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

Appendix L - Calibration of American River Watershed Model to Historical Floods

September 2005

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

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CALIBRATION OF AMERICAN RIVER WATERSHED MODEL TO HISTORICAL FLOODS

June 12, 2003
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OVERVIEW

A calibrated watershed model is needed for stochastic simulation of extreme floods for the American River watershed. A 29-subbasin HEC-1 watershed model has previously been developed by the Sacramento District COE[4] for computation of the standard project flood and probable maximum flood for use at Folsom Dam. Watershed model parameters were determined based on calibration to the January 1997 flood. The US Bureau of Reclamation[27] (USBR) reviewed this watershed model and conducted a separate calibration to the February 1986 flood. They confirmed that the unit hydrographs and channel routing parameters originally determined by the Sacramento District COE were appropriate for replicating the magnitude and timing of flood peaks on the American River for both the February 1986 and January 1997 floods.

Both watershed models determined infiltration losses using the initial abstraction and uniform loss rate method for each subbasin in the watershed. In both calibrations, uniform loss rates varied from 0.00-in/hr to 0.10-in/hr and were found to be smallest in the upper portions of the watershed, and generally increased in magnitude progressing downstream. However, there wasn't agreement between the two calibrations on the magnitude of the uniform loss rates for the majority of subbasins.

Stochastic simulations will be conducted throughout the storm season that historically spans the period from October through April. A watershed model is needed that can account for the varying antecedent and soil moisture conditions that can occur during this period. A number of changes have been made to the original Sacramento District HEC-1 watershed model to provide an all-season capability. These changes included: replacing the uniform loss rate method with a modified Holtan[9] method; adding a soil moisture accounting routine; adding the USBR snow compaction routine[26]; 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.

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]. 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. The parameter set for the calibrated model is obtained from those parameter sets that were identified as having the highest likelihoods based on the goodness-of-fit measures.

This report describes the changes that were made to the original HEC-1 model, application of the GLUE method to model calibration, and the results of the calibration to the November 1950, October 1962, February 1986, and January 1997 floods.

CHANGES TO SACRAMENTO DISTRICT HEC-1 WATERSHED MODEL

A number of changes were made to the Sacramento District HEC-1 watershed model for use in the stochastic simulation of extreme floods. Each of these changes is described below.

33 Subbasin Model – The original HEC-1 watershed model[4] had 29-subbasins. In that model, the North Fork of the American River was described by one subbasin. In the revised model, the North Fork (342 mi^2) has been subdivided into 5 subbasins (labeled 2A-2E, Figure 1) yielding a 33-subbasin model. This was done to allow for increased spatial resolution of precipitation over the North Fork and to provide compatibility with the spatial and temporal storm templates[22] previously developed for the stochastic simulation of storms. Unit-hydrographs for these 5 subbasins were provided by Mr. Jeff Harris of HEC[8]. These unit-hydrographs were subsequently adjusted to match the flood response of the original single unit-hydrograph for the North Fork.

Surface and Interflow Runoff Modeling Using the Holtan Equation – The initial abstraction and uniform loss rate method was replaced by a modified Holtan[9] approach. This change was made to provide the capability to account for the variability in soil moisture that occurs 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 2.

In using the modified Holtan method, the surface infiltration rate at the start of the storm is dependent upon 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.

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

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

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).

There are eight soil types (soil zones) defined for the American River watershed as part of the system of Hydrologic Runoff Units (HRUs). Each soil type/soil zone has unique parameter values for S_{max}, f_{max}, f_c, and f_d. The system of Hydrologic Runoff Units will be described in a later section.

USBR Snow Compaction Routine – Snowmelt computation and snow moisture accounting within the snowpack are accomplished using the USBR snow compaction routine[26]. Snowmelt and moisture release from the snowpack are used as inputs to the modified Holtan approach described previously. These computations are conducted external to the HEC-1 watershed model.

Recession Limb Modeling Via Linear Reservoir Routing – The original watershed model computed the recession limb(s) of the flood hydrograph using the standard HEC-1 exponential decay routine. In that routine, computation of the recession limb begins when the ratio of discharge to flood peak discharge reaches a user-defined value. Use of this routine does not provide for predetermination of the volume of runoff in the recession limb, or for a relationship to be defined between the volume of water lost to deep percolation and the volume that returns in the recession limb.

Reservoir operations at Folsom Dam are expected to be sensitive to runoff volume for extreme floods. Therefore, the exponential decay routine was replaced by a linear reservoir routing routine, wherein the input to the linear reservoir was provided by the computed interflow component of runoff. This approach provided for simulation of the total runoff volume, comprised of surface and interflow runoff, and allowed for computational description of the recession limb(s) of the flood hydrograph.

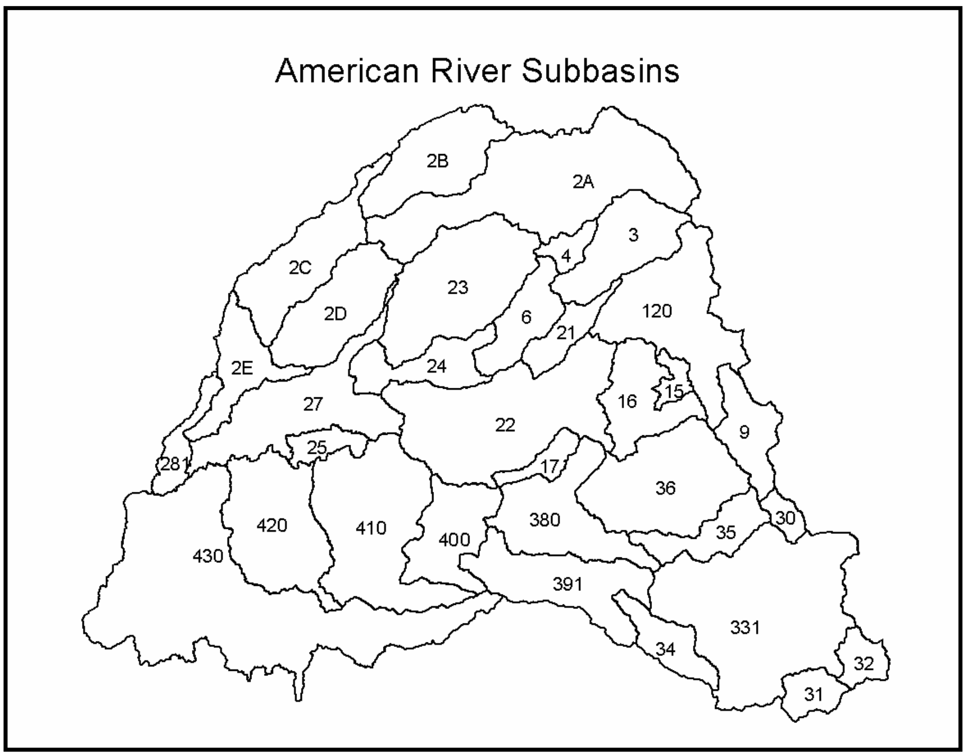

Figure 1 – Layout of 33-Subbasins for American River Watershed

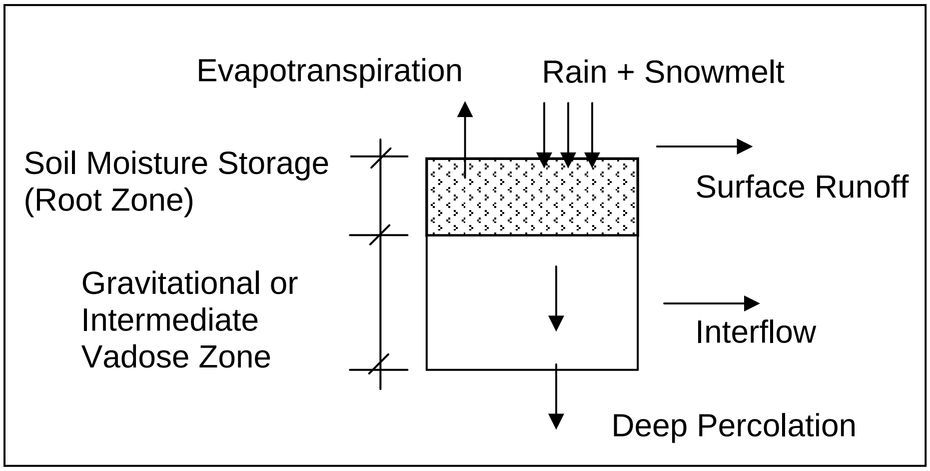

Figure 2 – Schematic of Soil Moisture and Runoff Processes Used in the Stochastic Model

DISTRIBUTED SURFACE RUNOFF AND INTERFLOW RUNOFF COMPUTATION USING HYDROLOGIC RUNOFF UNITS

Surface and interflow runoff are computed on a distributed basis using Hydrologic Runoff Units (HRUs). Surface runoff and interflow runoff are aggregated to the subbasin level, where surface runoff is converted to a runoff hydrograph using a unit-hydrograph and interflow runoff is converted to a runoff hydrograph using the linear reservoir routing routine described previously. Unit-hydrographs are applied within HEC-1 and all other computations[23] are done externally to the HEC-1 watershed model.

Hydrologic Runoff Units are used for the spatial allocation of antecedent precipitation and antecedent snowpack, for soil moisture accounting, and for computation of surface and interflow runoff. The American River watershed has been subdivided into 11 zones of mean annual precipitation[6,16], 9 elevation zones, and 8 soil zones. This resulted in 792 unique HRU combinations, of which, 263 HRUs actually occur in the watershed.

The zones of mean annual precipitation are listed in Table 1a and depicted in Figure 3a. The elevation zones are listed in Table 1b and depicted in Figure 3b.

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

Table 1b – Elevation Zones for the American River Watershed

ELEVATION ZONES (Feet)									
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Range	1000-2400	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

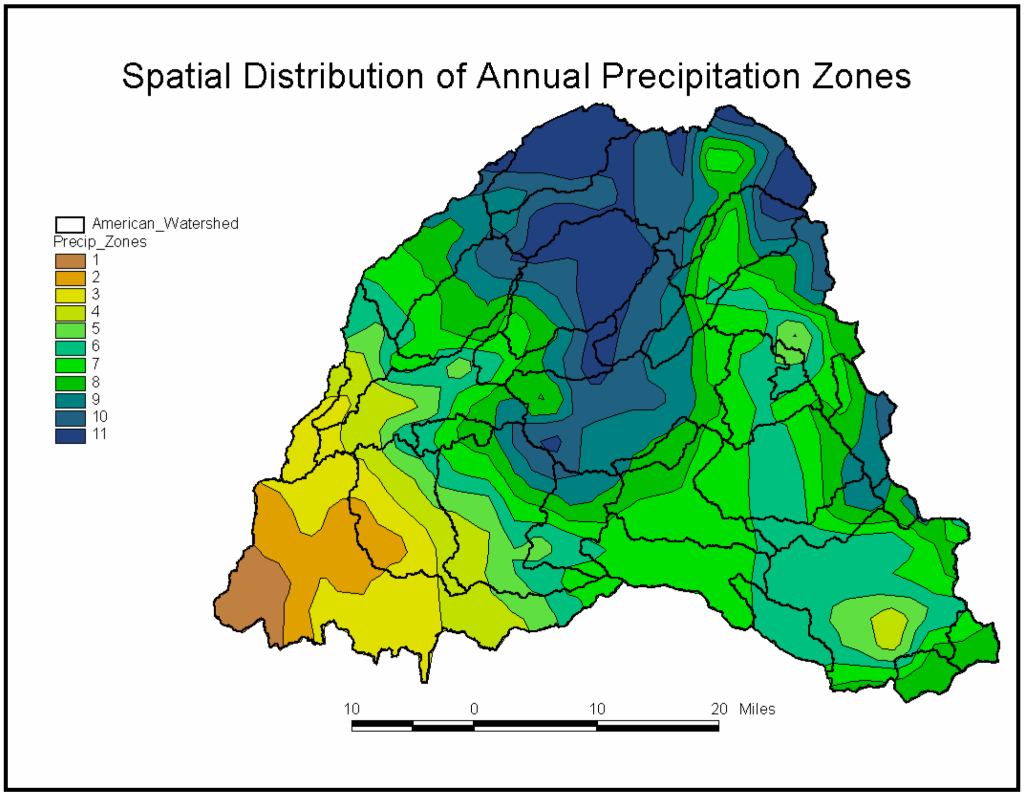

Figure 3a – Zones of Mean Annual Precipitation for the American River Watershed

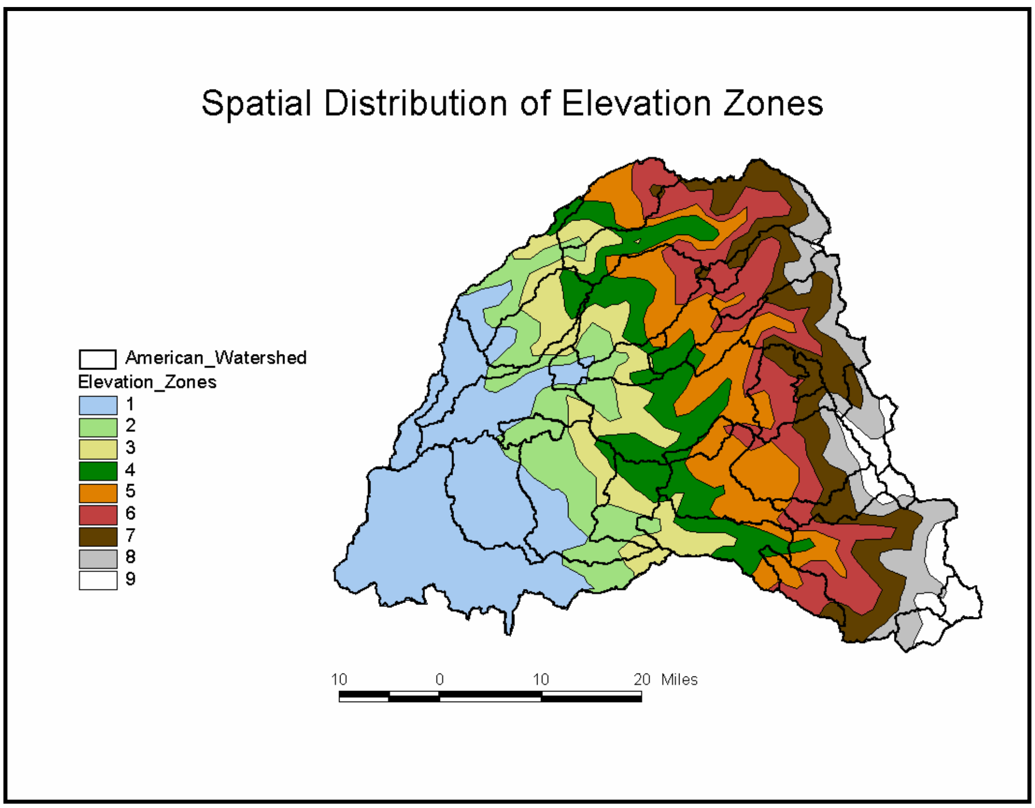

Figure 3b – Elevation Zones for the American River Watershed

Determination of Soil Zones

Information contained in the NRCS STATSGO[24] database was used to define eight soil zones. The NRCS soil associations[30,31,32,33] for the American River watershed are listed in Table 2 and depicted in Figure 4a. It was found that soil depth and bedrock parent material provided the greatest distinguishing characteristics between the various soil associations. Bedrock materials include granitic, metamorphic, and sedimentary rock units with some units being highly fractured or weathered at the soil-bedrock contact. 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 and/or highly fractured metamorphic rock. The spatial distribution of the eight soil zones is depicted in Figure 4b.

