US Army Corps
of Engineers
Hydrologic Engineering Center

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

Appendix E - Description of Stochastic Storm Resampling Approach and Selection of Prototype Storms for Resampling

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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DESCRIPTION OF STOCHASTIC STORM RESAMPLING APPROACH AND SELECTION OF PROTOTYPE STORMS FOR RESAMPLING

October 9, 2002

OVERVIEW

The stochastic storm resampling approach is an adaptation of standard Monte Carlo sampling techniques[3,6]. Resampling is simply the use of Monte Carlo methods for the random selection of a variate/event from a fixed group of possible variates/events. In this application, an event is comprised of the spatial and temporal distribution of precipitation over the American River watershed. Analyses of historical storms allow the determination of the spatial and temporal distributions of precipitation and the results are used to develop a spatial and temporal template for each historical storm. Detailed discussions of the methods used for conducting storm analyses and developing storm templates have been presented in prior reports[9].

Storm templates are used because they have been found to simplify application of the resampling approach in rainfall-runoff modeling. The spatial distribution for a given storm is described by a *spatial template*. For the case of the American River watershed, the spatial template is comprised of thirty-three 72-hour precipitation amounts, one 72-hour amount for each of the 33 sub-basins in the watershed.

The temporal distribution of precipitation for a given storm is described by a *temporal template*, where the temporal template is comprised of a collection of dimensionless storm mass curves. The number of dimensionless storm mass curves is equal to the number of sub-basins. The storm mass-curve for any particular sub-basin can be obtained by simple multiplication of the sub-basin dimensionless mass curve by the 72-hour precipitation amount for that sub-basin which is obtained from the spatial template. Thus, the system of spatial and temporal templates provides an easy way to store, view, and apply the spatial and temporal distributions of precipitation.

Thirty-seven historical storms[7] were analyzed and used to develop storm spatial and temporal templates. This included 31 storms with the largest 72-hour basin-average precipitation for the American River watershed[7,10] in the 1966-2002 period and 6 storms from the 1950-1964 period of frequent extreme storms. Twenty-four of the historical storms have been recommended for use in the stochastic storm resampling approach. The basis for that recommendation will be discussed in detail later in this report.

DESCRIPTION OF STORM TEMPLATES

The storm templates can best be described by example. The sub-basin layout for the HEC-1 watershed model to be used in the stochastic modeling of extreme floods has 33 sub-basins (Figure 1). The original HEC-1 watershed model that was used for Probable Maximum Flood computations by the Sacramento District had 29 sub-basins. The additional sub-basins are the result of subdivision of the North Fork of the American River into five sub-basins.

The spatial template for a given storm would have a separate 72-hour precipitation amount for each of the 33 sub-basins. The precipitation magnitudes would generally be greater in the headwaters than in the lower elevations due to orographic precipitation mechanisms, but there would be some variability in precipitation magnitudes across the watershed due to the storm track and location of the storm center(s).

