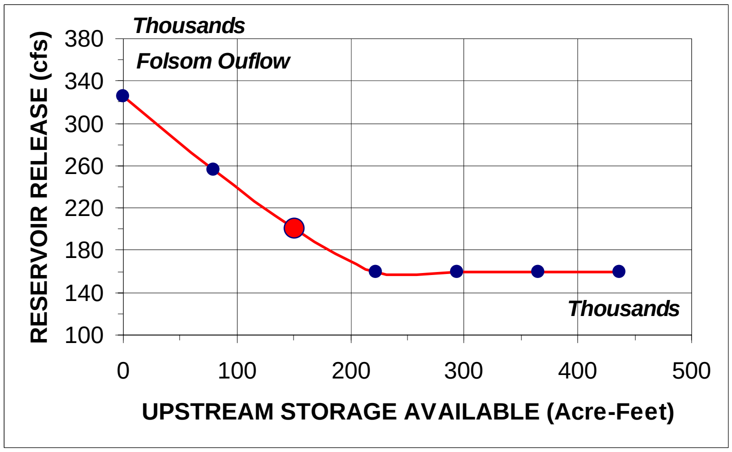

Figure A8c – Sensitivity of Maximum Folsom Releases to Changes in Upstream Reservoir Storage Availability for One-at-a-Time Sensitivity Analysis for End-of-January

Initial Storage in Folsom Reservoir

The initial storage in Folsom Reservoir only affects the reservoir response in Folsom Reservoir. For this analysis, values of initial storage at Folsom Reservoir were varied over the range of exceedance probabilities from 0.99 to 0.01 for the end-of-January. All other hydrometeorological inputs were set at the control values listed in Table A1.

The results of the sensitivity analysis for Folsom reservoir response are shown in Figures A9a,b. A review of Figures A9a,b indicates the initial storage in Folsom Reservoir greatly affects the maximum stage in Folsom Reservoir and maximum release from the outlet works and spillways produced by an inflow flood. Interpretation of these plots/results can be misleading without consideration of the procedures used for reservoir operation during flood events. Figure A9b clearly shows increasing discharges with higher initial storage values. Whereas, maximum reservoir levels (Figure A9a) suggests a flattening in the reservoir response. These shapes are, in part, due to the effect of the spillway operational procedures. In particular, the apparent anomalous dip in Figure A9a, and jump in Figure A9b, are due to a threshold being exceeded for spillway releases in the reservoir operational procedures (ESRD[45]). Setting aside the unusual shapes, reservoir response is none-the-less greatly affected by the initial storage in Folsom Reservoir.

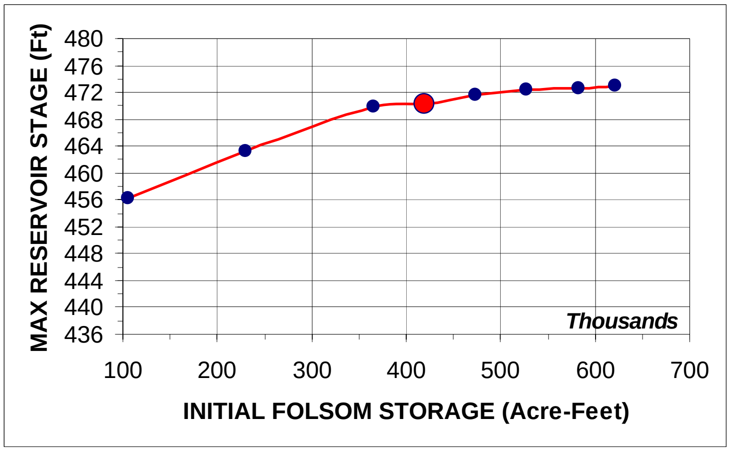

Figure A9a – Sensitivity of Folsom Reservoir Response to Changes in the Initial Storage in Folsom Reservoir for One-at-a-Time Sensitivity Analysis for End-of-January