As part of the calibration process, initial estimates were needed for the hydrologic soil characteristics for the various soil zones. A review of the STATSGO database and County Soil Reports[30,31,32,33] provided much of the information necessary for making the initial estimates of soil characteristics for S_{max}, f_{max}, f_c, and f_d.

The majority of soils were found to have soil textures with sandy or silty components that have similar permeabilities as defined by the classification system used by the NRCS. Therefore, maximum surface infiltration rates (f_{max}) for dry soil conditions were expected to be similar for the various soil zones and on the order of 2.0 in/hr.

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

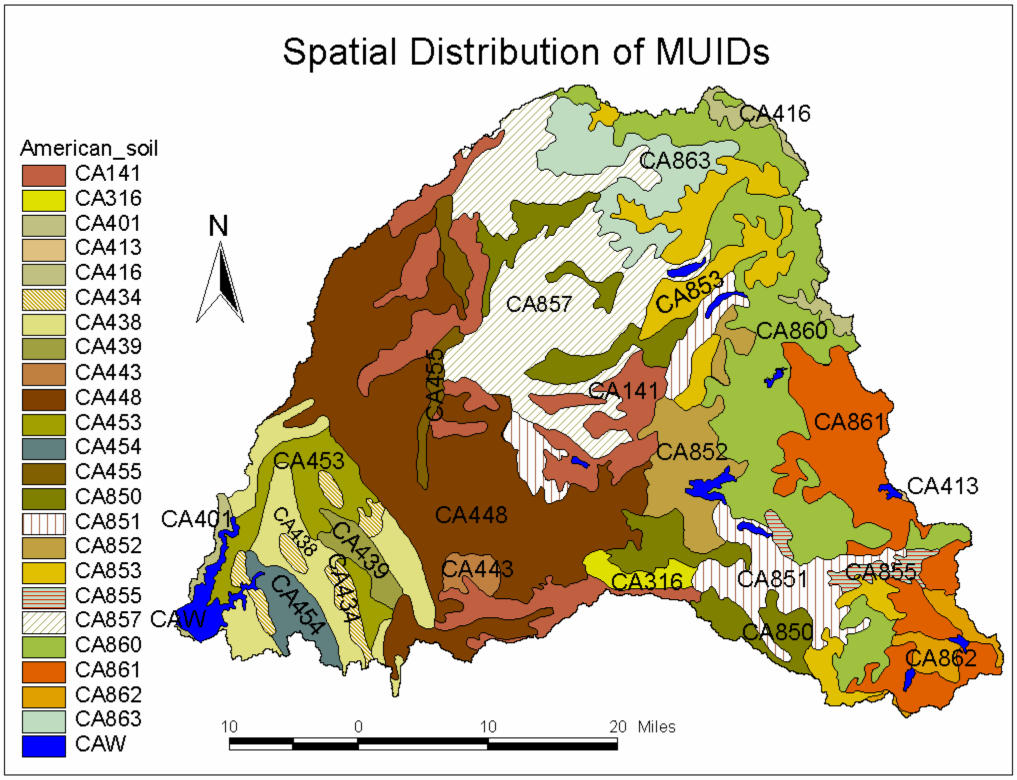

Figure 4a – NRCS Soil Associations as Delineated by Map Unit Identifiers (MUID) for the American River Watershed

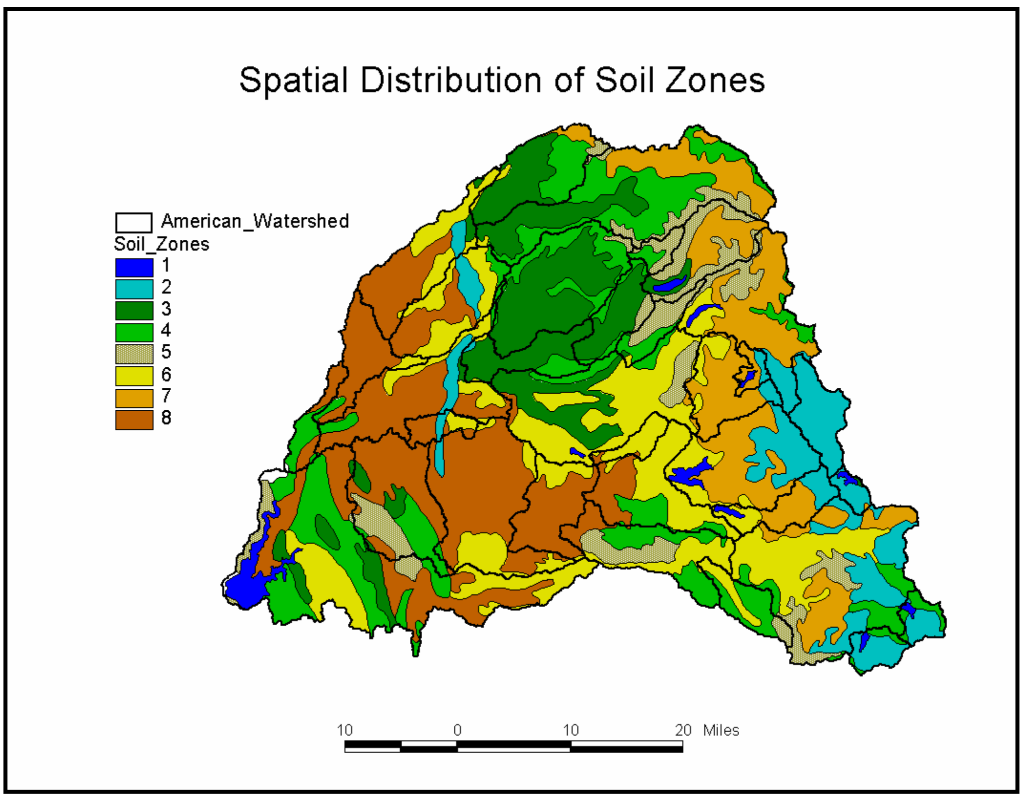

Figure 4b –Soil Zones for the American River Watershed

Review of NRCS soil descriptions indicated a nominal value of available water capacity of 0.16 inch per inch of soil depth for soils within most soil associations. This allowed for estimation of the maximum soil moisture capacity (S_{max}).

Comparisons were made between the spatial distribution of the soil zones and the uniform infiltration rates for the various subbasins determined by the US COE and USBR calibrations of the January 1997 and February 1986 floods, respectively. It was generally found that the shallowest soils had the lowest uniform infiltration rates and the deeper soils had higher uniform infiltration rates. The largest uniform infiltration rates were associated with soil zone 8 that overlies a steeply tilted and fractured metamorphic bedrock. This information allowed for an initial estimation of deep percolation rates (f_d).

The minimum infiltration rate (f_c) is used more as a model parameter than a physical soil characteristic. It is used to determine the precipitation rate, above which, surface runoff is produced. Lower rates of precipitation provide moisture to the soil column that reduce the soil moisture deficit, produce interflow, or exit the runoff process through deep percolation. The term *surface runoff* as used herein can generally be described as *quickflow*. Where, quickflow is defined as runoff that reaches a water course shortly after the precipitation event. It is comprised of Hortonian overland flow, saturated overland flow and water that has infiltrated the soil surface and emerges downslope via a variety of paths. It is distinguished from interflow runoff by its more rapid response following precipitation and/or snowmelt.

Initial estimates of f_c were made by recognizing that floods on the American River generally have very steep recession limbs and streamflow quickly returns to relatively low baseflow levels. This behavior is suggestive of small interflow contributions. Based on the available information and experience from modeling of other watersheds, it was anticipated that the deeper soils would generally be more capable of supporting the larger interflow contributions.

The information and deductions described above allowed the development of Table 3 that lists the initial estimates of the soil characteristics for the eight soil zones. These estimates were used as a starting point for calibration of the HEC-1 watershed model.

Table 3 – Initial Estimates of Soil Characteristics for the Eight Soil Zones for the American River Watershed

SOIL ZONE	RANGE SOIL DEPTH (IN)	MEDIAN SOIL DEPTH (IN)	DEEP PERCOLATION (IN/HR)	MINIMUM SURFACE INFILTRATION (IN/HR)	MAXIMUM SURFACE INFILTRATION (IN/HR)	STATSGO SOIL MOISTURE STORAGE CAPACITY (IN)	COMMENTS
1	water	0	0.00	0.00	0.00	0.00	water bodies
2	0 - 10	5	0.01	0.03	2.00	0.80	very shallow soils over bedrock
3	10 - 20	15	0.02	0.06	2.00	2.40	
4	20 - 30	25	0.03	0.09	2.00	4.00	
5	30 - 40	35	0.04	0.12	2.00	5.60	
6	> 40	50	0.05	0.15	2.00	8.00	
7	30 - 40	36	0.06	0.16	2.00	5.76	underlain by deep outwash soils
8	35 - 45	40	0.08	0.18	2.00	6.40	fractured and/or tilted bedrock

SOIL MOISTURE ACCOUNTING

Soil moisture accounting is used in the stochastic model for setting the initial soil moisture conditions in each of the Hydrologic Runoff Units. Soil moisture accounting was also used in the calibration process for setting the initial soil moisture deficits in each HRU for the start of each storm. A simple water-budget accounting procedure was used for tracking soil moisture on a monthly basis by adding precipitation, subtracting evapotranspiration, subtracting the change in snow-water equivalent, and carrying the soil moisture balance from month to month. This accounting was conducted for the period from October 1st to the date of storm occurrence. This accounting procedure is described in Equations 2a, 2b.

$$M = P - E - \Delta SWE \tag{2a}$$

$$SMD_t = SMD_{t-1} - M \quad (restricted\ to\ 0 \leq SMD \leq SMD_{max}) \tag{2b}$$

where: M is the monthly soil moisture input,
P is the monthly precipitation,
E is the monthly potential evapotranspiration,
ΔSWE is the change in snow-water equivalent over the month ($SWE_t - SWE_{t-1}$).
SMD_t is the soil moisture deficit for the current end-of-month,
SMD_{t-1} is the soil moisture deficit for the prior end-of-month, and
SMD_{max} is the maximum soil moisture deficit (equals soil moisture storage capacity).

To conduct soil moisture accounting for each HRU, precipitation, potential evapotranspiration and change in snow-water equivalent must be provided for each HRU on a monthly basis. This was accomplished by prorating the total antecedent precipitation (October 1st to storm date) for each zone of mean annual precipitation based on the monthly distribution of mean annual precipitation[18] (Figure 6) up to the date of the storm. In a similar manner, the change in snow-water equivalent is prorated for combinations of zones of mean annual precipitation and elevation based on the monthly distribution of mean values of snow-water equivalent[21] up to the date of the storm.

Monthly values of potential evapotranspiration for the nine elevation zones were computed based on application of the Jensen-Haise[10] equation using mean monthly air temperature and solar radiation data at Auburn, Blue Canyon and Twin Lakes, California. The findings of this analysis were validated by comparison to observed pan evaporation data at 9 NCDC stations[13] within or near the American River watershed (Figure 5a). A pan coefficient of 0.72 was used to estimate potential evapotranspiration from pan evaporation data.

The monthly distribution of annual potential evapotranspiration (Figure 5b) was used for determining the monthly values of potential evapotranspiration for each elevation zone. When snow covered the ground in a given HRU, potential evapotranspiration was reduced to 10% of the value that would have been used for snow-free conditions to account for evapotranspiration from coniferous trees.

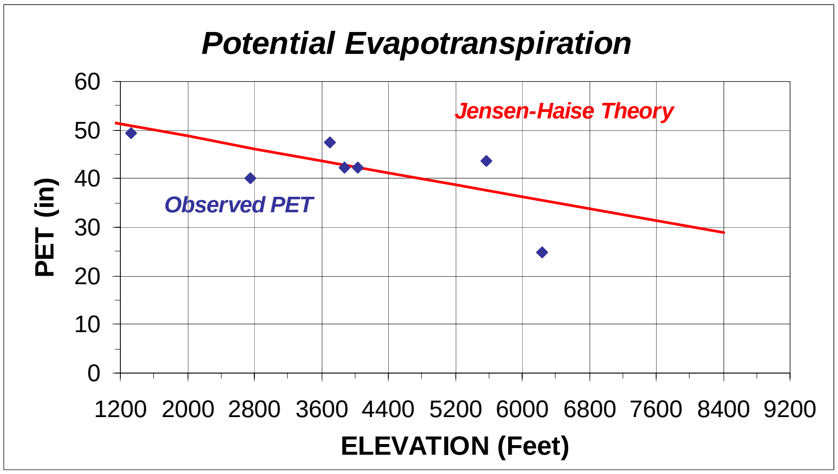

Figure 5a – Annual Potential Evapotranspiration Computed Using Jensen-Haise Equation as Compared with Observed Values of Potential Evapotranspiration

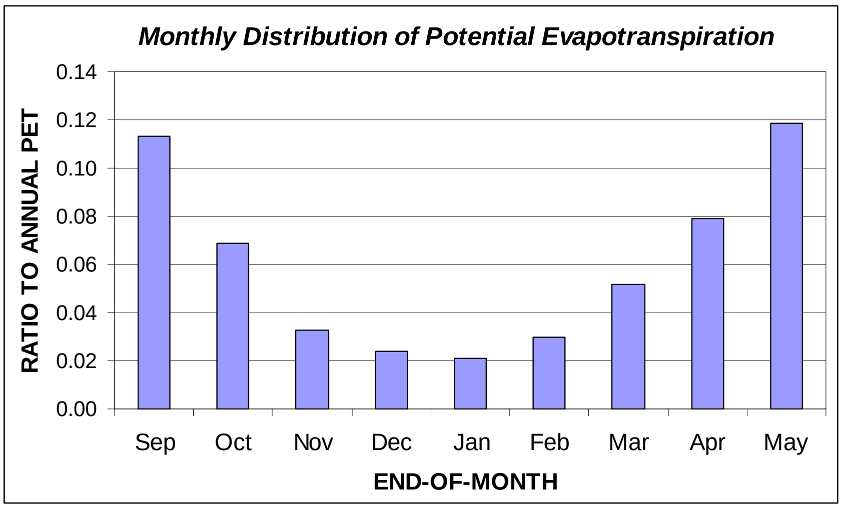

Figure 5b – Monthly Distribution of Annual Potential Evapotranspiration

ANTECEDENT CONDITIONS PRIOR TO HISTORICAL FLOODS

Examination of a wide range of antecedent conditions is preferred for calibration of the watershed model. This provides a more rigorous examination of the effects of changes in parameter values on flood response and assists in reducing uncertainties in determination of model parameter values.