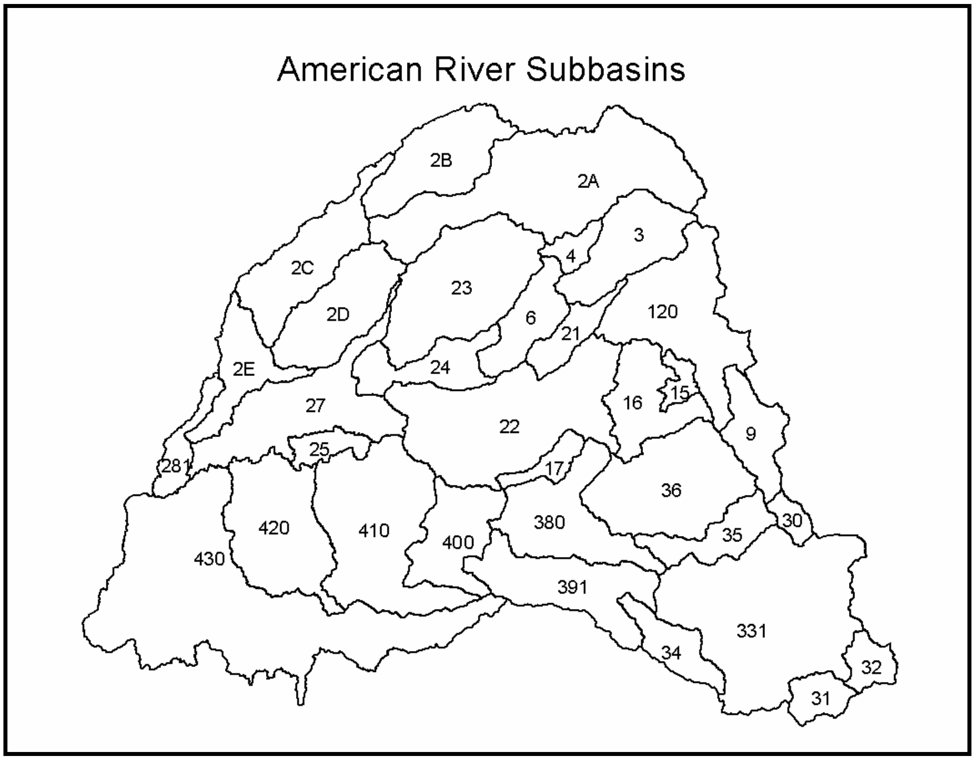

Figure 1 – 33 Sub-basin Layout used in HEC-1 Watershed Model for American River Watershed

As described previously, the storm temporal template for each storm is comprised of the collection of 33 dimensionless storm mass-curves, one per sub-basin. Figure 2 depicts an example of an observed incremental precipitation pattern; Figure 3a depicts a storm mass-curve for the observed incremental precipitation pattern; and Figure 3b depicts a dimensionless storm mass-curve that has been rescaled by the maximum 72-hour precipitation.

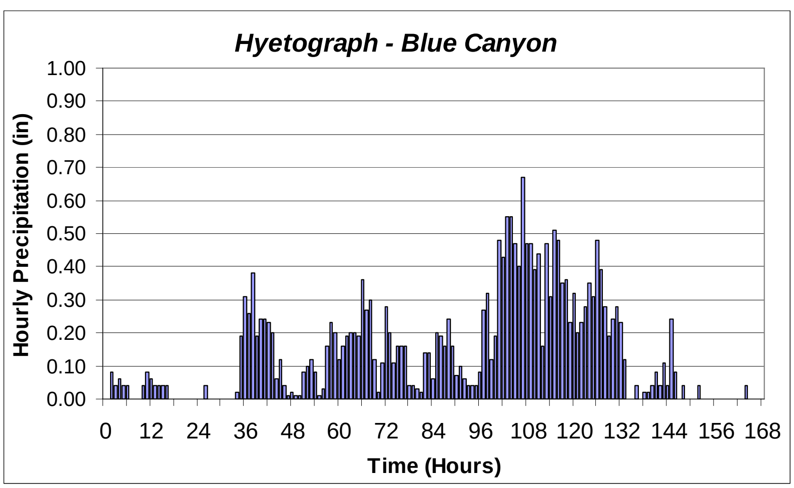

Figure 2 – Hourly Incremental Precipitation Pattern
for Storm of Dec 28, 1996 to Jan 3, 1997 at Blue Canyon Hourly Gage

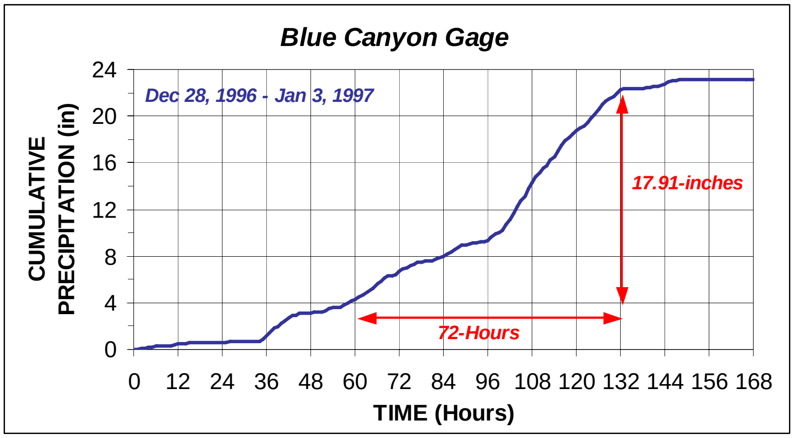

Figure 3a – Storm Mass Curve for Storm of Dec 28, 1996 to Jan 3, 1997
at Blue Canyon Hourly Gage

