US Army Corps of Engineers
Hydrologic Engineering Center

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

Appendix D - Procedures Implemented for Conducting Storm Analyses in Support of Developing Storm Templates for the Stochastic Storm Resampling Approach for the American River Watershed

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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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PROCEDURES IMPLEMENTED FOR CONDUCTING STORM ANALYSES IN SUPPORT OF DEVELOPING STORM TEMPLATES FOR THE STOCHASTIC STORM RESAMPLING APPROACH FOR THE AMERICAN RIVER WATERSHED

Original October 23, 2000
Revised June 7, 2002
Revised September 21, 2005

OVERVIEW

The original October 2000 report provided recommendations on procedures for analysis of historical storms. This revised report updates the original report to document the procedures that were actually employed in analyzing historical storms to produce spatial and temporal storm templates for use in the stochastic storm resampling approach.

The stochastic storm resampling approach is an adaptation of standard Monte Carlo sampling techniques[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. The spatial and temporal distributions are obtained from analyses of historical storms.

Storm templates are used to describe the spatial and temporal distribution of precipitation to simplify application of the resampling approach in rainfall-runoff modeling. The spatial distribution of a given storm is described by a *spatial template*. In a fully distributed approach, a gridded field is overlain on the watershed, and precipitation associated with each of the grid cells provides the spatial distribution of precipitation. For the case of the American River watershed, the spatial template is comprised of the 72-hour precipitation amount for each of the sub-basins in the watershed. There is one spatial template for each historical storm that is utilized in the Monte Carlo resampling approach.

The temporal distribution of a given storm is described by a *temporal template*, where the temporal template is comprised of a collection of dimensionless storm mass curves. Specifically, each of the storm mass curves for the precipitation gages active during the storm are made dimensionless by dividing the ordinates of the mass curve by the 72-hour precipitation maximum observed at the gage for the given storm. In a fully distributed approach, the number of dimensionless storm mass curves for a given storm would correspond to the number of precipitation gages. For the case of the American River watershed, each sub-basin in the watershed is assigned one of the dimensionless storm mass curves from a nearby station. Therefore, the temporal template for a given storm is comprised of a collection of dimensionless storm mass curves equal to the number of sub-basins, with some dimensionless storm mass curves being used for more than one sub-basin. There is a collection of temporal template for each spatial template.

STORM ANALYSES

Analyses of storms, particularly depth-area-duration analyses, are complicated to conduct in mountainous terrain. In non-orographic areas with generally flat topography, simple linear interpolation or inverse distance weighting algorithms are often used for estimating precipitation amounts for locations between precipitation measurement sites. In mountainous terrain, such as in the American River watershed, orographic influences on precipitation can result in abrupt changes in precipitation over short distances. Thus, the orographic influence of the terrain renders simple interpolation procedures invalid.

The standard approach taken in mountainous terrain by the National Weather Service Hydromet Office[8] and the US Bureau of Reclamation[14] is to transform observed precipitation amounts to values that reflect orographic influences and are more amenable to simplified interpolation methods. This transformation procedure is generally termed an isopercental method[8,14]. Therein a location-specific index value is used to rescale/transform the observed precipitation amounts. Indexing values have evolved over-the-years from the use of mean annual precipitation to the use of frequency-based indices such as the 24-hour 100-year or 72-hour 100-year precipitation amounts. These latter values are typically obtained from precipitation-frequency information such as NOAA Atlas 2[7].

Index Used in Isopercental Method

The indexing value used in this study was the 72-hour mean annual maxima. This index was chosen because it is a frequency-based index available from regional frequency analyses[4] conducted for the West Face of the Sierra Mountains[11] and can be spatially mapped[2,9] at a gridded resolution of 1.25 minutes (approximately 1.6 mi^2). This resolution is much greater than available through NOAA Atlas 2[7]. It should be noted that use of either the 72-hour mean annual maxima or 72-hour 100-year values will yield the same results because the 72-hour 100-year values are a fixed ratio of the 72-hour mean annual maxima for the American River watershed[11]. Transformed values expressed as a ratio of the 72-mean annual maxima can also be readily converted to annual exceedance probabilities (Table 2) and provide an indication of the rarity of precipitation at a given location.