The February 1986 and January 1997 floods are two of the largest floods in the record and are logical choices for calibration. Antecedent conditions were very wet with significant snowpack present in the watershed for both of these floods events. Calibration to floods produced under dry antecedent conditions is also needed for estimation of model parameters for the soil zones. The November 1950 and October 1962 floods were chosen as representative of flood response under dry antecedent conditions. The storm of October 1962 had the largest 72-hour basin-average precipitation on record and occurred with very dry antecedent conditions. The resultant flood was moderate in magnitude and ranked in the 2nd quartile of recorded floods. The storm of November 1950 produced the 5th largest 72-hour basin-average precipitation. This storm occurred following moderate amounts of antecedent precipitation in the fall of 1950 and there was a small snowpack present in the upper watershed. The November 1950 flood had the 5th largest 72-hour peak discharge of recorded floods.

Antecedent Precipitation

Antecedent precipitation for the stochastic model is defined as cumulative precipitation from October 1st to the date of storm occurrence. Antecedent precipitation values for the four flood events, as measured at the Lake Spaulding precipitation station, are shown in Table 4. The Lake Spaulding precipitation station is used as a key station for regression relationships for several hydrometeorological inputs for stochastic simulations[18,23]. It was chosen because it had a long, high-quality record, and was located near the upper-central portion of the watershed.

Antecedent precipitation is spatially allocated to the zones of mean annual precipitation using relationships between the mean monthly antecedent precipitation for the zones of mean annual precipitation and the mean monthly antecedent precipitation for the Lake Spaulding station. The monthly distribution of annual precipitation (Figure 6) is then used to allocate incremental monthly antecedent precipitation for each of the zones of mean annual precipitation. These procedures are described in detail in the prior report on Antecedent Precipitation[18].

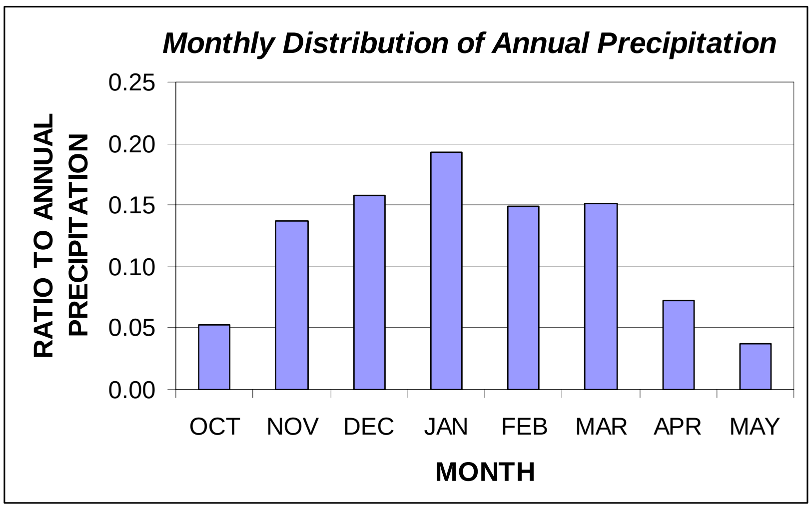

Figure 6 – Monthly Distribution of Annual Precipitation for American River Watershed

Table 4 – Incremental Antecedent Precipitation at Lake Spaulding
Prior to Date of Storm Occurrence for Four Historical Floods for the American River Watershed

FLOOD EVENT	LAKE SPAULDING MONTHLY PRECIPITATION (Inches)					
	SEP	OCT	NOV	DEC	JAN	FEB
Nov 1950	1.13	10.42	1.96			
Oct 1962	0.16	0.00				
Feb 1986	3.53	2.49	11.55	7.60	11.14	4.37
Jan 1997	1.64	2.63	11.49	24.75		

Antecedent Snowpack

Antecedent snowpack and snow densities for the four flood events were determined based on snotel and snow-course data from NRCS[14] and California Dept. of Water Resources[3], snow-on-ground data from NCDC[13] stations, and miscellaneous snow-water equivalent data used in the USBR[27] and US COE[29] flood calibrations for the Feb 1986 and Jan 1997 floods, respectively.

An indexing approach is utilized in the stochastic model to spatially distribute the antecedent snow-water equivalent throughout the watershed. The snowpack data is normalized by converting snow-water equivalent from the site of measurement to that expected for a similar setting located at a site with mean annual precipitation of 50-inches. This conversion is done by a simple ratio of the mean annual precipitation for the site of measurement to that at 50-inches. Tables 5a,b list snow-water equivalent and snow density for the nine elevation zones for the four flood events. The snow-water equivalent values are indexed to a zone of mean annual precipitation of 50-inches. Snow-water equivalent values for other zones of mean annual precipitation are determined by scaling by the ratio of zone mean annual precipitation to 50-inches. Procedures for spatial allocation of snowpack are described in detail in the prior report on Snowpack for the American River[21].

Table 5a – Antecedent Snow-Water Equivalent for 50-inch Zone of Mean Annual Precipitation for Four Historical Floods for the American River Watershed

FLOOD EVENT	SNOW-WATER EQUIVALENT (Inches)								
	ELEVATION ZONES								
	1	2	3	4	5	6	7	8	9
	2000 ft	2800 ft	3600 ft	4400 ft	5200 ft	6000 ft	6800 ft	7600 ft	8400 ft
Nov 1950	0.0	0.0	0.5	1.0	1.5	2.0	2.5	2.9	3.4
Oct 1962	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb 1986	0.0	0.0	0.0	0.5	5.1	12.4	18.8	24.4	29.5
Jan 1997	0.0	0.0	1.3	4.2	7.2	10.2	13.1	16.1	19.0

Table 5b – Snowpack Densities for Four Historical Floods for the American River Watershed

FLOOD EVENT	SNOW DENSITY								
	ELEVATION ZONES								
	1	2	3	4	5	6	7	8	9
	2000 ft	2800 ft	3600 ft	4400 ft	5200 ft	6000 ft	6800 ft	7600 ft	8400 ft
Nov 1950			0.20	0.20	0.20	0.20	0.20	0.20	0.20
Oct 1962									
Feb 1986				0.28	0.25	0.23	0.22	0.20	0.18
Jan 1997			0.20	0.20	0.21	0.26	0.30	0.28	0.25

HISTORICAL FLOODS USED FOR CALIBRATION OF THE WATERSHED MODEL

Four historical floods were used for calibration. To improve the calibration process, flood hydrographs from multiple recording sites were utilized for each flood event. This approach was taken to avoid over-reliance on one or two flood hydrographs. It also helped reduce the uncertainties in the calibration due to unavoidable errors and inaccuracies that are present in flood measurements, hydrometeorological inputs, and algorithms used in the watershed model.

As background, numerous streamflow measurement gages have been operated on the American River for various periods of time over the past century. Flood records include instantaneous peak discharges, hourly hydrographs, hydrographs with irregular measurement intervals, and summaries of mean daily flows for locations on the North Fork, Middle Fork, South Fork and at Folsom Reservoir.

The following sections describe the flood measurement data that were used in the calibration process for each of the four historical floods. Graphical depiction of observed flood hydrographs will be presented in a later section when comparisons are shown between observed and simulated hydrographs. Information is also provided about the timing of construction of major reservoirs in the watershed that required changes to the HEC-1 watershed model. Initial storage levels for all reservoirs were obtained from CDEC[3] records and used to set initial conditions for reservoir routing at these projects. Goodness-of-fit measures between observed and simulated hydrographs were computed for the contiguous portion of the flood hydrograph surrounding the peak discharge. This resulted in comparisons of the larger observed and simulated discharges with a discharge of about 20% of the flood peak being the minimum discharge considered.

<u>Flood of November 16-22, 1950</u> – The flood of November 1950 predated the construction of all reservoirs with large storage that now exist in the watershed. The HEC-1 watershed model was modified and all five major reservoirs in the upper watershed and Folsom Lake were removed. Table 6 lists the flood measurement data that were used for comparison to simulated discharges as part of the calibration process. Goodness-of-fit measures for calibration were computed for the flood hydrographs from November 17 through November 23, 1950.

Table 6 – Streamflow Measurement Data for Flood of November 1950 on the American River

USGS STREAM GAGE INFORMATION		DRAINAGE AREA (mi^2)	PEAK DISCHARGE (cfs)	STREAMFLOW DATA FOR CALIBRATION
GAGE #	STATION NAME			
11-427000	North Fork American River at North Fork Dam	343	46,600	mean daily discharge
11-443500	South Fork American River near Camino	497	46,000	mean daily discharge
11-446500	American River at Fair Oaks	1888	180,000	mean daily discharge

<u>Flood of October 9-18, 1962</u> – At the time of the October 1962 flood, Ice House Reservoir had been in operation for several years and the Union Valley Reservoir had just begun first filling. The HEC-1 watershed model was modified to incorporate the existence of these two reservoirs. Table 7 lists the flood measurement data that were used for comparison to simulated discharges as part of the calibration process.

This flood was noteworthy because of the large precipitation input and small resultant runoff volumes. It was the first storm of the fall season following many months of dry conditions and soil moisture deficits were at a maximum throughout the watershed. The October 1962 flood was used indirectly in the calibration process. It was used primarily to set upper and lower bounds for soil moisture storage capacity (S_{max}) for the soil zones. The flood peak discharges for the three major forks were small to moderate in magnitude relative to that of the other three historical floods and were not used in the calibration process to avoid undue influence in attempting to calibrate to these smaller floods. Goodness-of-fit measures were computed for the flood hydrographs from October 12 through October 15, 1962.

Table 7 – Streamflow Measurement Data for Flood of October 1962 on the American River

USGS STREAM GAGE INFORMATION		DRAINAGE AREA (mi^2)	PEAK DISCHARGE (cfs)	STREAMFLOW DATA FOR CALIBRATION
GAGE #	STATION NAME			
11-427000	North Fork American River at North Fork Dam	343	31,000	mean daily discharge
11-433500	Middle Fork American River near Auburn	612	36,500	hydrograph, irregular reporting
11-445500	South Fork American River near Lotus	673	less than 10,000	mean daily discharge

Flood of February 12-20, 1986 – The flood of February 1986 was used for verification of the "best-fit" parameter set obtained from the calibration process that considered the 1950, 1962, and 1997 floods. After verification, the calibration procedures were rerun to allow consideration of the February 1986 flood to produce an improved calibrated parameter set based on all four historical floods.

All five reservoirs in the upper watershed were in operation at the time of the February 1986 flood. Table 8 lists the flood measurement data that were used for comparison to simulated discharges as part of the calibration process. Goodness-of-fit measures for calibration were computed for the flood hydrographs from February 15 through February 21, 1986.

Table 8 – Streamflow Measurement Data for Flood of February 1986 on the American River

USGS STREAM GAGE INFORMATION		DRAINAGE AREA (mi^2)	PEAK DISCHARGE (cfs)	STREAMFLOW DATA FOR CALIBRATION
GAGE #	STATION NAME			
11-427000	North Fork American River at North Fork Dam	343	60,200	hourly hydrograph
11-445500	South Fork American River near Lotus	673	57,000	mean daily discharge
	Inflow to Folsom Reservoir	1862	207,500	hourly hydrograph

Flood of December 25, 1996 - January 3, 1997 – All five reservoirs in the upper watershed were in operation at the time of the January 1997 flood. Table 9 lists the flood measurement data that were used for comparison to simulated discharges as part of the calibration process. Goodness-of-fit measures for calibration were computed for the flood hydrographs from December 29 through January 4, 1997.

Table 9 – Streamflow Measurement Data for Flood of January 1997 on the American River

USGS STREAM GAGE INFORMATION		DRAINAGE AREA (mi^2)	PEAK DISCHARGE (cfs)	STREAMFLOW DATA FOR CALIBRATION
GAGE #	STATION NAME			
11-433800	American River at Auburn Dam Site	973	175,000	hourly hydrograph
11-445500	South Fork American River near Lotus	673	90,000	hourly hydrograph
	Inflow to Folsom Reservoir	1862	255,600	hourly hydrograph

CALIBRATION PROCEDURES – GLUE APPROACH

Calibration of the watershed model was accomplished using concepts from the Generalized Likelihood Uncertainty Estimation (GLUE) procedures developed by Beven and Binley[1]. The basic premise of the GLUE approach is that "there is no reason to expect that any one set of parameters will represent a true parameter set (within some particular model structure) to be found by some calibration procedures". The search for the "true" parameter set is obstructed by the errors and uncertainties that exist in the flood measurements, hydrometeorological inputs, and the model structure and algorithms. Recognizing these limitations, a realistic approach is to identify those combinations of parameter values (parameter sets) that can reasonably replicate the observed flood hydrograph(s) and then assign a likelihood to each parameter set based on some objective measure of the goodness-of-fit between observed and simulated flood discharges.

The basic approach is to assemble multi-thousand trial parameter sets based on sampling over the plausible range of values for each parameter. The watershed model is then executed and a measure is made of the goodness-of-fit between observed and simulated streamflows for each of the parameter sets. A numerical threshold is set for the goodness-of-fit measure that is used to accept or reject parameter sets based on the closeness between observed and simulated streamflows. Parameter sets that produce simulations acceptably close to the observed streamflows are termed *behavioral*. An objective measure is then used to set the likelihood for each behavioral parameter set with greater likelihood assigned to parameter sets that more closely replicate the observed flood hydrographs.

The information provided by a GLUE analysis may be used to make a more informed selection of a single parameter set for use in project design/analysis in a manner consistent with traditional practice. However, it has its greatest advantage for this study in developing a best estimate and uncertainty bounds for flood-frequency relationships. Development of uncertainty bounds for flood-frequency relationships is a future task of this project and the information from the GLUE procedures will be used in conducting those analyses. This will involve using the behavioral parameter sets in a resampling scheme to examine plausible flood-frequency curves.