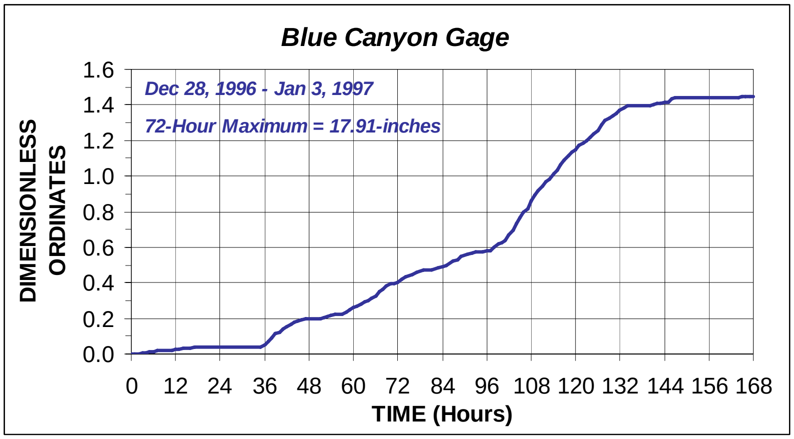

Figure 3b – Dimensionless Storm Mass Curve for Storm of Dec 28, 1996 to Jan 3, 1997
at Blue Canyon Hourly Gage

CANDIDATE PROTOTYPE STORMS

One of the important tasks for application of the resampling approach was the selection of the prototype storms to be used for resampling. Several criteria were established to assist in the selection of prototype storms. One criterion was that the largest storm events of the 37 historical storms should be preferred because the primary interest is modeling of extreme storms. However, if this criterion were strictly applied, only a limited number of storms would be selected because the storm dataset only includes a few very extreme storms.

Another desirable criterion was that a large number of storms should be used to allow adequate modeling of the spatial and temporal diversity of precipitation. This would provide the diversity of flood hydrograph shapes needed for a robust examination of reservoir response to floods. However, this approach could result in inclusion of many smaller storms that may not be representative of extreme storms when scaled to larger magnitudes.

A third criterion was established to avoid problems of excessive scaling of smaller storms. Any storm selected must be capable of being scaled by a factor of three without producing an implausible temporal distribution. A temporal distribution could be considered implausible for a variety of reasons. The primary concern is that it could contain short-duration bursts of precipitation markedly out of character relative to behavior experienced in the most extreme historical storms.

These three criteria were accommodated in several steps. First, candidate storms were identified that exceeded a 72-hour basin-average precipitation of 6.20-inches. This is near the basin-average mean annual maxima of 6.30-inches, and represents the upper 40% of the storms that would be contained in the annual maxima series. This threshold was chosen in attempting to utilize as large a storm sample as possible to provide diversity in the spatial and temporal distribution of precipitation while still giving preference to the larger storms. This selection procedure resulted in identification of 24 candidate storms.

Next, storm temporal characteristics were examined by comparing depth-duration ratios for the 24 candidate storms. Depth-duration ratios were computed for each storm by dividing the maximum *n*-hour basin-average precipitation by the 72-hour basin-average precipitation. Probability-plots of the depth-duration ratios for the 24 candidate storms for durations of 2-hours, 6-hours, 12-hours and 24-hours are depicted in Figures 4a,b,c,d. It is seen that the depth-duration ratio data for the 24 candidate storms are well described by a normal distribution and provide a reasonably high level of variability. This suggests the candidate storms should provide a high level of diversity in storm temporal distributions and resultant flood peaks and hydrograph shapes.

Comparisons were made between storms for depth-duration ratios for durations of 2-hours, 6-hours, 12-hours and 24-hours to identify any ratios that were markedly different from that of the group (Table 1). Two storms, December 1992 and January 1995, had several depth-duration ratios that were the largest of the 24 candidate storms. In addition, these two storms have basin-average precipitation near 7.00-inches and are two of the smaller storms in the sample set. This combination of characteristics raised concerns that unrealistically large short-duration precipitation intensities could result when these storms were scaled to the magnitude of extreme storms. Thus, additional tests were needed to make a determination if these two storms should continue to be considered for selection as prototype storms.

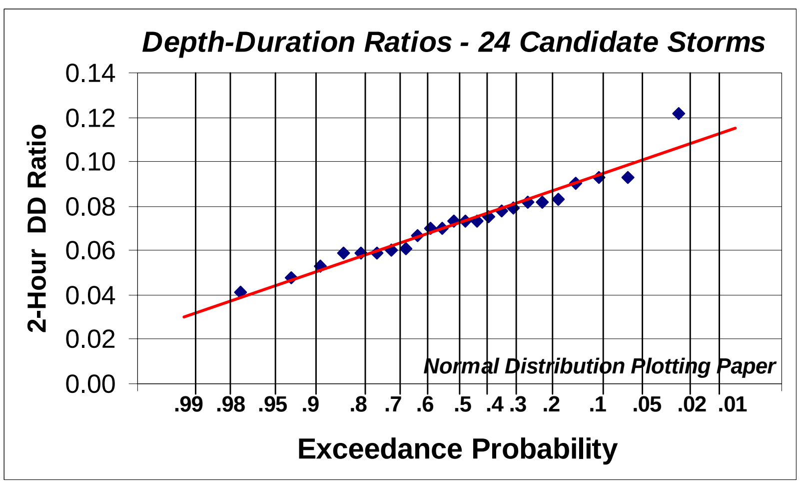

Figure 4a – Probability-Plot of 2-Hour Depth-Duration Ratios for 24 Candidate Storms