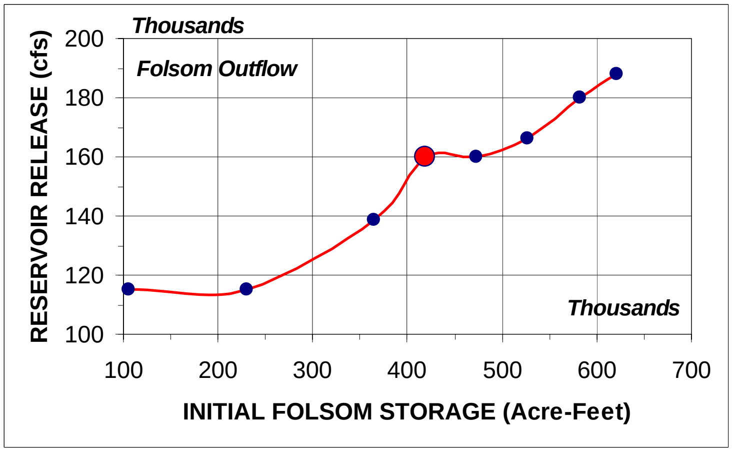

Figure A9b – Sensitivity of Maximum Folsom Reservoir Releases to Changes in the Initial Storage in Folsom Reservoir for One-at-a-Time Sensitivity Analysis for End-of-January

Seasonality of Storms

All prior sensitivity analyses were conducted for the end-of-January. This approach was taken to simplify the analyses because flood and reservoir responses vary seasonally, in addition to varying with all the other hydrometeorological inputs. The end-of-January was chosen as the control because it is in the middle of the historical flood season. The relative magnitudes of the flood and reservoir responses are similar for the various months, and therefore, one-at-a-time sensitivity results for the end-of-January are indicative of those for the other months.

The sensitivity of the seasonality of storms was examined using a control value of 15.8-inches for 72-hour basin-average precipitation and prototype storm pattern 7. All other inputs were set at mean values for the selected end-of-month. The sensitivity of the flood response to seasonality of storms is depicted in Figure A10a. It is seen that the flood response is least at the end-of-October and increases throughout the fall and winter period. This response is primarily due to low antecedent precipitation and drier soil conditions in the early fall, and wetter soil conditions and heavier snowpacks in the winter and early-spring.

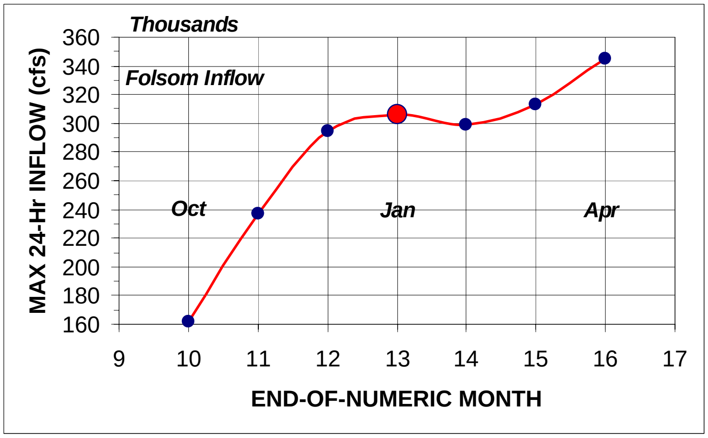

Figure A10a – Sensitivity of Flood Response to Changes in the Seasonality of Storms

Similarly, there is high sensitivity in the reservoir response to changes in the season of occurrence of the storm event (Figure A10b). This sensitivity reflects reduced initial storage levels in Folsom Reservoir at the beginning of the water-year in addition to the seasonal changes that affect the flood responses that are depicted in Figure A10a.