As indicated above, the GLUE procedure was used to identify a parameter set that yields the "best-fit" for the four historical floods. This represents the traditional approach to calibration that seeks the "true" parameter set. This is a deliverable for the current phase of work.
A second product will be produced using the GLUE procedures as part of a future task. That product will include a collection of behavioral parameter sets, with each parameter set assigned a likelihood value. The collection of behavioral parameter sets will be used to develop uncertainty bounds for the flood-frequency relationships.

Objective Functions for Goodness-of-Fit Measures of Historical Floods
There are a number of objective functions cited in the literature[1,2,7,11,28] that have been used as goodness-of-fit measures for comparing observed and simulated streamflows. Two measures were utilized in this analysis that includes the Nash-Sutcliffe Efficiency measure[11] and a modification of the objective function used by the US COE in the HEC-1 watershed model[28].

The Nash-Sutcliffe Efficiency (NSE) measure is computed as:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Qobs_i - Qsim_i)^2}{\sum_{i=1}^{n} (Qobs_i - \overline{Qobs})^2} \right] \tag{3}$$

where: $Qobs_i$ is the observed streamflow at time i; $Qsim_i$ is the simulated streamflow at time i, and $\overline{Qobs}$ is the average discharge for the time interval of interest $(i=1 \text{ to } n)$.

Review of the formulation for NSE indicates it is essentially a coefficient of determination as is common to regression analyses. It represents the portion of the variance in observed discharges that is explained by the simulated discharges. A value of 0.90 for NSE indicates that 90% of the variance in the observed hydrograph is explained by the simulation. A perfect match between observed and simulated discharges would yield a NSE value of one. The NSE measure places equal weight on all streamflow comparisons without regard to the magnitude of the streamflows.

Figure 7a depicts a comparison between simulated and observed discharges at North Fork Dam for the February 1986 flood event. In this example, streamflows above approximately 10,000 cfs (Feb 15-21, 1986) were used in computing NSE. A graphical depiction of the NSE measure for this simulation is shown in Figure 7b.

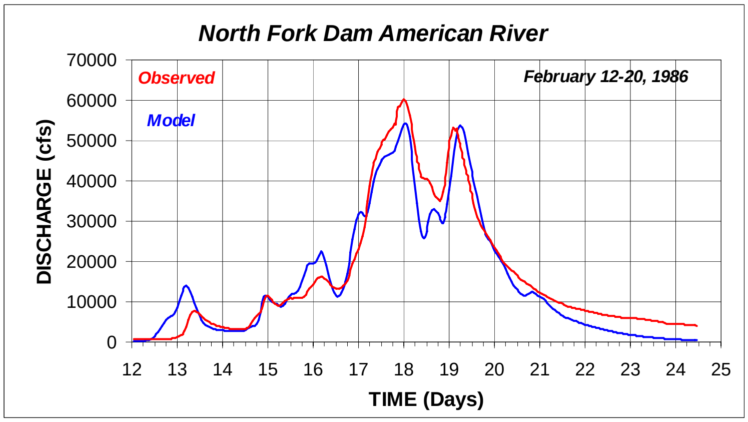

Figure 7a – Example Comparison between Simulated and Observed Streamflows at North Fork Dam for the February 1986 Flood Event

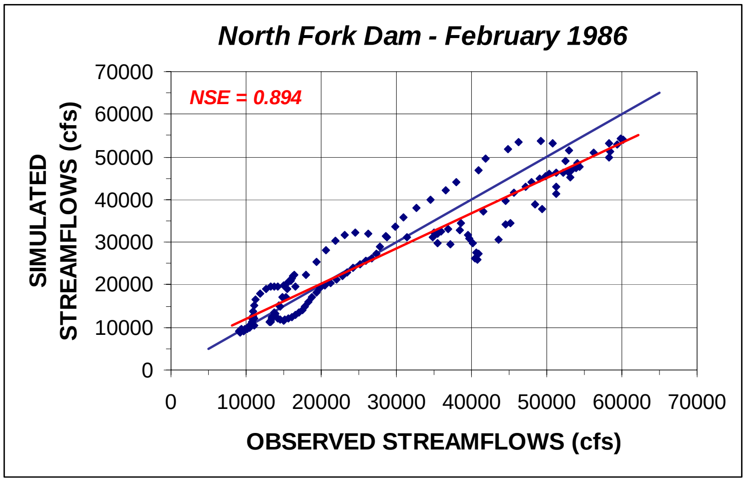

Figure 7b – Example of Nash-Sutcliffe Efficiency Measure for the February 1986 Flood at North Fork Dam

The USCOE objective function[28] is the second objective function that was considered. It was designed for usage on a single hydrograph. It has been modified here for usage on multiple flood hydrographs with different flood peak discharges. The modified USCOE objective function (OF_{hec}) is computed as:

$$OF_{hec} = \sum_{i=1}^{n} \left(\frac{Qobs_i - Qsim_i}{\overline{Qobs}} \right)^2 \frac{WT_i}{n} \tag{4a}$$

$$WT_i = \frac{(Qobs_i + \overline{Qobs})}{2\overline{Qobs}} \tag{4b}$$

Examination of Equation 4a indicates that the first group of terms is analogous to the square of the coefficient of variation for the residuals. The second term (WT_i) is a weighting function that gives greater weight to the fit near the flood peak and lesser weight for smaller discharges near the tails of the flood hydrograph. A perfect match between observed and simulated discharges would yield an OF_{hec} value of zero.

Both objective functions were computed for each flood hydrograph for each flood event. Three flood hydrographs were used for comparing simulated flows to observed flows for each flood event. This involved using recorded hydrographs for some combination of sites on the North Fork, Middle Fork, South Fork, and inflow to Folsom Dam. This situation required that an objective function be computed for the flood event by combining the goodness-of-fit measures from the various sites. This was accomplished as a weighted sum of the objective functions with weighting factors based on the drainage area above the point where the flood data were recorded. For the general case:

$$\Omega_g = \sum_{j=1}^{n} \Omega_j \, W_j \qquad (5a)$$

where: Ω_g is the group measure of the objective function for a given flood event; Ω_j is the objective function for the recorded flood hydrograph at site *j*; W_j is a weighting factor where the weighting factors sum to unity for the multiple flood observation sites; as applied W_j was computed as the drainage area for site *j*, divided by the summation of drainage areas for the multiple sites. In this computation, the drainage area weighting factor for the Folsom Dam recording site was reduced by 50% to reduce the effect of double counting of drainage area for the other streamflow recording sites in the watershed.

The modified USCOE objective function was utilized in this study for identifying behavioral parameter sets. Substitution into Equation 5a yields:

$$OFhec_g = \sum_{j=1}^{n} OFhec_j \, W_j \qquad (5b)$$

where: $OFhec_g$ is the group measure of the objective function for a given flood event observed at multiple sites; $OFhec_j$ is the objective function for the recorded flood hydrograph at site *j*.

Likelihood Measures

Likelihood measures were used in the calibration process to assist in identification of those behavioral parameter sets that were most likely to produce a watershed model that are well-suited to depicting the flood response to extreme storm events.

A likelihood measure can be computed for a parameter set for a flood event at a given site and can also be computed for flood events at multiple sites. Parameter sets that are rejected as non-behavioral are assigned a likelihood of zero. The likelihood (L_s) of a parameter set that is determined to be behavioral at a specific site is computed as:

$$L_s = \left(\frac{1}{OF_{hec}} \right)^M \qquad (6a)$$

The likelihood (L_k) of a parameter set that is determined to be behavioral for a given flood event at multiple sites is computed as:

$$L_k = \left(\frac{1}{OF_{hec_g}} \right)^M \qquad (6b)$$

where: L_s is the likelihood measure for a parameter set for a given flood event at site *s*; L_k is the likelihood measure for flood event *k*; M is a user-specified parameter.

As indicated above, each parameter set has a separate likelihood value for each flood event. In computing the likelihood measure, selection of $M=0$ yields all behavioral parameter sets equally likely. As $M \rightarrow \infty$, the likelihood for the parameter set with the single best simulation will dominate over all over likelihood values. The value of *M* was set to 1 for these analyses as suggested by Beven et al[1,2].

The likelihood value for each parameter set for the group of flood events is computed as the weighted average of the likelihood for each flood event, as:

$$Lps = \sum_{k=1}^{n} L_k \, W_k \tag{7}$$

where: L_{ps} is the likelihood measure for a given parameter set for the group of flood events; L_k is the likelihood measure for flood event *k*; W_k is a weighting factor for flood event *k*, where the weighting factors sum to unity for the multiple flood events. Equal weighting factors were used for computing the likelihood measure for the group of flood events.

Lastly, the probability of occurrence of a given parameter set (Pps) is computed as the likelihood of that parameter set (Lps_i) divided by the summation of likelihood for all *n* behavioral parameter sets.

$$Pps = \frac{Lps_i}{\sum_{i=1}^{n} Lps_i} \tag{8}$$

The probability computations shown in Equation 8 were not used in this analysis but will be used in the future in conducting the uncertainty analysis. Equation 8 is shown here for convenience of the reader to show how the likelihood values relate to probabilities for use in a resampling scheme.

CALIBRATION OF THE HEC-1 WATERSHED MODEL

The HEC-1 model was calibrated using all of the hydrometeorological data previously described for the four historical floods. This included: the precipitation temporal and spatial templates that were developed for dates of the historical floods[22]; the antecedent precipitation and antecedent snowpack information described previously; and the initial reservoir storage levels for the reservoirs that were in existence at the time of the flood events. The same computational routines were used for calibration that will be used in the stochastic modeling of extreme floods. This included routines for: spatial distribution of antecedent precipitation and antecedent snowpack; soil moisture accounting; snow compaction and snowmelt runoff computation; and computation of surface and interflow runoff volumes and hydrographs.

Prior investigations and calibrations by the USCOE[29] and USBR[27] yielded surface runoff unit-hydrographs and channel routing parameters that reasonably reproduced the timing and magnitude of peak discharges for several historical floods. Given their prior success in validating the unit-hydrographs and channel routing parameters, these watershed parameters were not included in the calibration process.

The GLUE process focused on identifying behavioral parameter sets for the soil moisture storage capacity (S_{max}), maximum surface infiltration rate (f_{max}), minimum surface infiltration rate (f_c), and deep percolation rate (f_d) for each of the soil zones. Identification of behavioral parameter sets can be a computationally laborious task when there are a large number of parameters to be considered. The general approach is to start with wide limits on the bounds for parameter values and then to progressively restrict those limits based on the flood responses.

The behavior/sensitivity for a given parameter can be examined by a scatterplot that depicts values of the individual parameter and the goodness-of-fit measure for the parameter set used to generate the flood response. For example, Figure 8 depicts a scatterplot of NSE measures associated with deep percolation rates in soil zone 3 for the results of flood simulations for 1000 parameter sets as compared against the January 1997 flood hydrograph recorded at the Auburn Dam site. The general trend is clear with lower values of deep percolation for soil zone 3 producing better matches to the observed hydrograph. Using an NSE value of 0.85 as a preliminary threshold for behavioral parameter sets, it is seen that deep percolation rates for soil 3 less than about 0.08 in/hr are possible elements of behavioral parameter sets. Larger deep percolation rates are associated with non-behavioral flood responses.

These type of scatterplots can be helpful in understanding the flood responses for parameters that are dominant factors. However, scatterplots may provide little assistance for parameters that are not significant contributors to the flood response. This is often the case for soils that occupy a small portion of the watershed tributary to a recording stream gage, and generally when there are a large number of parameters.

An efficient approach to utilizing the GLUE method is to start by analyzing a wide range of values for each of the parameters and progressively narrowing the plausible range of values based on the simulated flood response. This iterative approach to calibration was accomplished in three phases as described in the following sections.

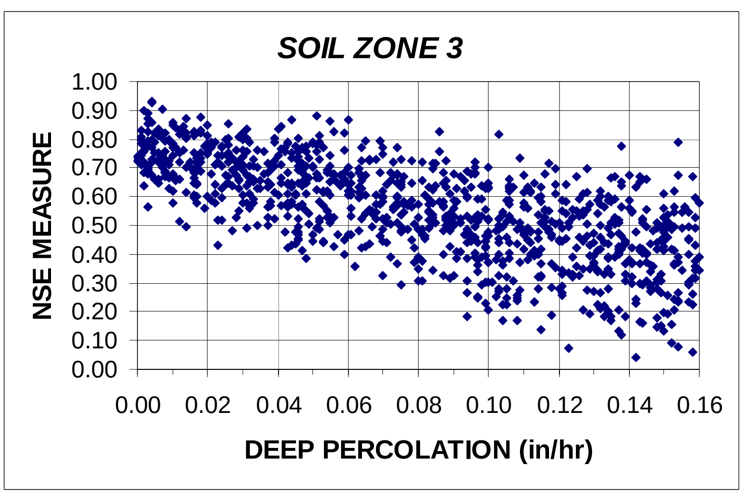

Figure 8 – Scatterplot of Nash-Sutcliffe Efficiency Measures versus Deep Percolation Rates for Soil Zone 3 in Simulating Flood Hydrographs for the January 1997 Flood Observed at the Auburn Dam Site

Phase I Calibration

The first phase of calibration was conducted by examining the flood responses to a very wide range of values for each parameter. One-thousand parameter sets were generated by standard Monte Carlo sampling methods for the four soil parameters listed above for each of the soil zones. Sampling was conducted from the uniform distribution using very wide lower and upper bounds to avoid an early commitment to the range of plausible parameter values. The very dry antecedent conditions associated with the October 1962 flood event and the very wet antecedent conditions associated with the January 1997 were most useful in examining the flood response of the watershed model. Therefore, the first phase of calibration was executed for each of the parameter sets using antecedent conditions and the model configuration appropriate for October 1962 and January 1997.

Comparisons were made between observed and simulated hydrographs. It was found that the observed October 1962 hydrographs could only be replicated using much larger initial losses than indicated by the soil moisture storage capacity for the soil depths listed in Table 3. It was concluded that the weathered and fractured bedrock immediately underlying the soil units[24] was responding as an extension of the soil column. Thus, the effective soil moisture storage capacity was much greater than indicated by simple computation from the soils information contained in the STATSGO database. This runoff behavior for dry antecedent conditions was confirmed by Mr. Robert Collins of the Sacramento District[5] who stated that "6 to 8-inches of precipitation commonly occur at the start of the fall rainy season before any runoff is produced from the watershed". Subsequent analysis of the November 1950 flood, which also occurred following relatively dry antecedent conditions, confirmed the need for large moisture storage capacity to replicate the observed 1950 flood hydrographs.