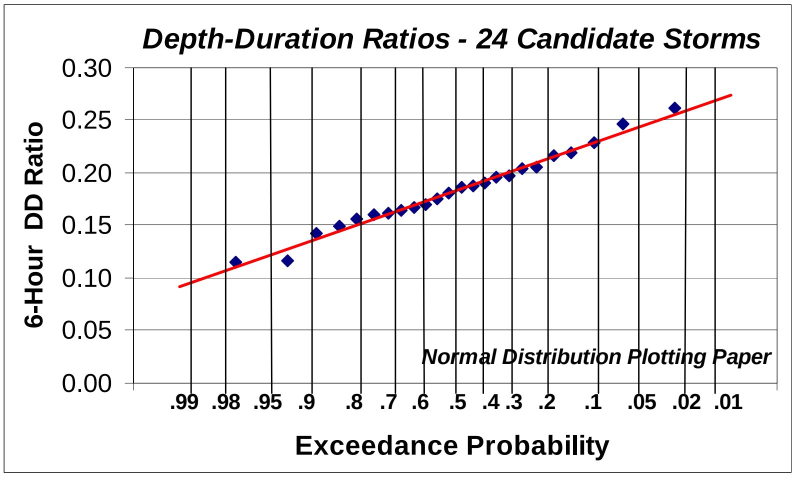

Figure 4b – Probability-Plot of 6-Hour Depth-Duration Ratios for 24 Candidate Storms

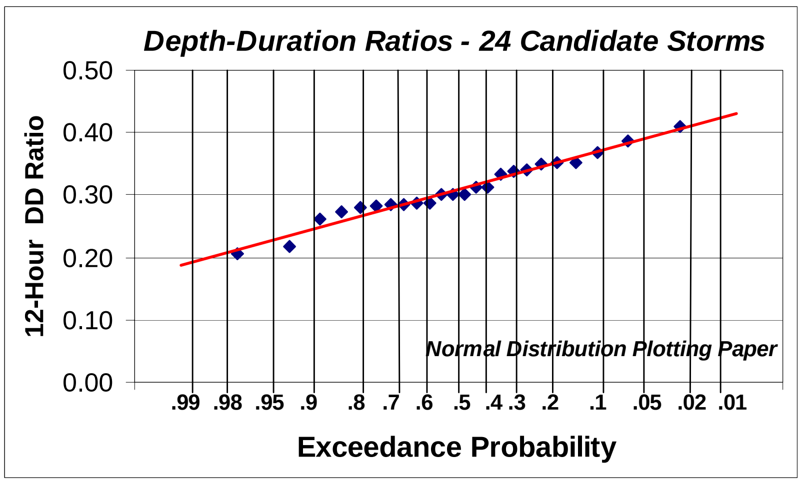

Figure 4c – Probability-Plot of 12-Hour Depth-Duration Ratios for 24 Candidate Storms

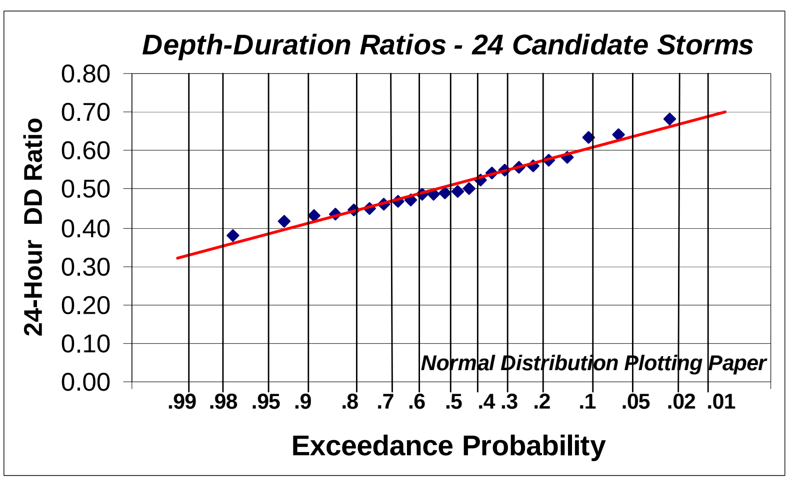

Figure 4d – Probability-Plot of 24-Hour Depth-Duration Ratios for 24 Candidate Storms