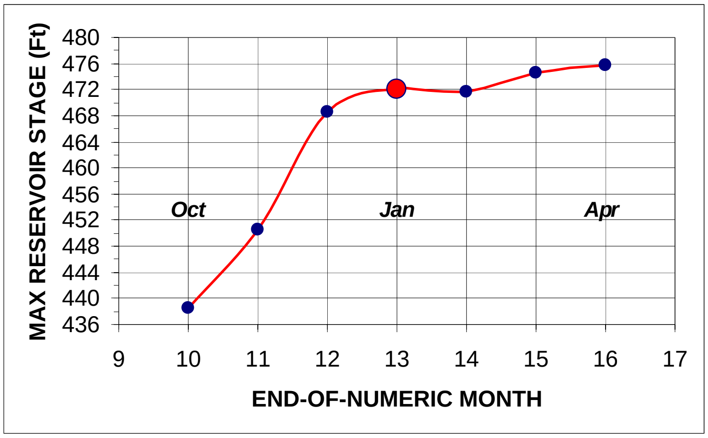

Figure A10b – Sensitivity of Reservoir Response to Changes in the Seasonality of Storms

Modified Holtan Rainfall-Runoff Model Parameters

During calibration of the HEC-1 watershed model, 30 sets of soil parameters (Calibration report[35]) were identified that were capable of adequately reproducing the Nov 1950, Oct 1962, Feb 1986 and Jan 1997 floods. These 30 parameter sets were identified specifically for use in conducting the uncertainty analysis. They represent one component of uncertainties associated with watershed modeling.

Results have been excerpted from the GLUE analysis[1,35] for the 1997 flood and rescaled to provide comparison with the prior OAT sensitivity analyses. The sensitivity of flood peak discharge to the various soil parameter sets are displayed in Figure A11. There is a variation of about 9% in peak discharge over the range of 30 parameter sets. This level of variation can be characterized as low sensitivity relative to the sensitivity for many of the hydrometeorological inputs presented previously.

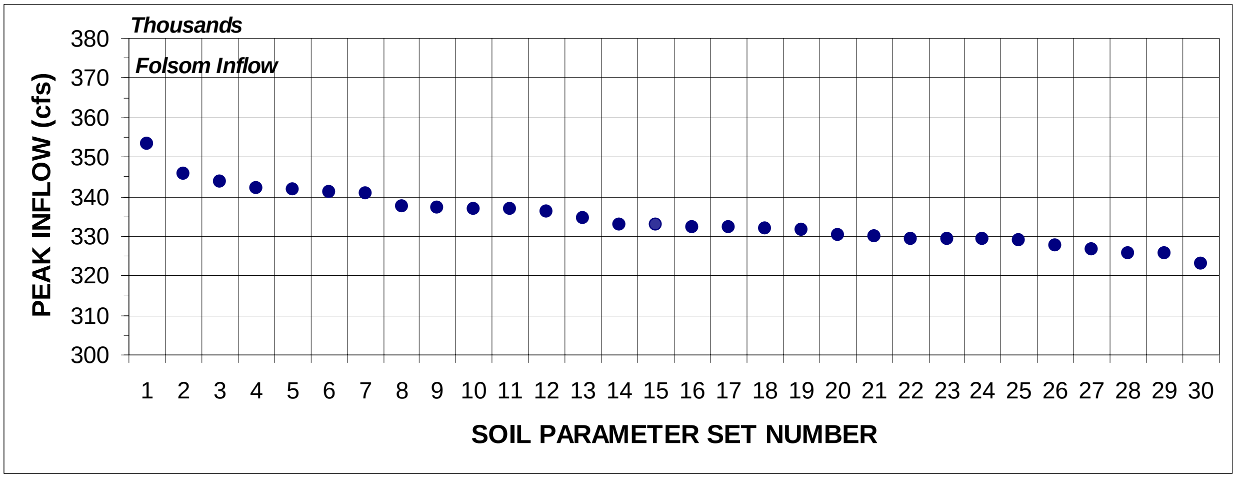

Figure A11 – Sensitivity of Flood Response (Peak Inflow) for 30 Soil Parameter Sets