Scatterplots were examined for all of the soil parameters, in a manner similar to Figure 8, to determine where sampling bounds could be restricted. The next round of simulations then focused on sampling over a more narrow range of parameter values (see Table 10).

Phase II Calibration

A second group of 1000 parameter sets was generated by standard Monte Carlo sampling methods for the four soil parameters for each of the soil zones. Sampling was conducted from the uniform distribution using lower and upper bounds as indicated in Table 10. The HEC-1 watershed model was executed for each of the parameter sets using antecedent conditions and the model configuration appropriate for the Nov 1950 and Jan 1997 floods, respectively. The February 1986 flood was not use in this phase because it was being reserved for model verification. NSE and likelihood measures were computed for flood comparisons at each of the streamflow measurement sites (Tables 6 and 9).

Scatterplots were prepared to examine the sensitivity/behavior of the flood response to values of the soil parameters. Figure 9 depicts an example scatterplot of likelihood values versus deep percolation rate for soil zone 8 for the January 1997 flood hydrograph recorded on the South Fork. This type of result was used for further narrowing of the sampling bounds for the soil parameters (see Table 11).

Table 10 – Lower and Upper Bounds Used for Sampling Soil Parameters for Phase II Calibration

SOIL ZONE	STATSGO SOIL MOISTURE STORAGE CAPACITY (IN)	DEEP PERCOLATION (IN/HR)	MINIMUM SURFACE INFILTRATION (IN/HR)	MAXIMUM SURFACE INFILTRATION (IN/HR)	EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (IN)	COMMENTS
1	0.00	0.00	0.00	0.00	0.0	water bodies
2	0.80	0.00 – 0.10	Deep Perc + 0.00 to 0.14	1.0 – 5.0	0.8 – 16.8	
3	2.40	0.00 – 0.10	Deep Perc + 0.00 to 0.14	1.0 – 5.0	2.4 – 18.4	
4	4.00	0.00 – 0.10	Deep Perc + 0.00 to 0.14	1.0 – 5.0	4.0 – 20.0	
5	5.60	0.00 – 0.10	Deep Perc + 0.00 to 0.14	1.0 – 5.0	5.6 – 21.6	
6	8.00	0.00 – 0.10	Deep Perc + 0.00 to 0.14	1.0 – 5.0	8.0 – 24.0	
7	5.76	0.00 – 0.10	Deep Perc + 0.00 to 0.14	1.0 – 5.0	5.8 – 21.8	
8	6.40	0.00 – 0.10	Deep Perc + 0.00 to 0.14	1.0 – 5.0	6.4 – 22.4	

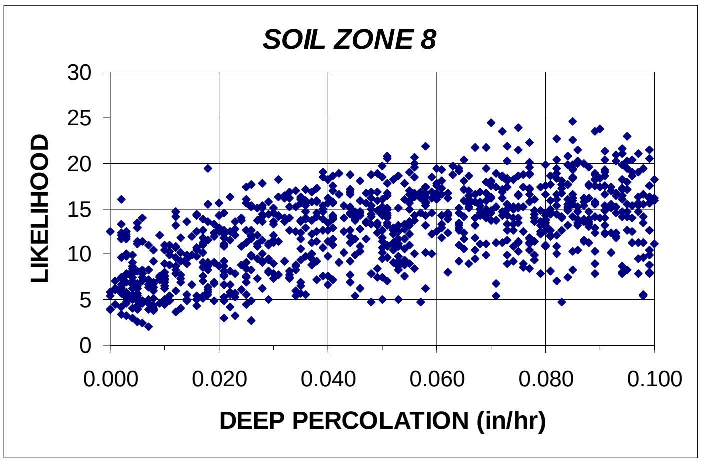

Figure 9 – Scatterplot of Likelihood Values versus Deep Percolation Rates for Soil Zone 8 for the South Fork of the American River near Lotus for the January 1997 Flood

Phase III Calibration

The lower and upper parameter bounds had been sufficiently narrowed during the Phase I and Phase II simulations that reasonable efficiency could be attained in Monte Carlo sampling to identify behavioral parameter sets. The approach was to use the November 1950 and January 1997 floods for identification of a "best-fit" parameter set. That parameter set was then used to simulate the February 1986 for verification of the calibration. Once the calibration had been verified, the February 1986 flood was incorporated into the GLUE process to further refine the calibration and the behavioral parameter sets that would be used in the future in conducting the uncertainty analysis.

Three-thousand parameter sets were generated by standard Monte Carlo sampling methods for the four soil parameters for each of the soil zones. Sampling was conducted from the uniform distribution using lower and upper bounds as indicated in Table 11. The HEC-1 watershed model was executed for each of the parameter sets using antecedent conditions and the model configuration appropriate for the November 1950 and January 1997 floods, respectively. NSE and likelihood measures were computed for flood comparisons at each of the streamflow measurement sites.

Table 11 – Lower and Upper Bounds Used for Sampling Soil Parameters for Phase III Calibration

SOIL ZONE	STATSGO SOIL MOISTURE STORAGE CAPACITY (IN)	DEEP PERCOLATION (IN/HR)	MINIMUM SURFACE INFILTRATION (IN/HR)	MAXIMUM SURFACE INFILTRATION (IN/HR)	EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (IN)	COMMENTS
1	0.00	0.00	0.00	0.00	0.0	water bodies
2	0.80	0.00 – 0.07	Deep Perc + 0.01 to 0.08	2.0 – 5.0	3.0 – 13.0	
3	2.40	0.00 – 0.07	Deep Perc + 0.01 to 0.08	2.0 – 5.0	8.0 – 16.0	
4	4.00	0.00 – 0.07	Deep Perc + 0.01 to 0.08	2.0 – 5.0	6.0 – 18.0	
5	5.60	0.00 – 0.07	Deep Perc + 0.01 to 0.08	2.0 – 5.0	8.0 – 20.0	
6	8.00	0.00 – 0.07	Deep Perc + 0.01 to 0.08	2.0 – 5.0	14.0 – 22.0	
7	5.76	0.00 – 0.07	Deep Perc + 0.01 to 0.08	2.0 – 5.0	12.0 – 20.0	
8	6.40	0.03 – 0.10	Deep Perc + 0.01 to 0.08	2.0 – 5.0	12.0 – 20.0	

<u>Calibration of Linear Reservoir Routing Routine for Hydrograph Recession Limb</u> – The hydrograph recession was simulated by a linear reservoir routing routine, wherein the input to the linear reservoir was provided by the computed interflow component of runoff. In calibrating the watershed model, it was found that the goodness-of-fit measures were relatively insensitive to the simulation of the recession limb(s) of the flood hydrographs. Trial and error investigation resulted in selection of a two-stage linear reservoir routine (cascade of linear reservoirs), that provided an acceptable match with the observed data.

In the linear reservoir routing routine, storage (S) in the linear reservoir at a given time is determined by the product of the storage constant (K) and the outflow (O) from the linear reservoir at that time.

$$S = KO \tag{9a}$$

Studies of linear reservoirs (Linsley etal[34], Overton[35], and Viesmann etal[36]) have shown that the storage constant can be expressed as a function of some characteristic response time for the system, such as the time lag between peak rates of input and output. Using this approach, the storage constant (K) for each subbasin was conceptually defined as a function of the time-lag for surface runoff, and a subsurface delay that was a function of the STATSGO soil depth. Specifically:

$$K = T_{lagsurface} + T_{subsurface} \tag{9b}$$

$$T_{subsurface} = C_{subsurface}\,(D_{soil}) \tag{9c}$$

where: K is the storage constant; $T_{lagsurface}$ is the time lag for the surface runoff unit-hydrograph for a given subbasin; $T_{subsurface}$ is a time delay associated with the interflow response; $C_{subsurface}$ is a coefficient found by calibration; and D_{soil} is the subbasin areal-average soil depth obtained from analysis of the STATSGO data (Table 3).

In relative terms, larger values of the storage constant produce more attenuated interflow hydrographs and sustained recession limbs. It would be expected that a smaller value of K would be associated with subbasins with thin surficial soils and predominately steep slopes. Larger K values would be expected for subbasins with deeper surficial soils, mild slopes, or highly fractured bedrock. Equations 9b,c provide a simple method for small subbasins with thin soils to have smaller values of K than larger subbasins with deeper soils. The form of Equation 9c provides a mechanism such that one parameter value ($C_{subsurface}$) can be used to set K for simulation of each of the subbasins in the watershed.

A $C_{subsurface}$ value of 3.5 was found through the calibration process to adequately simulate the recession limbs of the observed flood hydrographs. For example, Equations 9a,b,c yield a storage constant (K) of 17.5 hours for subbasin 2A on the North Fork of the American River. This value is representative of the magnitude of the storage constant for each of the linear reservoirs in the two-stage routing routine for many of the subbasins.

Identification of Behavioral Parameter Sets

Behavioral parameter sets were identified using a combination of the NSE and modified USCOE ($OFhec_g$) measures. The NSE measure is more intuitive in that it can be viewed as a coefficient of determination (Figure 7b) between observed and simulated flood hydrographs. The modified USCOE measure has the advantage of giving greater weight to matching the larger discharges in the flood hydrographs. As a first approximation, a minimum NSE value of 0.850 was set as the threshold for identifying behavioral parameter sets. The minimum NSE value was increased to 0.900 for the February 1986 flood and 0.930 for the January 1997 flood to limit the number of behavioral parameter sets for these two floods (last row Table 12).

In application, the modified USCOE measure was utilized for identifying behavioral parameter sets based on relationships developed between the NSE and USCOE measures for the various flood events. This relationship was needed to provide consistency of application between flood events because the USCOE measure varies with the shape of the flood hydrograph (Equations 4a,b). Figure 10 depicts an example relationship between NSE and modified USCOE measures. Table 12 lists summary information about the range and magnitudes of objective function measures for the Nov 1950, Feb 1986 and Jan 1997 flood events.

Review of Table 12 indicates a relatively large number of behavioral parameter sets for the Feb 1986 and Jan 1997 floods. However, in many cases, a parameter set that is deemed behavioral for one flood event is found to be non-behavioral for one or both of the other flood events. Of the sample of 3000 parameter sets, only 29 parameter sets were found to be behavioral for all three flood events.

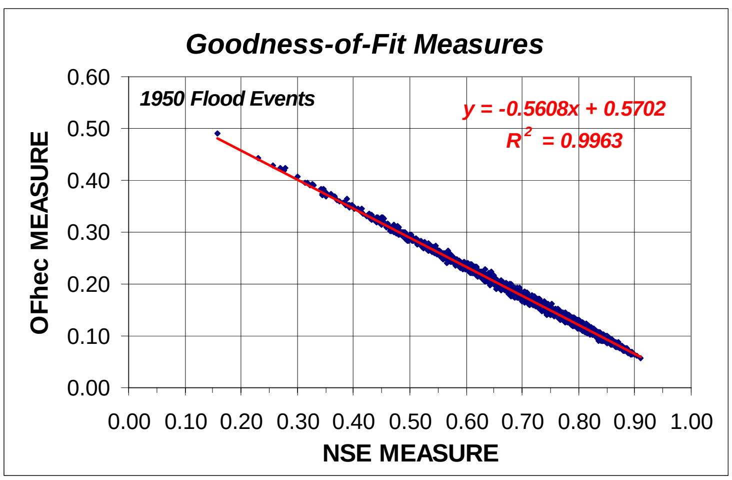

Figure 10 – Relationship of Nash-Sutcliffe Efficiency (NSE) Measure to Modified USCOE Goodness-of-Fit Measure for November 1950 Flood Event

Table 12 – Summary of Goodness-of-Fit Measures
for Sample of 3000 Parameter Sets from Phase III Calibration

GOODNESS-OF-FIT MEASURE	NOV 1950 FLOOD EVENT	FEB 1986 FLOOD EVENT	JAN 1997 FLOOD EVENT
NSE MEASURES			
Best Simulation	0.911	0.926	0.952
Approximate Behavioral Threshold	0.850	0.900	0.930
Median Value	0.748	0.880	0.924
Worst Simulation	0.159	0.708	0.812
$OFhec_g$ MEASURES			
Worst Simulation	0.491	0.117	0.184
Median Value	0.150	0.049	0.067
Behavioral Threshold	0.093	0.042	0.062
Best Simulation	0.057	0.032	0.042
Number of Behavioral Parameter Sets	199	563	1105

Identification of First-Stage Calibrated Parameter Set

The first-stage calibrated parameter set was identified utilizing the behavioral parameter sets obtained from simulation of the Nov 1950 and Jan 1997 flood hydrographs. Eighty-eight parameter sets, out of the sample of 3000 parameter sets, were found to be behavioral for both the Nov 1950 and Jan 1997 flood events. Likelihood measures (Equation 7) were computed for these 88 parameter sets using the likelihood measures from each flood event (Equations 5b and 6b). The top ten parameter sets based on the highest combined likelihood measure (Equation 7) were then identified. A mean value was computed for each parameter based on the parameter values within the top ten parameter sets. The parameter values obtained from this procedure are listed in Table 13 and are deemed the "first-stage calibrated parameter set".

Table 13 – First Stage Calibrated Parameter Set based on GLUE Procedures
Applied to Nov 1950 and Jan 1997 Flood Events

SOIL ZONE	MEDIAN SOIL DEPTH (IN)	DEEP PERCOLATION (IN/HR)	MINIMUM SURFACE INFILTRATION (IN/HR)	MAXIMUM SURFACE INFILTRATION (IN/HR)	EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (IN)	COMMENTS
1	0	0.000	0.000	0.00	0.0	water bodies
2	5	0.023	0.068	3.25	5.5	very shallow soils over bedrock
3	15	0.020	0.074	3.25	11.1	
4	25	0.043	0.099	3.25	10.3	
5	35	0.014	0.064	3.25	13.7	
6	50	0.028	0.072	3.25	19.5	
7	36	0.024	0.075	3.25	13.0	underlain by deep outwash soils
8	40	0.071	0.129	3.25	16.4	fractured and/or tilted bedrock

VERIFICATION OF CALIBRATED PARAMETER SET

The first-stage calibrated parameter set was verified by simulation of the February 1986 flood at the North Fork Dam, USGS gaging station on the South Fork near Lotus, and as inflow to Folsom Dam. The results of the simulations are shown in Figures 11a,b,c,d and goodness-of-fit measures are listed in Table 14. A visual comparison of the observed and simulated hydrographs shows a high degree of similarity in the flood hydrographs. This is confirmed by the goodness-of-fit measures in Table 14 where the first-stage parameter set is determined to be behavioral for the 1986 flood event.