Basic Isopercental Method

The basic approach used in the isopercental method can be explained as follows. For a given storm, transformed (percental) values are computed for each of the precipitation measurement sites whereby 72-hour precipitation maxima are indexed (divided by) the 72-hour mean annual maxima applicable to the site. An inverse weighting algorithm is then used to interpolate the variation of transformed values between precipitation measurement sites. This yields the spatial distribution of 72-hour transformed values over the grid-cells for the watershed for the given storm (Figure 1a,b). The spatial distribution of precipitation on-the-ground is obtained by converting the transformed values back to precipitation by rescaling by the 72-hour mean annual maxima (Figure 1c,d). All of this analysis is accomplished on a gridded (raster) basis using a Geographical Information System (GIS). It may be electronically stored as a gridded system in a matrix format or the gridded data may be spatially averaged and aggregated to a sub-basin level, whichever is most convenient.

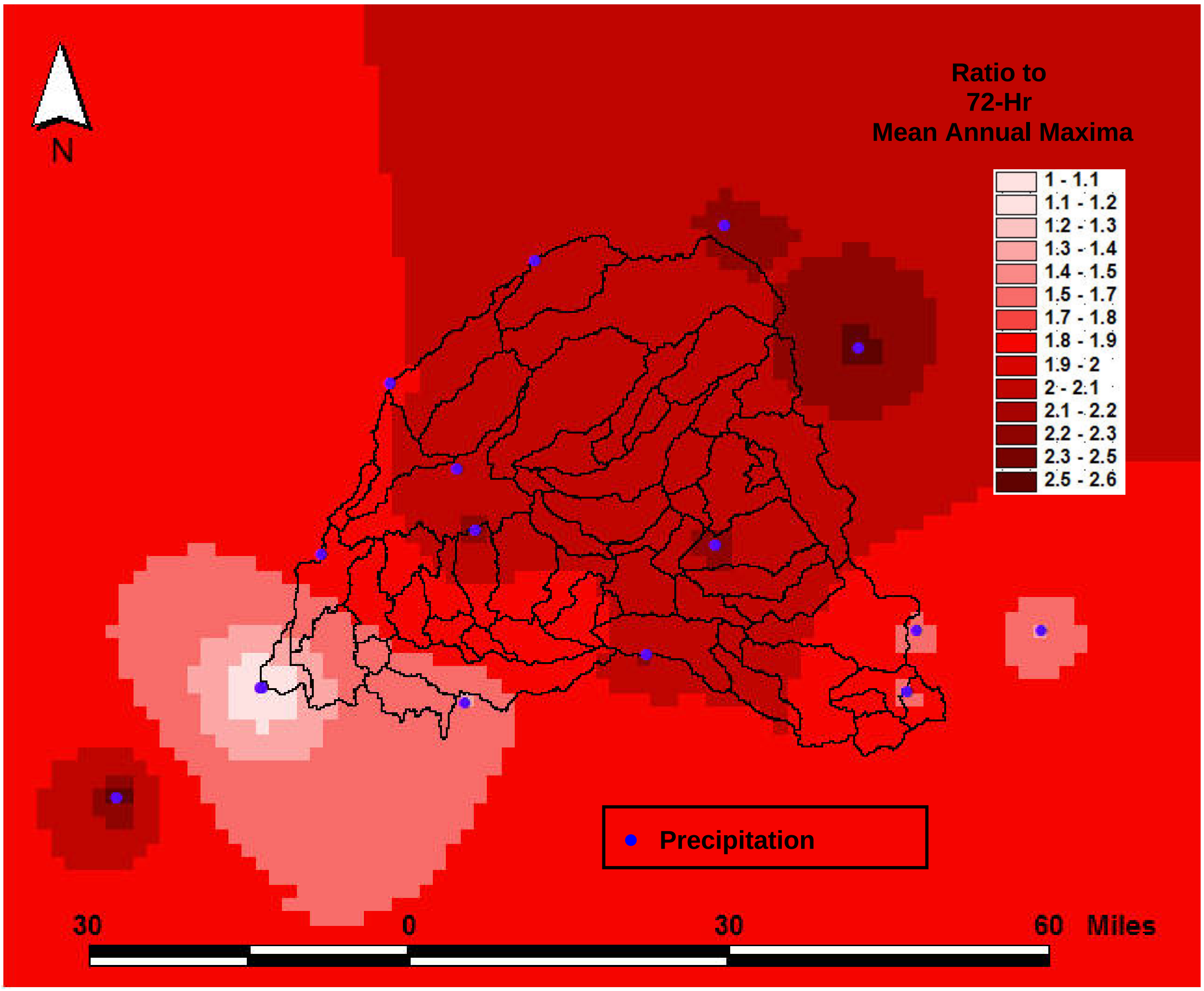


Figure 1a – Example Spatial Distribution of Transformed 72-Hour Precipitation using the Isopercental Method for Storm of February 10-16, 1986 for American River Watershed