Table 1 – Depth-Duration Ratios for 24 Candidate Storms

STORM DATE TO INCLUDE	72-HOUR BASIN-AVERAGE PRECIPITATION (in)	DEPTH-DURATION RATIOS – RATIO TO 72-HOUR PRECIPITATION			
		2-HOUR	6-HOUR	12-HOUR	24-HOUR
12 Oct 1962	14.05	0.0670	0.1750	0.2620	0.4880
15 Feb 1986	13.99	0.0410	0.1150	0.2170	0.4160
20 Dec 1955	13.81	0.0600	0.1600	0.3020	0.4360
21 Dec 1964	12.47	0.0590	0.1430	0.2800	0.4860
20 Nov 1950	12.46	0.0530	0.1500	0.2870	0.5000
02 Feb 1963	11.39	0.0730	0.1960	0.3390	0.5240
01 Jan 1997	11.22	0.0700	0.1810	0.3120	0.5840
20 Jan 1969	10.34	0.0480	0.1170	0.2060	0.3790
12 Jan 1980	9.94	0.0610	0.1560	0.3010	0.4330
08 Feb 1999	8.41	0.0590	0.1620	0.2840	0.4600
22 Dec 1982	8.24	0.0730	0.1670	0.2720	0.4710
20 Dec 1981	8.17	0.0590	0.1640	0.2840	0.5490
15 Feb 1982	8.17	0.0820	0.2040	0.3530	0.5570
10 Mar 1995	7.93	0.0730	0.1700	0.2820	0.4500
12 Dec 1995	7.88	0.0930	0.2190	0.3670	0.6430
09 Feb 1962	7.36	0.0750	0.1900	0.3410	0.4940
09 Jan 1995	7.35	0.1220	0.2610	0.3340	0.5740
09 Dec 1992	7.19	0.0930	0.2460	0.4090	0.6330
25 Jan 1967	7.05	0.0780	0.1970	0.3530	0.6820
13 Nov 1981	6.77	0.0900	0.2290	0.3870	0.5610
16 Jan 1970	6.46	0.0820	0.1870	0.3500	0.4920
17 Feb 1980	6.39	0.0700	0.1860	0.2880	0.4460
28 Jan 1981	6.37	0.0790	0.2170	0.3130	0.5420
12 Nov 1973	6.20	0.0830	0.2050	0.3020	0.4680

Another check on the suitability of the candidate storms was made by scaling the candidate storms to a 72-hour basin-average precipitation of 19-inches (Appendix A). This equates to an Annual Exceedance Probability (AEP) of 10^{-3} for 72-hour basin-average precipitation. The incremental precipitation patterns for basin-average precipitation were then examined to determine if any of the incremental precipitation patterns contained anomalous behavior or were otherwise implausible. It was noticed that several storms had brief periods of relatively high precipitation intensities including the previously mentioned December 1992 and January 1995 storm events. While these short-duration precipitation intensities were noticeably larger that contained in other storms, there was nothing that warranted an outright rejection of these or any other storms. At this stage all 24 candidate storms were judged to be plausible realizations of extreme storms.

Another check on the suitability of the 24 candidate storms was made by conducting rainfall-runoff modeling of the scaled 19.0-inch storms and examining the resultant flood hydrographs. The rainfall-runoff modeling was conducted using the PMP/PMF version of the HEC-1 watershed model developed by Mr. Robert Collins of the Sacramento District. The simulations were conducted with a uniform loss rate of 0.10-inch/hour and without snowmelt contribution. These computer simulations were not intended to replicate any particular condition. Rather, they were intended to provide a common ground for examining the effect of the different temporal and spatial distributions of precipitation.

The results of the rainfall-runoff modeling comparisons are depicted in Figures 5a,b,c for flood peak discharge, maximum 24-hour discharge, and maximum 72-hour discharge, respectively. It is seen that the flood discharges are well behaved and exhibit high variability due to the variability in the spatial and temporal distributions of precipitation. Prior concerns about the large bursts of short-duration precipitation in the December 1992 and January 1995 storms did not materialize as both flood events ranked near the middle of the flood dataset.