Table 14 – Goodness-of-Fit Measures for Verification of First-Stage Calibration Using February 1986 Flood Event

GOODNESS-OF-FIT MEASURE	NORTH FORK DAM	SOUTH FORK NEAR LOTUS	INFLOW FOLSOM DAM	1986 FLOOD EVENT
NSE MEASURE	0.905	0.916	0.899	0.906
OFhec MEASURES	0.0500	0.0261	0.0404	0.0372

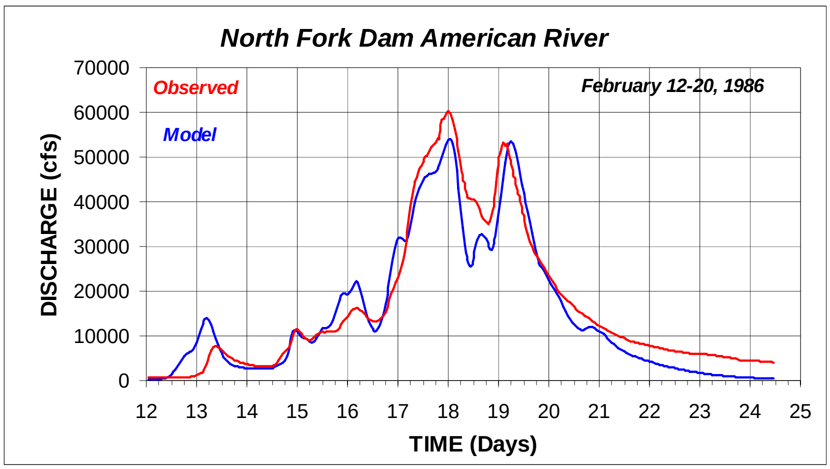

Figure 11a – Comparison of Simulated and Observed Flood Hydrographs for North Fork Dam on the American River for the February 1986 Flood Event for Verifying Calibration

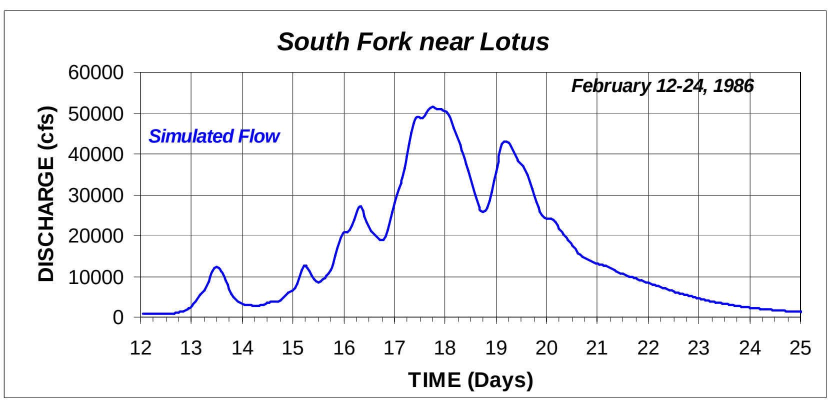

Figure 11b – Simulated Flood Hydrograph at the USGS Gaging Station 11-445500 on the South Fork of the American River for the February 1986 Flood Event for Verifying Calibration

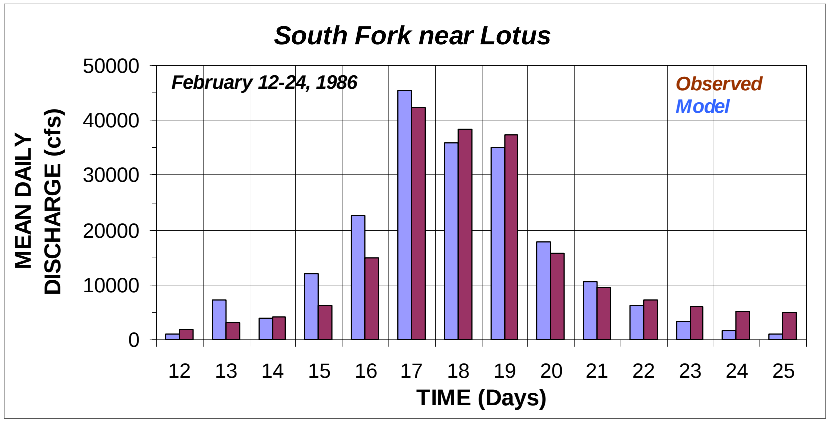

Figure 11c – Comparison of Simulated and Observed Mean Daily Discharges
at the USGS Gaging Station 11-445500 on the South Fork of the American River
for the February 1986 Flood Event for Verifying Calibration

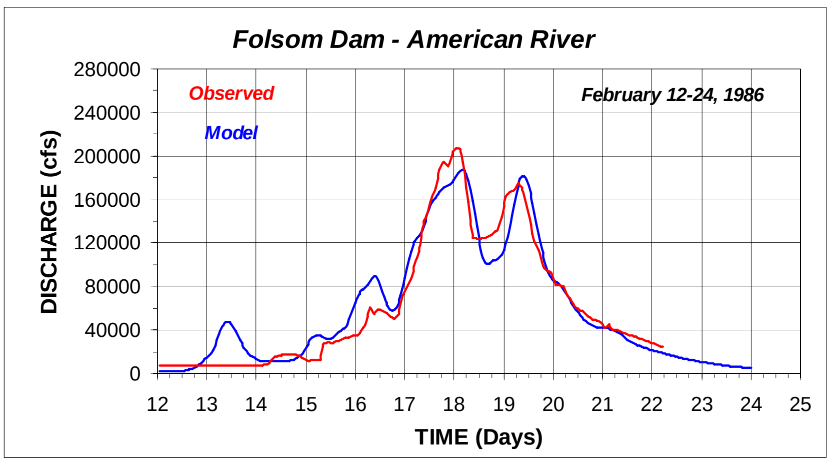

Figure 11d – Comparison of Simulated and Observed Flood Hydrographs
for Inflow to Folsom Dam on the American River for the February 1986 Flood Event
for Verifying Calibration

DETERMINATION OF FINAL CALIBRATED PARAMETER SET

After the first-stage calibrated parameter set had been verified, the Feb 1986 flood event was then incorporated into the GLUE process to improve the first-stage calibrated parameter set. This was done in a manner similar to that described previously for developing the first-stage calibrated parameter set. Only parameter sets that were determined to be behavioral for each of the Nov 1950, Feb 1986 and Jan 1997 flood events were considered. Twenty-nine parameter sets, out of the sample of 3000 parameter sets, were found to be behavioral for all three flood events (Appendix A). Likelihood measures (Equation 7) were computed for these 29 parameter sets using the likelihood measures from each flood event (Equations 5b and 6b).

The top ten parameter sets based on the highest combined likelihood measure (Equation 7) were then identified. A mean value was computed for each parameter based on the parameter values for the top ten parameter sets. These parameter values were used as a starting point for a trial and error process to yield a parameter set with the highest likelihood by comparison to the other 29 behavioral parameter sets. This was a practical approach to estimating a "calibrated parameter set" consistent with the traditional approach to calibration. The concept being that values of a given parameter for the parameter sets with the highest likelihood would have a tendency to cluster on a sensitivity plot (Figures 8,9). This clustering would tend to occur in a more narrow range within the sampling bounds for the given parameter. This approach follows the procedures developed by Lamb[11] who used Monte Carlo sampling and GLUE concepts to identify a group of behavioral parameter sets with the highest likelihood. He then used those parameter sets as a starting point for a trial and error solution of a (traditional) calibrated parameter set.

The suitability of this final calibrated parameter set was confirmed by simulation of the three flood events and computation of goodness-of-fit and likelihood measures. The parameter values obtained from this procedure are listed in Table 15 and are termed the "final calibrated parameter set". A comparison with Table 13 shows minor changes due to the addition of the Feb 1986 flood event. The final calibrated parameter set had the highest likelihood measure of the now 30 behavioral parameter sets (Appendix A).

Table 15 – Final Calibrated Parameter Set based on GLUE Procedures
Applied to Nov 1950, Feb 1986 and Jan 1997 Flood Events

SOIL ZONE	MEDIAN SOIL DEPTH (IN)	DEEP PERCOLATION (IN/HR)	MINIMUM SURFACE INFILTRATION (IN/HR)	MAXIMUM SURFACE INFILTRATION (IN/HR)	EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (IN)	COMMENTS
1	0	0.000	0.000	0.0	0.00	water bodies
2	5	0.022	0.071	3.2	3.80	very shallow soils over bedrock
3	15	0.016	0.071	3.2	11.30	
4	25	0.048	0.100	3.2	9.10	
5	35	0.023	0.065	3.2	13.70	
6	50	0.035	0.094	3.2	20.40	
7	36	0.023	0.060	3.2	12.60	underlain by deep outwash soils
8	40	0.078	0.136	3.2	17.10	fractured and/or tilted bedrock

Comparisons of simulated and observed hydrographs for the three flood events are shown in Figures 12a-g, 13a-e, and 14a-d. Goodness-of-fit measures (Table 16) were computed for all flood events and the final calibrated parameter set was found to behavioral. The standard error of estimate was also computed for comparison of observed and simulated flood hydrographs and values are listed in Table 16. The values of the standard error of estimate are all less than 10%. These values are all within the tolerances of inaccuracies commonly associated with measurement of streamflow, precipitation and other hydrometeorological inputs, and inaccuracies inherent to computer modeling algorithms.

Comparisons of instantaneous peak discharges and 3-day maximum discharges for observed and simulated hydrographs are shown in Table 17. Review of Table 17 shows a high degree of similarity for peak discharges and runoff volumes, particularly for the 3-day maximum discharges that have been traditionally considered a critical duration for operations at Folsom Dam.

In summary, the final calibrated parameter set yielded simulated hydrographs that satisfy the adopted goodness-of-fit measures. Therefore, the calibrated parameter set was judged suitable for conducting production runs of the stochastic flood model for the American River watershed.

Table 16 – Goodness-of-Fit Measures for Final Calibrated Parameter Set

GOODNESS-OF-FIT MEASURE	1950 FLOOD EVENT	1986 FLOOD EVENT	1997 FLOOD EVENT
Nash-Sutcliffe Efficiency (NSE) Measure	0.874	0.911	0.949
Modified USCOE ($OFhec_g$) Measure	0.0805	0.0351	0.0456
Standard Error of Estimate	9.0 %	6.2 %	3.8 %

Table 17 – 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%

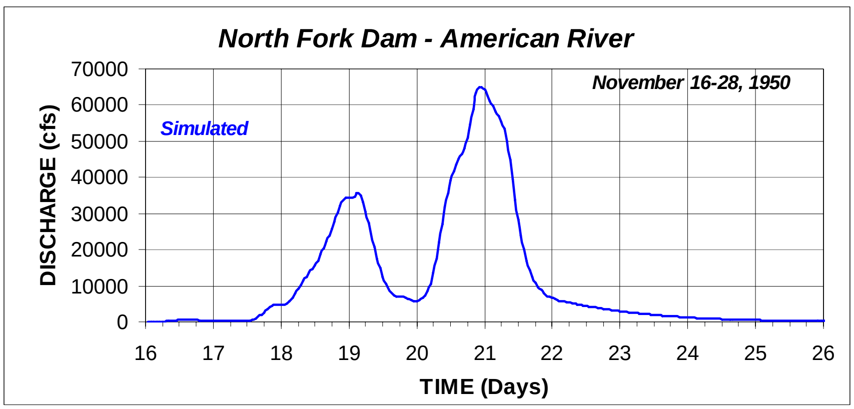

Figure 12a –Simulated Flood Hydrograph at North Fork Dam on the American River for the November 1950 Flood Event for Final Calibrated Parameter Set

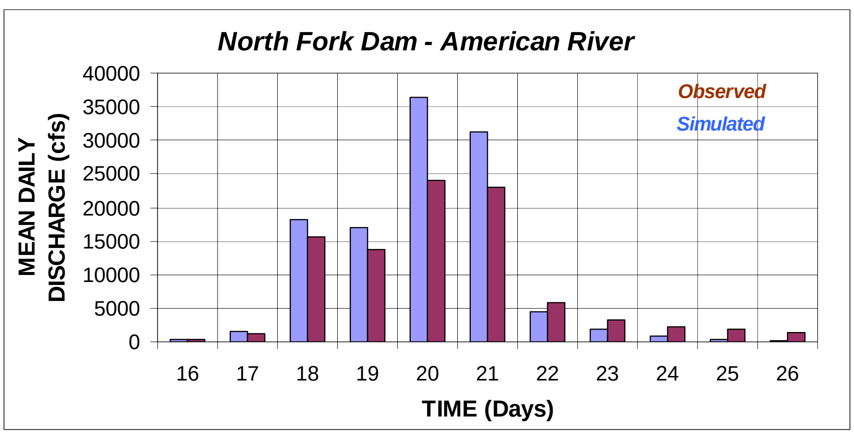

Figure 12b – Comparison of Simulated and Observed Mean Daily Discharges at the North Fork Dam on the American River for the November 1950 Flood Event for Final Calibrated Parameter Set

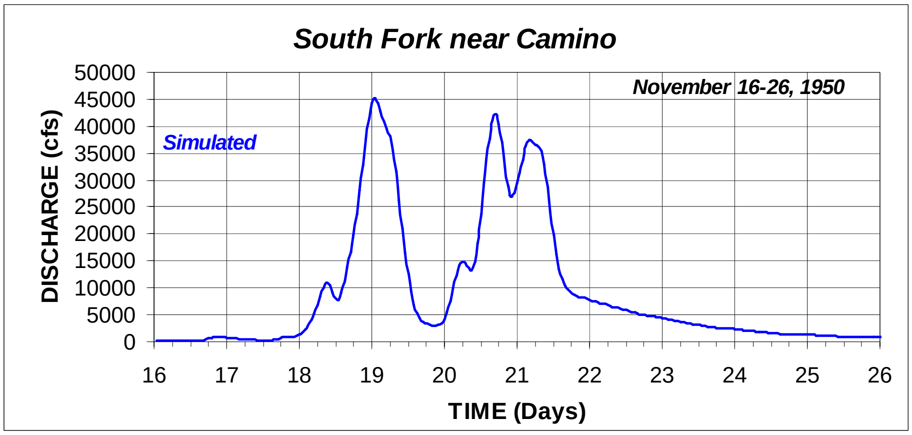

Figure 12c –Simulated Flood Hydrograph at USGS Gaging Station 11-443500 on the South Fork of the American River near Camino for the November 1950 Flood Event for Final Calibrated Parameter Set