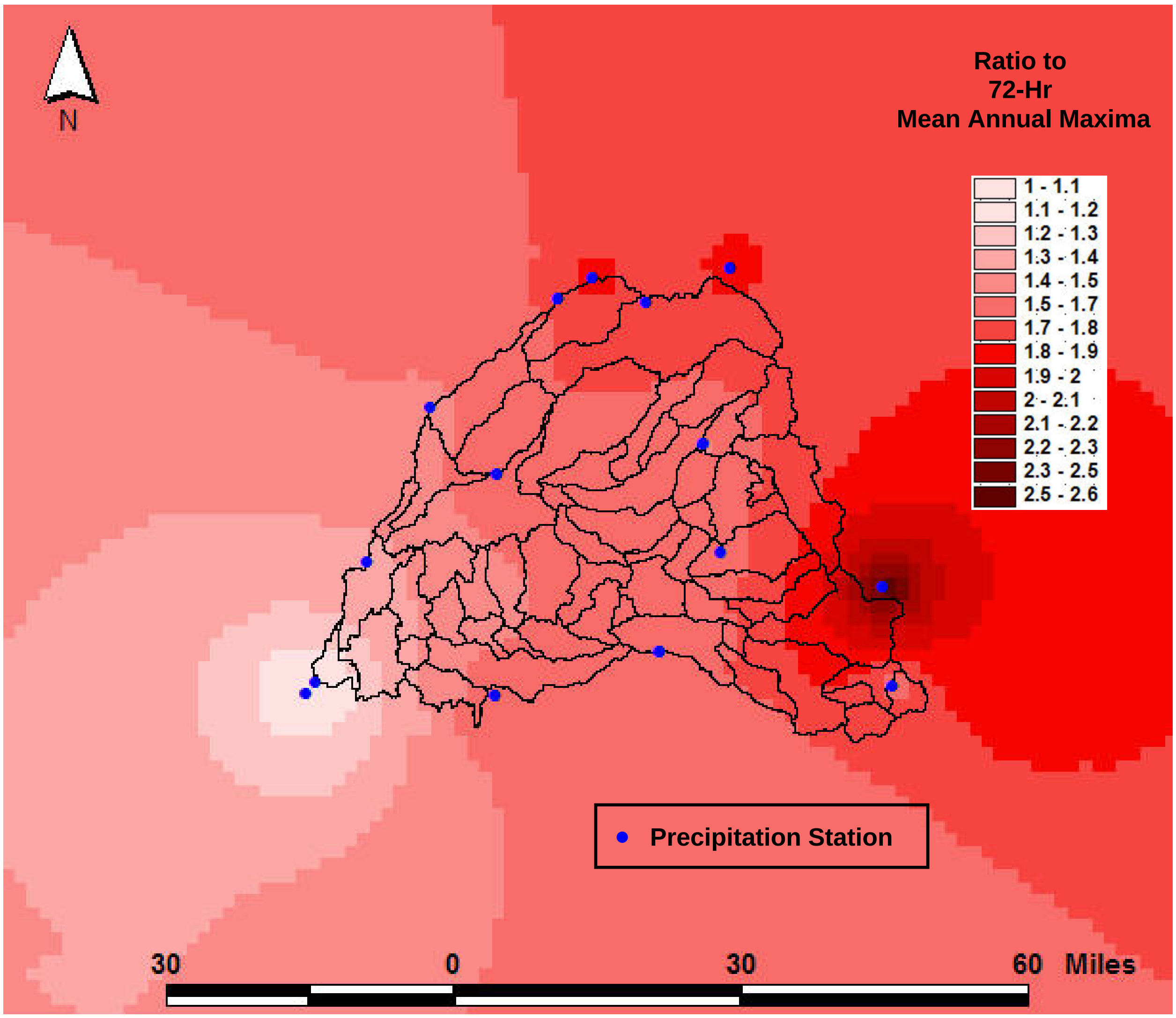


Figure 1b – Example Spatial Distribution of Transformed 72-Hour Precipitation using the Isopercental Method for Storm of December 28, 1996 - January 3, 1997 for American River Watershed