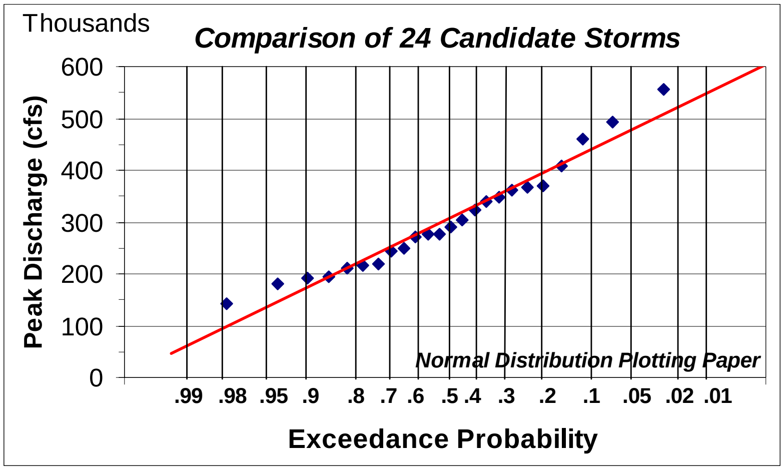

Figure 5a – Probability-Plot of Flood Peak Discharge Produced by 24 Candidate Storms
Scaled to have a 72-Hour Basin-Average Precipitation of 19.0-inches

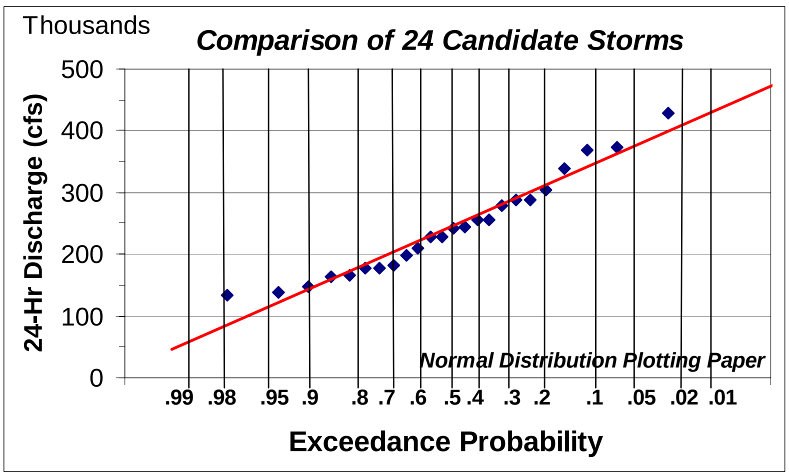

Figure 5b – Probability-Plot of Maximum 24-Hour Discharge Produced by 24 Candidate Storms
Scaled to have a 72-Hour Basin-Average Precipitation of 19.0-inches

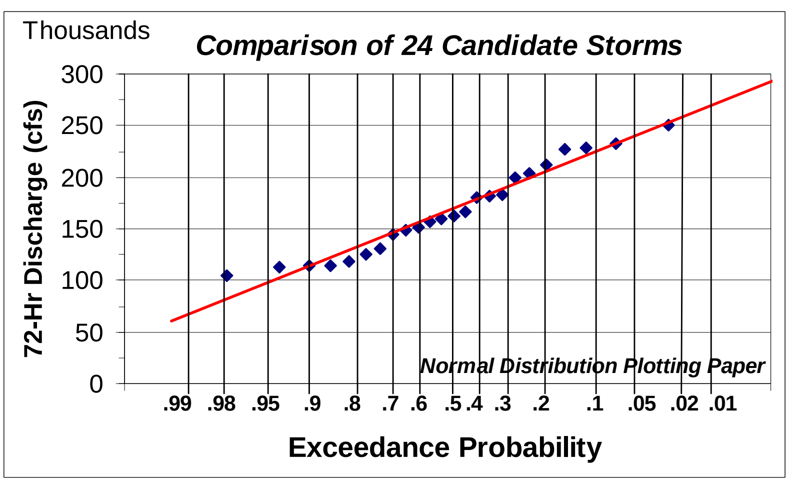

Figure 5b – Probability-Plot of Maximum 72-Hour Discharge Produced by 24 Candidate Storms
Scaled to have a 72-Hour Basin-Average Precipitation of 19.0-inches

A final issue relates to the scaling of storms. Linear scaling procedures are traditionally used by meteorologists[5] and hydrologists for scaling storms. Smaller historical storms require greater scaling than larger historical storms to achieve the magnitudes of extreme storms. Thus, the higher level of scaling could result in excessive enhancement of some storm characteristics if the true meteorological scaling process were non-linear rather than being nearly linear.