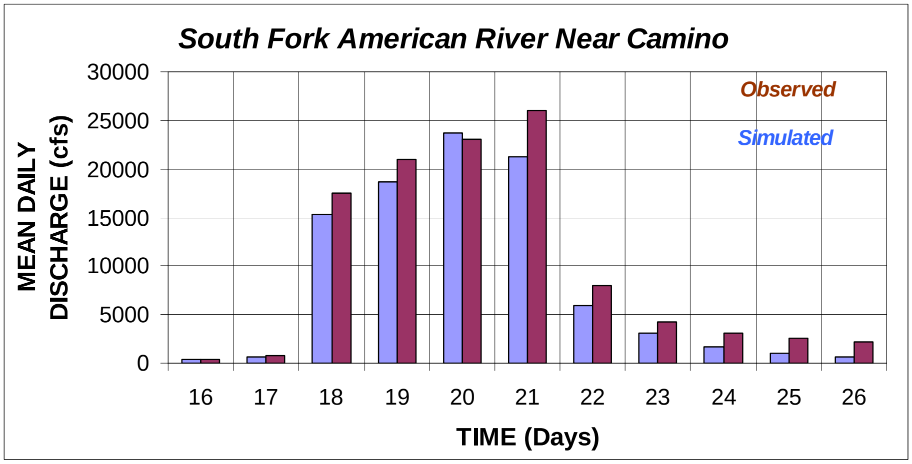

Figure 12d – Comparison of Simulated and Observed Mean Daily Discharges at USGS Gaging Station 11-443500 on the South Fork of the American River near Camino for the November 1950 Flood Event for Final Calibrated Parameter Set

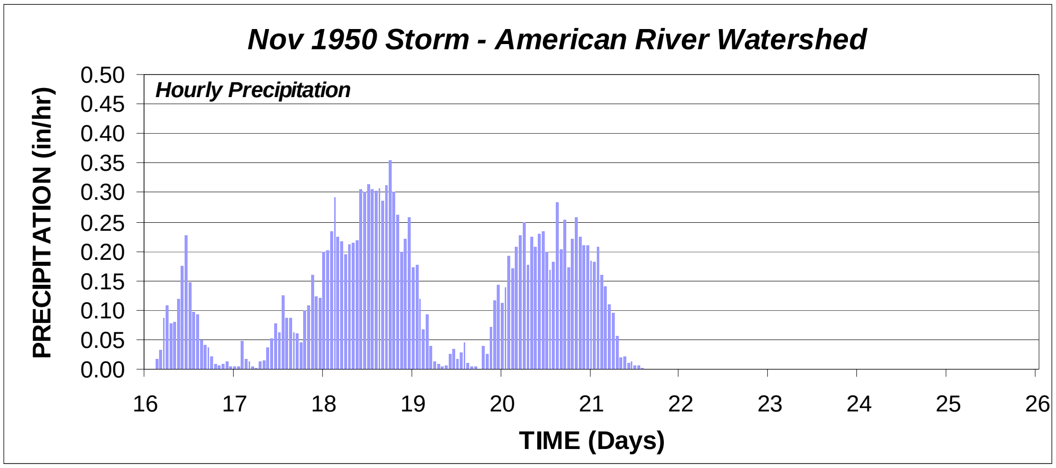

Figure 12e – Basin-Average Precipitation for 1862-mi^2 American River Watershed for Storm of November 16-21, 1950

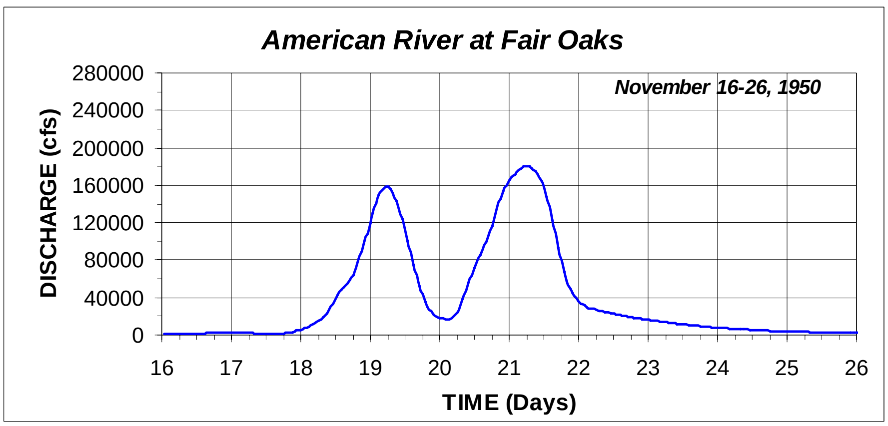

Figure 12f –Simulated Flood Hydrograph at USGS Gaging Station 11-446500 on the American River at Fair Oaks for the November 1950 Flood Event for Final Calibrated Parameter Set

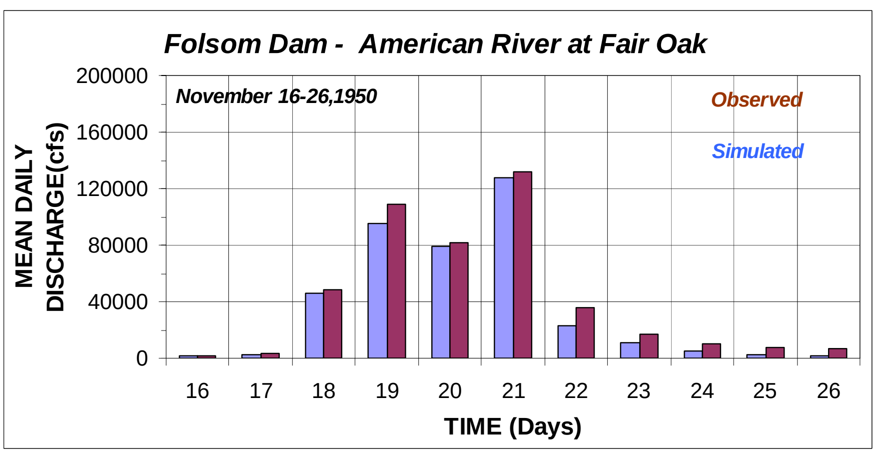

Figure 12g – Comparison of Simulated and Observed Mean Daily Discharges at USGS Gaging Station 11-446500 on the American River at Fair Oaks for the November 1950 Flood Event for Final Calibrated Parameter Set

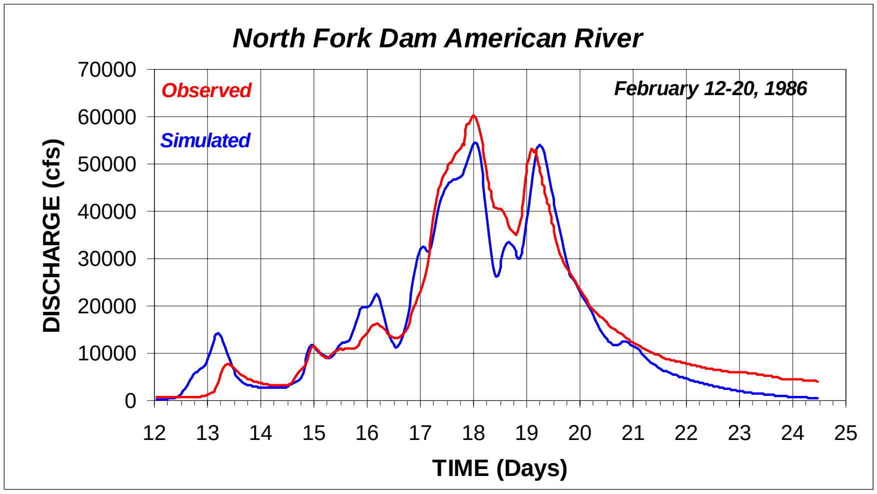

Figure 13a – Comparison of Simulated and Observed Flood Hydrographs for North Fork Dam on the American River for the February 1986 Flood Event for Final Calibrated Parameter Set

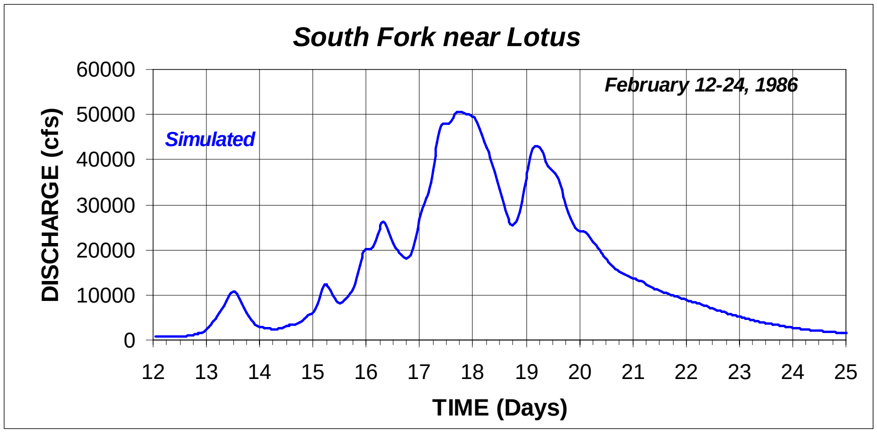

Figure 13b –Simulated Flood Hydrographs for USGS Gaging Station 11-445500 on the South Fork American River near Lotus for the February 1986 Flood Event for Final Calibrated Parameter Set

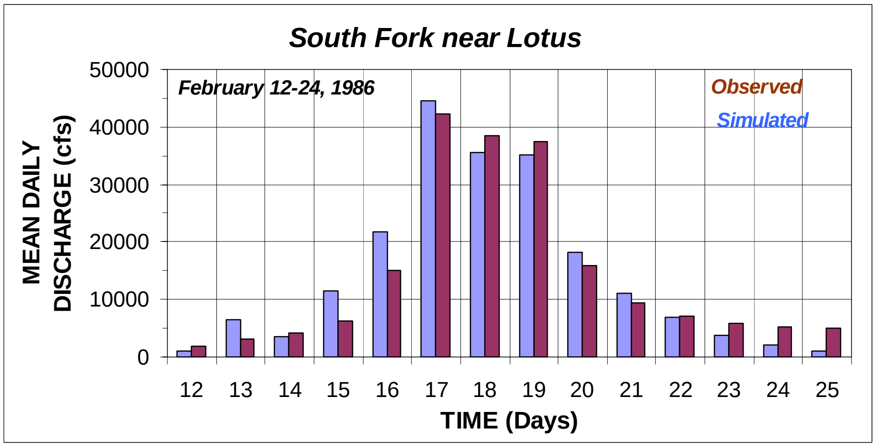

Figure 13c – Comparison of Simulated and Observed Mean Daily Discharges at the USGS Gaging Station 11-445500 on the South Fork of the American River for the February 1986 Flood Event for Final Calibrated Parameter Set

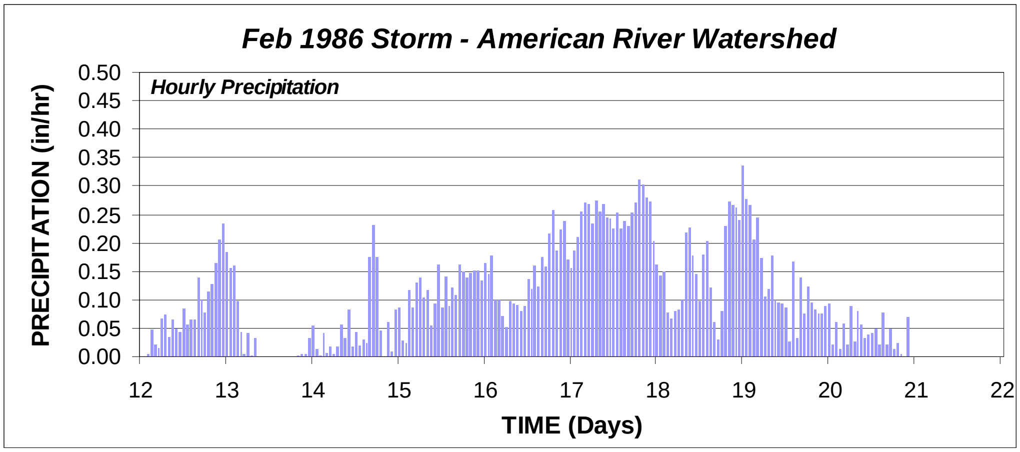

Figure 13d – Basin-Average Precipitation for 1862-mi^2 American River Watershed for Storm of February 12-21, 1986

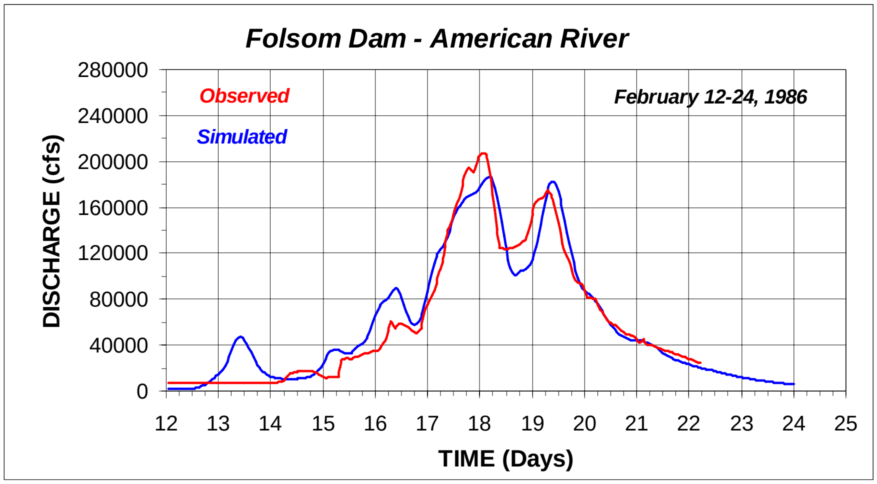

Figure 13e – Comparison of Simulated and Observed Flood Hydrographs for Inflow to Folsom Dam on the American River for the February 1986 Flood Event for Final Calibrated Parameter Set