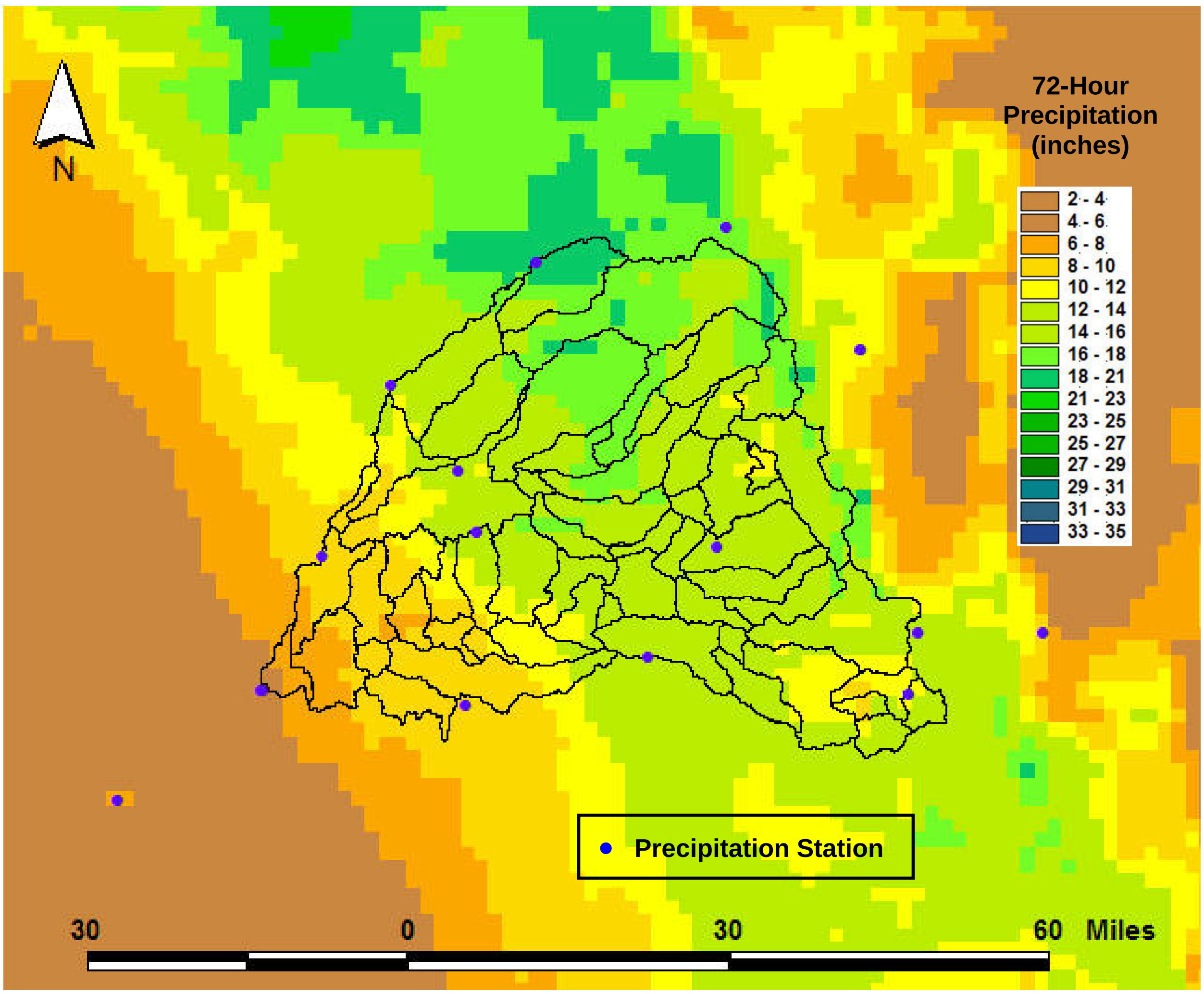


Figure 1c– Spatial Distribution of Maximum Basin-Average 72-Hour Precipitation
for Storm of February 12-20, 1986
for American River Watershed