This situation was examined by splitting the historical storms into two sample sets. One group contained the 12 largest historical storms based on 72-hour basin-average precipitation (Table 1) and the second group contained the remaining 12 smaller storms. The results of the rainfall-runoff modeling exercise were then used to prepare probability-plots that identified the floods associated with the groups of larger and smaller storms. It should be noted that all storms have been scaled to have 72-hour basin-average precipitation of 19.0-inches (AEP of 10^{-3}). Therefore, differences in flood discharge are attributable to the differences in the spatial and temporal storm patterns. The results are shown in Figures 6a,b,c for peak discharge, and maximum 24-hour and 72-hour flood discharge, respectively.

It is seen that there is a high degree of overlap between the floods produced by storms created using storm templates from the largest and smallest candidate storms. Sample statistics from the datasets were similar, with the greatest differences in sample statistics occurring for peak discharge and lesser differences for maximum 24-hour and 72-hour discharge. The results for peak discharge (Figure 6a) are suggestive that there may be some minor effects of excessive scaling of short-duration precipitation intensities for some of the smaller storms. This is indicated by a greater number of the largest floods are produced by storm templates created from the smaller storms. However, these effects are muted at the longer 24-hour and 72-hour durations (Figures 6b,c), where there is a more random arrangement of floods attributable to the largest and smallest storms. Reservoir levels at Folsom Dam are more responsive to maximum flood discharges at the 24-hour and 72-hour durations than to peak discharge. Therefore, the benefits gained from additional storm temporal distributions would be far more important than a minor bias for peak discharge that may be present due to scaling of smaller candidate storms.

The reasonableness of accepting the results from the two groups of storms as being equivalent was examined by conducting a standard two-sample t-test. The null hypothesis of equal mean values was tested against the alternative that the mean values were not equal. The null hypothesis of equal mean values could not be rejected at the 5% level for either the peak discharge or the maximum 24-hour or 72-hour flood discharges. The t-tests results had p-values of 0.159, 0.294, and 0.674 for peak discharge, 24-hour and 72-hour discharges, respectively. It was concluded that the two sample sets of storm templates could be considered to be realizations from the same parent population.

After consideration of all of the information discussed above, the 24 candidate storms were deemed acceptable as prototype storms for use in the stochastic resampling approach. Appendix A depicts incremental precipitation patterns for each of the 24 prototype storms scaled to a have 72-hour basin-average precipitation of 19.0-inches. A review of the high diversity in storm temporal patterns and sequences of storm events indicates the prototype storms should produce floods with a high variability of flood peak discharges, runoff volumes, and hydrograph shapes. This diversity should provide a robust test of dam and reservoir performance under a wide variety of flood conditions.

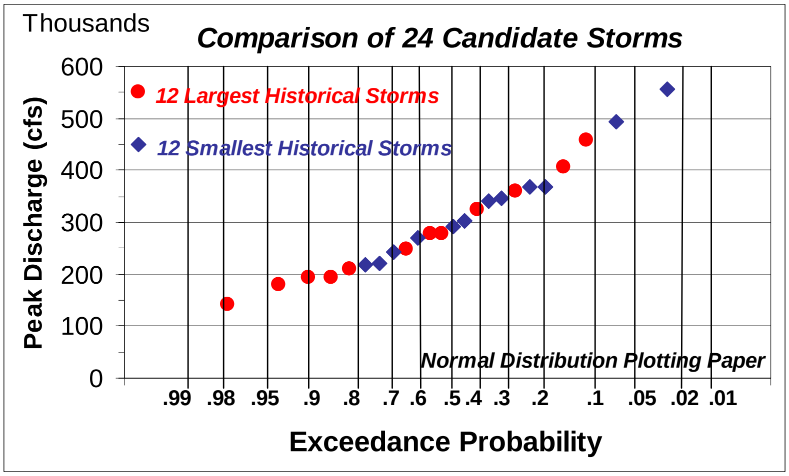

Figure 6a – Probability-Plot of Flood Peak Discharge Produced by 24 Candidate Storms
Comparison of Floods Produced by Largest 12 and Smallest 12 Candidate Storms
Scaled to have a 72-Hour Basin-Average Precipitation of 19.0-inches