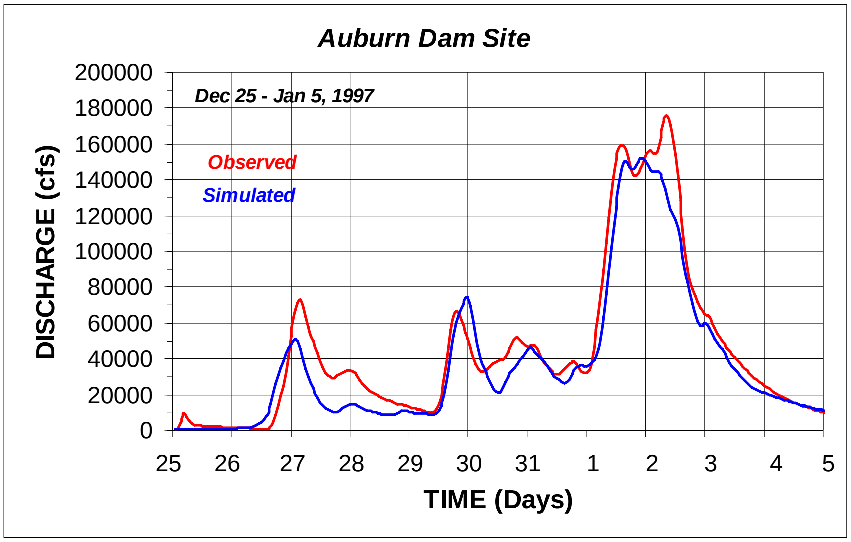

Figure 14a – Comparison of Simulated and Observed Flood Hydrographs at Auburn Dam Site on the American River for the January 1997 Flood Event for Final Calibrated Parameter Set

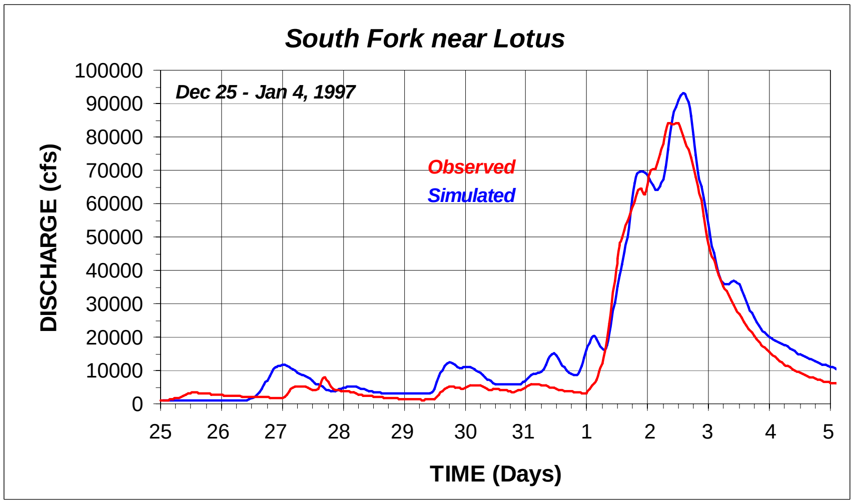

Figure 14b – Comparison of Simulated and Observed Flood Hydrographs for USGS Gaging Station 11-445500 on the South Fork American River near Lotus for the January 1997 Flood Event for Final Calibrated Parameter Set

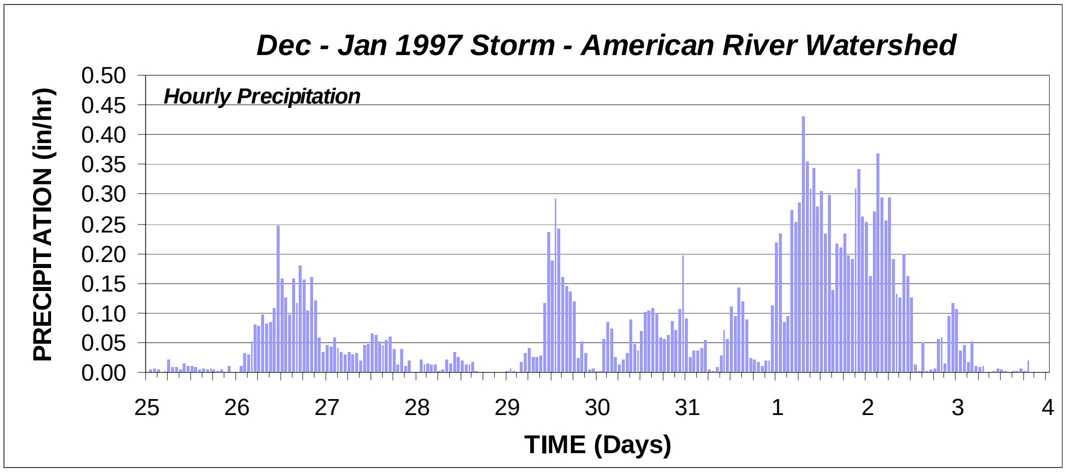

Figure 14c – Basin-Average Precipitation for 1862-mi^2 American River Watershed
for Storm of December 25, 1996 to January 3, 1997

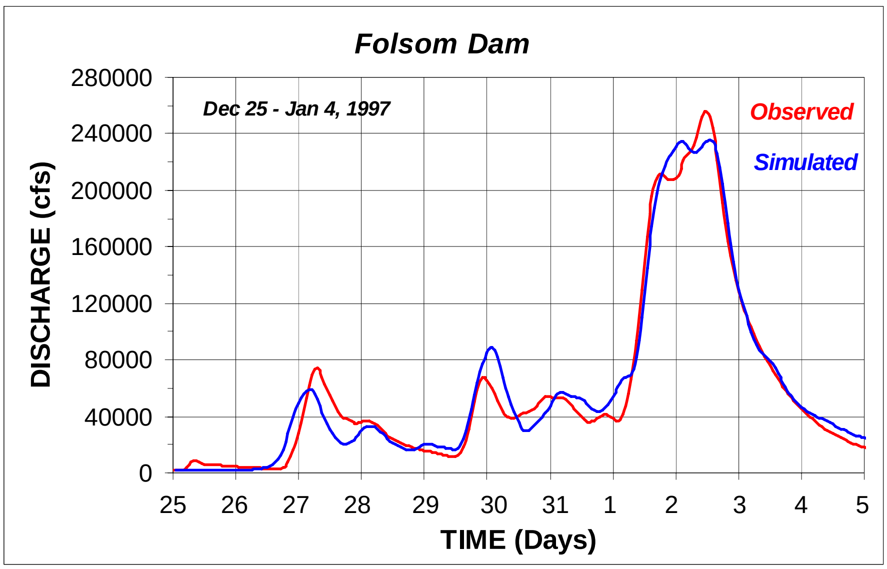

Figure 14d – Comparison of Simulated and Observed Flood Hydrographs
for Inflow to Folsom Dam on the American River
for January 1997 Flood Event for Final Calibrated Parameter Set

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APPENDIX A - LISTING OF BEHAVIORAL PARAMETER SETS

Table A1 – Listing of Behavioral Parameter Sets for Use in Developing Flood-Frequency Relationships for American River at Folsom Dam and Uncertainty Bounds for Flood-Frequency Relationships

PARAMETER SET NUMBER	DEEP PERCOLATION RATE (in/hr)								MIMIMUM SURFACE INFILTRATION RATE (in/hr)								MAXIMUM SURFACE INFILTRATION RATE (in/hr)	EFFECTIVE SOIL MOISTURE STORAGE CAPACITY (in)								LIKELIHOOD MEASURE
	SOIL ZONE								SOIL ZONE									SOIL ZONE								
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8	
FINAL CALIBRATED	0.000	0.022	0.016	0.048	0.023	0.035	0.023	0.078	0.000	0.071	0.071	0.100	0.065	0.094	0.060	0.136	3.2	0.00	3.80	11.30	9.10	13.70	20.40	12.60	17.10	24.43
1	0.000	0.025	0.007	0.070	0.006	0.069	0.012	0.042	0.000	0.046	0.081	0.128	0.070	0.137	0.024	0.111	3.7	0.00	5.74	8.69	10.22	16.06	19.75	12.48	17.78	23.64
2	0.000	0.015	0.000	0.052	0.015	0.060	0.012	0.079	0.000	0.034	0.057	0.115	0.086	0.076	0.092	0.152	2.0	0.00	6.43	13.33	6.52	11.17	17.48	14.30	13.95	22.98
3	0.000	0.000	0.009	0.006	0.024	0.055	0.053	0.088	0.000	0.042	0.078	0.038	0.084	0.119	0.104	0.138	4.5	0.00	3.79	11.30	10.93	15.38	21.89	13.07	16.07	22.75
4	0.000	0.024	0.017	0.054	0.019	0.009	0.039	0.097	0.000	0.042	0.059	0.131	0.091	0.020	0.054	0.171	2.3	0.00	3.04	10.08	9.63	16.94	21.74	13.01	18.62	22.68
5	0.000	0.020	0.030	0.037	0.069	0.016	0.037	0.082	0.000	0.035	0.066	0.111	0.100	0.091	0.084	0.148	2.4	0.00	3.49	8.14	6.08	14.01	21.99	12.39	16.15	22.05
6	0.000	0.025	0.004	0.057	0.034	0.035	0.023	0.096	0.000	0.045	0.057	0.090	0.059	0.105	0.097	0.155	4.3	0.00	3.51	11.05	8.25	9.44	14.42	16.06	19.28	22.05
7	0.000	0.038	0.041	0.051	0.037	0.025	0.010	0.096	0.000	0.075	0.081	0.087	0.116	0.063	0.047	0.166	3.3	0.00	4.96	12.76	6.13	9.33	21.42	12.10	14.89	21.95
8	0.000	0.019	0.004	0.067	0.015	0.018	0.006	0.094	0.000	0.095	0.030	0.126	0.044	0.087	0.070	0.162	2.2	0.00	4.27	9.85	17.03	14.76	16.50	12.41	12.31	21.88
9	0.000	0.022	0.013	0.041	0.069	0.058	0.023	0.060	0.000	0.095	0.059	0.120	0.103	0.115	0.076	0.085	4.0	0.00	5.50	12.04	8.68	8.33	16.80	13.96	19.07	21.59
10	0.000	0.020	0.030	0.010	0.045	0.063	0.048	0.081	0.000	0.047	0.106	0.040	0.069	0.124	0.071	0.142	4.3	0.00	3.17	9.55	11.84	11.23	18.65	12.70	14.45	21.50
11	0.000	0.024	0.060	0.006	0.033	0.033	0.016	0.081	0.000	0.095	0.137	0.038	0.046	0.107	0.089	0.123	3.7	0.00	6.38	15.44	9.32	9.72	21.97	14.00	13.10	21.31
12	0.000	0.013	0.032	0.004	0.000	0.060	0.001	0.078	0.000	0.077	0.101	0.054	0.011	0.114	0.024	0.113	2.4	0.00	5.33	13.31	7.83	18.23	14.05	18.21	19.70	21.06
13	0.000	0.039	0.031	0.038	0.037	0.049	0.010	0.068	0.000	0.117	0.091	0.081	0.081	0.093	0.037	0.135	2.4	0.00	4.89	10.38	11.14	12.22	14.38	14.33	14.87	20.83
14	0.000	0.050	0.044	0.031	0.063	0.040	0.007	0.066	0.000	0.105	0.099	0.053	0.126	0.108	0.027	0.142	3.9	0.00	4.38	8.37	12.69	10.67	14.31	12.97	18.58	20.75
15	0.000	0.011	0.027	0.054	0.007	0.060	0.032	0.074	0.000	0.048	0.068	0.123	0.085	0.139	0.088	0.085	4.5	0.00	3.27	15.23	6.61	9.92	19.81	15.57	17.75	20.72
16	0.000	0.016	0.041	0.051	0.010	0.028	0.018	0.097	0.000	0.046	0.100	0.081	0.021	0.092	0.088	0.158	4.1	0.00	3.39	13.78	13.06	12.31	17.55	13.60	15.40	20.52
17	0.000	0.062	0.027	0.045	0.011	0.050	0.016	0.056	0.000	0.084	0.088	0.123	0.053	0.079	0.060	0.136	2.3	0.00	4.12	14.75	7.92	13.88	14.12	17.50	17.62	20.52
18	0.000	0.046	0.021	0.033	0.019	0.014	0.038	0.077	0.000	0.073	0.086	0.059	0.073	0.032	0.075	0.153	5.0	0.00	5.49	10.63	6.42	10.83	21.70	13.84	17.50	20.43
19	0.000	0.050	0.064	0.007	0.025	0.035	0.026	0.079	0.000	0.124	0.105	0.061	0.036	0.092	0.050	0.157	2.9	0.00	4.08	8.64	17.14	11.13	14.14	12.65	17.95	20.35
20	0.000	0.029	0.012	0.044	0.041	0.048	0.051	0.089	0.000	0.058	0.077	0.120	0.073	0.059	0.065	0.124	4.0	0.00	4.28	13.36	7.37	14.33	16.55	12.74	17.05	20.14
21	0.000	0.048	0.015	0.009	0.067	0.068	0.030	0.061	0.000	0.118	0.075	0.024	0.138	0.093	0.090	0.125	2.8	0.00	7.22	14.23	10.09	11.06	14.87	12.47	19.07	19.97
22	0.000	0.020	0.055	0.014	0.024	0.067	0.024	0.063	0.000	0.062	0.074	0.039	0.052	0.083	0.078	0.131	4.8	0.00	8.35	13.36	6.48	9.47	21.82	13.43	19.36	19.92
23	0.000	0.025	0.009	0.023	0.032	0.012	0.052	0.080	0.000	0.091	0.046	0.095	0.079	0.071	0.097	0.159	2.1	0.00	3.77	12.57	12.85	10.73	17.38	14.08	17.49	19.81
24	0.000	0.026	0.063	0.001	0.061	0.020	0.009	0.095	0.000	0.098	0.084	0.033	0.119	0.048	0.058	0.170	2.1	0.00	4.03	13.22	7.28	15.36	20.32	14.11	15.16	19.80
25	0.000	0.034	0.056	0.038	0.043	0.048	0.004	0.086	0.000	0.091	0.100	0.118	0.067	0.115	0.017	0.133	4.8	0.00	11.66	14.52	8.01	10.30	14.55	13.06	12.39	19.63
26	0.000	0.028	0.039	0.033	0.039	0.033	0.010	0.068	0.000	0.068	0.086	0.085	0.102	0.100	0.058	0.082	3.7	0.00	6.64	12.78	10.84	12.91	21.41	12.10	16.76	19.63
27	0.000	0.019	0.030	0.054	0.016	0.061	0.031	0.058	0.000	0.049	0.095	0.102	0.093	0.136	0.056	0.080	2.4	0.00	5.55	8.13	9.25	11.95	16.98	14.58	14.79	19.60
28	0.000	0.039	0.046	0.003	0.005	0.051	0.045	0.063	0.000	0.073	0.106	0.036	0.023	0.077	0.081	0.132	4.9	0.00	3.83	15.33	7.75	8.34	20.70	15.19	18.56	19.46
29	0.000	0.001	0.047	0.021	0.064	0.063	0.022	0.076	0.000	0.031	0.082	0.057	0.099	0.075	0.055	0.151	2.9	0.00	6.94	9.18	7.29	10.58	21.40	15.59	19.68	19.42