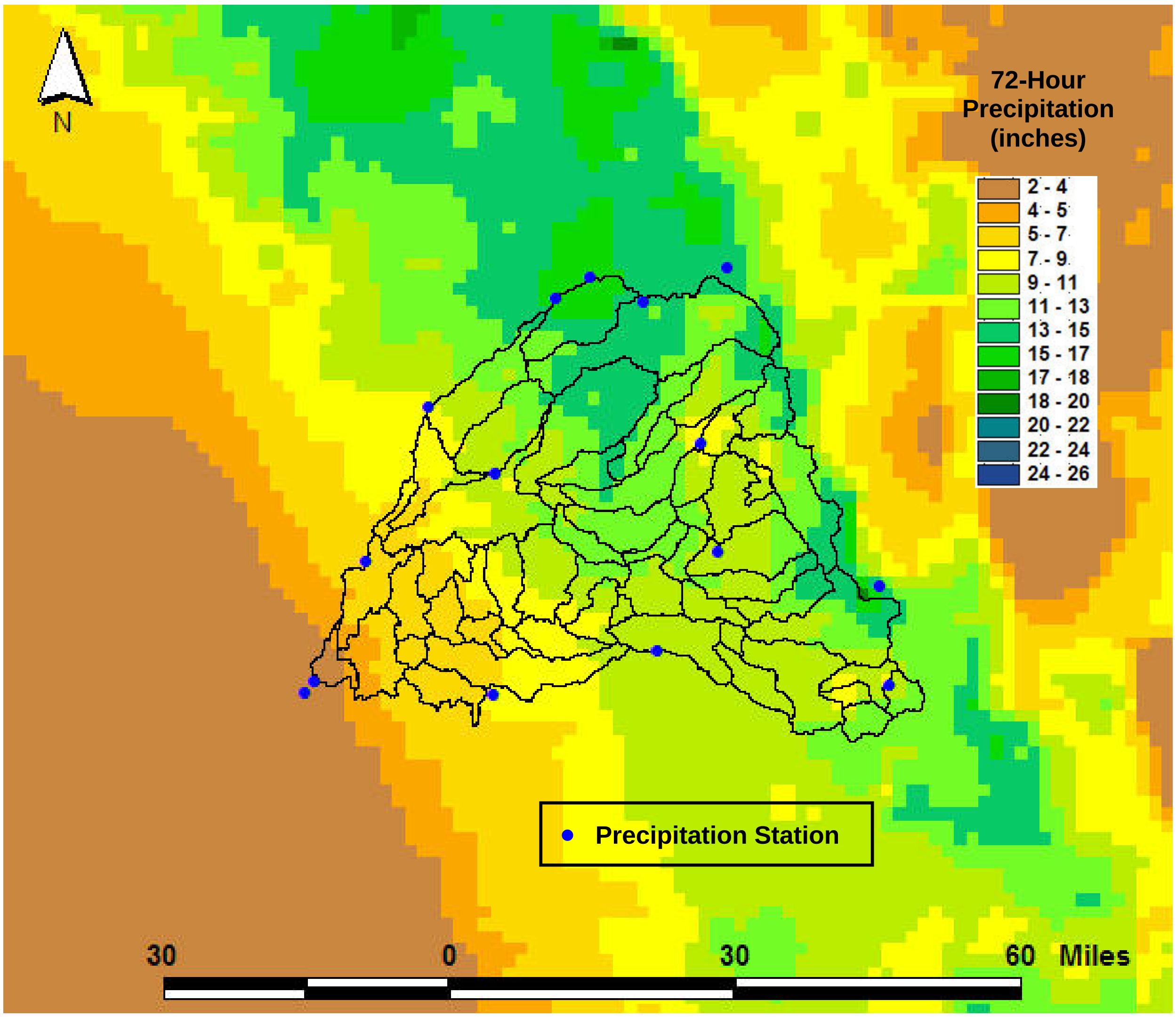


Figure 1d – Example Spatial Distribution of Maximum Basin-Average 72-Hour Precipitation
for Storm of December 28, 1996 - January 3, 1997
for American River Watershed

DEVELOPMENT OF STORM TEMPLATES FOR RESAMPLING OF HISTORICAL STORMS

The development of spatial and temporal storm templates was accomplished through the analysis of historical storms. A catalog[13] of large storm events was previously developed for this project. The historical precipitation record was examined and 37 storms from the catalog were identified with sufficient data to conduct a GIS storm analysis (Table 1). This included 31 storms with the largest basin-average precipitation for the American River watershed[13] in the 1966-2002 period and 6 storms from the 1950-1964 period of frequent extreme storms.

Table 1 – Catalog of Storms for Spatial Analysis for the American River Watershed
Sorted by 72-Hour Basin-Average Precipitation

72-HOUR STORM STORM DATE TO INCLUDE			PRELIMINARY ESTIMATE BASIN-AVERAGE PRECIPITATION (Inches)
MONTH	DAY	YEAR	
12	20	1955	13.10
12	21	1964	12.71
10	12	1962	12.46
2	16	1986	11.24
2	2	1963	9.84
1	1	1997	9.74
1	20	1969	9.39
1	12	1980	8.74
11	12	1973	7.11
12	20	1981	6.97
2	9	1962	6.92
12	12	1995	6.90
12	22	1982	6.84
3	10	1995	6.66
2	15	1982	6.59
11	29	1970	6.48
1	22	1967	6.43
3	3	1991	6.25
1	28	1981	6.14
12	9	1992	5.99
1	16	1970	5.95
11	30	1982	5.76
1	5	1982	5.66
11	13	1981	5.53
12	22	1969	5.40
12	26	1983	5.39
2	21	1996	5.21
10	24	1982	5.02
1	14	1969	4.93
3	13	1967	4.93
3	2	1974	4.87
11	25	1989	4.85
2	17	1980	4.84
1	9	1995	4.78
11	23	1988	4.74
1	21	1970	4.67
1	26	1969	4.65
12	6	1966	4.47

The following conditions are required to conduct the storm analyses and to develop the storm templates:

- Network of hourly and daily precipitation measurement gages within the American River watershed and surrounding areas