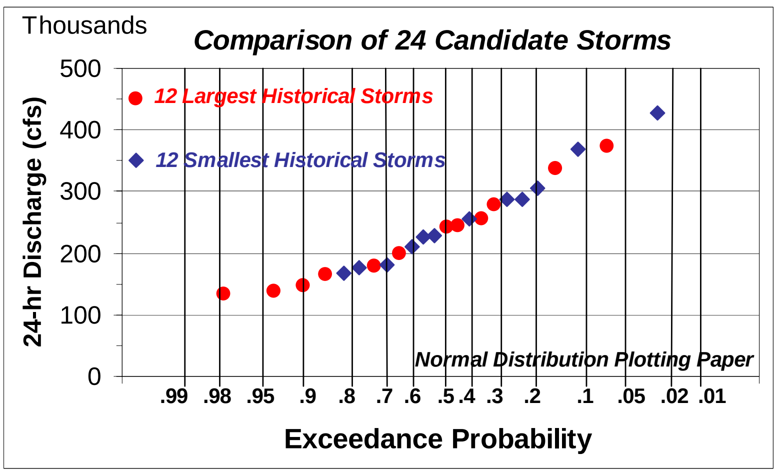

Figure 6b – Probability-Plot of Maximum 24-Hour Discharge Produced by 24 Candidate Storms
Comparison of Floods Produced by Largest 12 and Smallest 12 Candidate Storms
Scaled to have a 72-Hour Basin-Average Precipitation of 19.0-inches

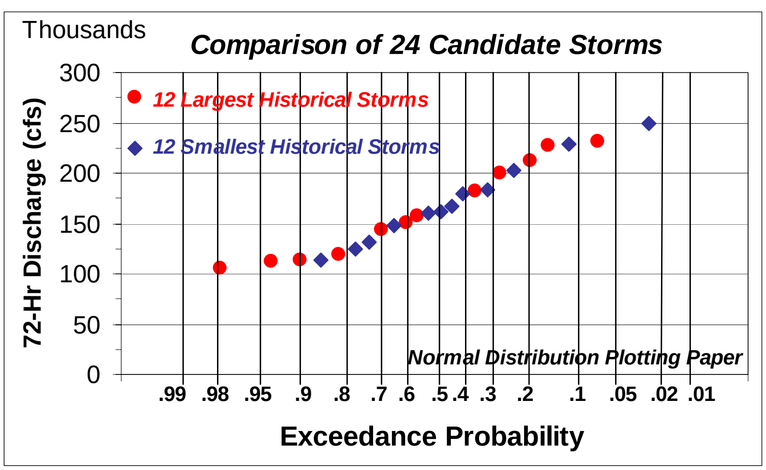

Figure 6c – Probability-Plot of Maximum 72-Hour Discharge Produced by 24 Candidate Storms
Comparison of Floods Produced by Largest 12 and Smallest 12 Candidate Storms
Scaled to have a 72-Hour Basin-Average Precipitation of 19.0-inches

PAST IDEAS – FINAL DECISIONS

A number of ideas and concepts were put forth in the past about application of the storm templates. Each of these concepts was examined and decisions were made for application of the stochastic storm resampling approach.

Format for Electronic Storing of Storm Templates

One idea was to electronically store the spatial templates with a common 72-hour watershed-average precipitation of 10-inches. This would have been accomplished by rescaling the spatial templates so the 33 sub-basin precipitation temporal distributions summed to a 72-hour watershed-average of 10-inches. The thought was that it would be easier to make comparisons between storms if they were scaled to a common magnitude. It was decided to store the spatial templates with the 72-hour sub-basin precipitation as was observed in the historical storm. This preserved the original magnitude of the storm and allowed easier identification of larger versus smaller storm events.

It should be noted that the 72-hour precipitation amount in the storm spatial template for each sub-basin is the precipitation for that 72-hour period that yielded the maximum 72-hour basin-average precipitation for the watershed. The maximum 72-hour precipitation for any given sub-basin may, or may not, coincide with the 72-hour period of maximum precipitation for the watershed. Synchronization between any given sub-basin and the watershed is dependent upon the location of the sub-basin within the watershed, the spatial variability of the temporal precipitation patterns, and the storm track across the watershed.

Storm Permutations to Increase Number of Storms for Resampling

Another idea was that the number of storm templates available for resampling could be increased by treating the spatial distribution and temporal distribution of historical storms as independent of each other. This would have produced n^2 possible storm events to be obtained from *n* historical storms. This approach was examined through rainfall-runoff modeling and it was found that the random combination of storm spatial and temporal templates did not significantly increase the variability and diversity of flood hydrographs and flood peaks relative to the original sample-set of *n* storms. Therefore, it was concluded that there was little benefit in producing the additional storm templates.

Likelihood of Occurrence of Any Specific Prototype Storms

A decision was also required on setting the likelihood of occurrence of any given prototype storm. The prototype storms will be selected on an equally-likely basis. There is nothing in the analyses conducted to date that would suggest setting likelihoods for storm templates at anything other than equally likely.

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