- Multi-day precipitation has been measured at a collection of hourly and daily gages for each of the storms of interest
- A grid cell layout at a resolution of 1.25 minutes is in-place for the American River watershed and surrounding areas that matches the grid cell system used by Oregon Climate Service in preparing the mean annual precipitation map of California[9].

List of Tasks for the Analysis of Each Storm

The following sections describe the procedures that were used for conducting the storm analyses and developing spatial and temporal storm templates. Comparison with the sequence of tasks originally proposed[19] indicates procedural changes that were made to accommodate data and electronic data processing constraints. These procedures/tasks yielded the following work products:

<u>Work Products for Each Storm</u>

Observed Precipitation

- Spatial distribution of 72-hour precipitation maxima
- Storm mass curve for each hourly and daily gage

Transformed Units (percental units)

- Spatial distribution of 72-hour transformed units on a gridded basis

Storm Templates

- Spatial Template – spatial distribution of 72-hour precipitation maxima on a gridded basis
- Temporal Template – dimensionless storm mass curves in hourly increments, one per sub-basin

<u>Task 1: Assemble Hyetograph and Dimensionless Storm Mass Curve at Each Hourly Gage</u>

a) Assembled the hyetograph of hourly incremental precipitation at each hourly gage. This often required data collection for 5 to 8 days, spanning the total period of precipitation and including other periods of storm activity in addition to the 72-hour period of interest (Figure 2). Assembled the storm mass curve (Figure 3a) and computed the 72-hour precipitation maxima. Rescaled the storm mass curve by the 72-hour precipitation maxima to produce a dimensionless storm mass curve (Figure 3b).

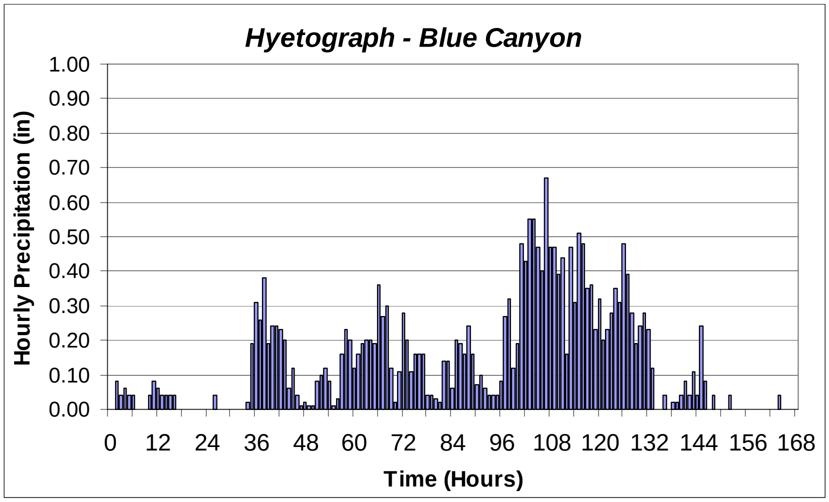


Figure 2 – Hourly Incremental Precipitation Pattern for Storm of Dec 28, 1996 to Jan 3, 1997 at Blue Canyon Hourly Gage

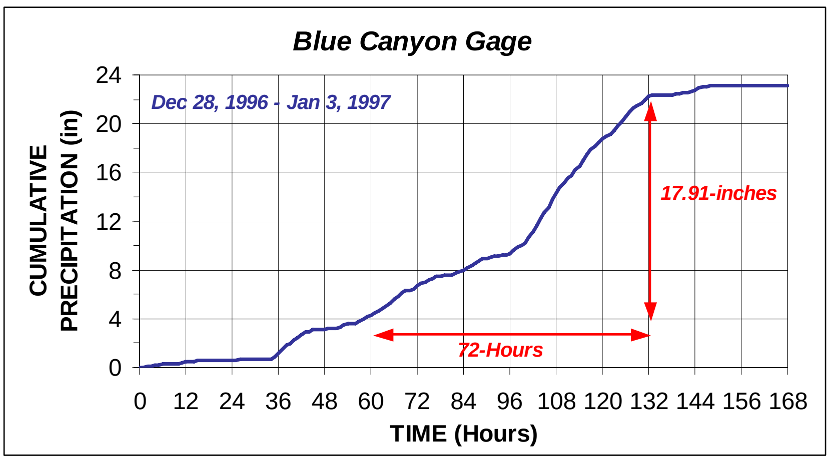


Figure 3a – Storm Mass Curve for Storm of Dec 28, 1996 to Jan 3, 1997 at Blue Canyon Hourly Gage

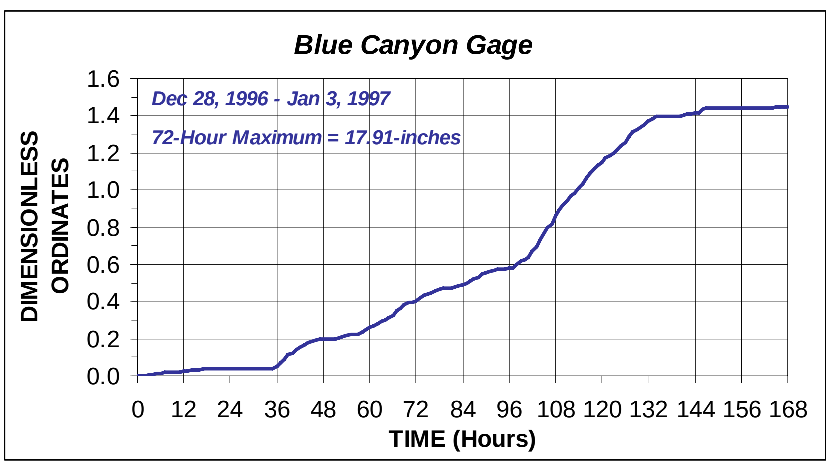


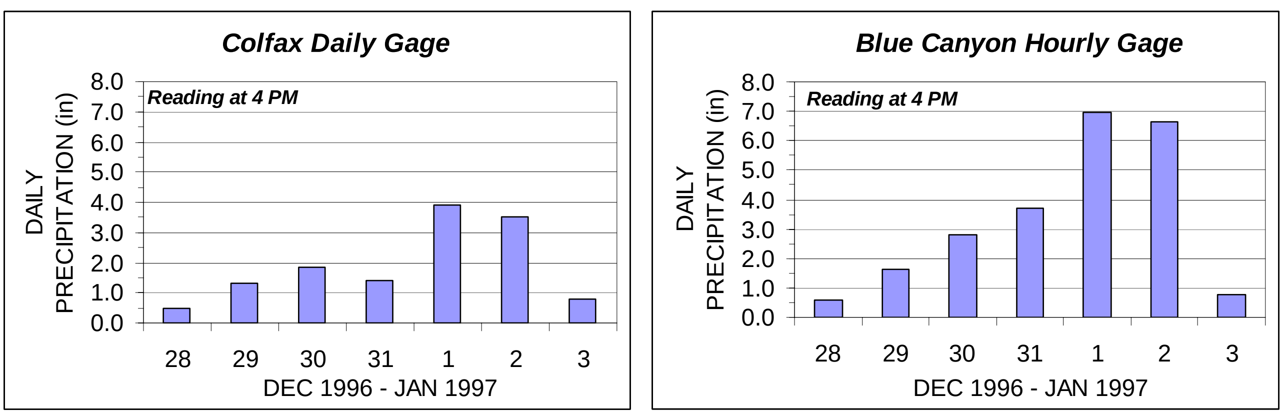
Figure 3b – Dimensionless Storm Mass Curve for Storm of Dec 28, 1996 to Jan 3, 1997 at Blue Canyon Hourly Gage

Task 2: Develop Hyetograph and Dimensionless Storm Mass Curve at Each Daily Gage

a) Developed the hyetograph of hourly incremental precipitation for each daily gage (Figure 5) by separately fitting/scaling the magnitude of precipitation at the daily gage (Figure 4a) by the corresponding shape and magnitude of each 24-hour period from a nearby hourly gage (Figure 4b).   Used the nearest hourly gage for scaling that had the greatest similarity in mean annual precipitation, elevation, and topographic orientation/setting to the daily gage under consideration. In some cases, a weighted average of the temporal patterns at surrounding gages was utilized where the weighting factors were based on a combination of distance and mean annual precipitation of adjacent gage. Used the measurement observation time at the daily gage to synchronize clocks between the hourly and daily gages.

   Paid particular attention to the possibility of data measurement and reporting errors due to early/late measurements, missing data, and missing flags for accumulations. In some cases this required scaling using 48-hour periods rather than 24-hour periods. Carefully reviewed the computed hourly incremental patterns for reasonableness with regard to the timing and magnitude of hourly precipitation amounts and how the computed temporal pattern fits with surrounding gages. The primary concern being the presence of excessively large hourly amounts that were due to over-scaling flaws rather than reflecting intense storm/convective activity. In those cases where unreasonable or implausible patterns occurred, adjustments were made to the temporal pattern based on comparison with the temporal patterns at all surrounding gages.

b) Assembled the storm mass curve and computed the 72-hour precipitation maxima. Rescaled the storm mass curve by the 72-hour precipitation maximum to produce a dimensionless storm mass curve (similar to Figure 3b).



Figures 4a,b – Daily Precipitation Patterns at Colfax and Blue Canyon Gages
for Storm of Dec 28, 1996 to Jan 3, 1997

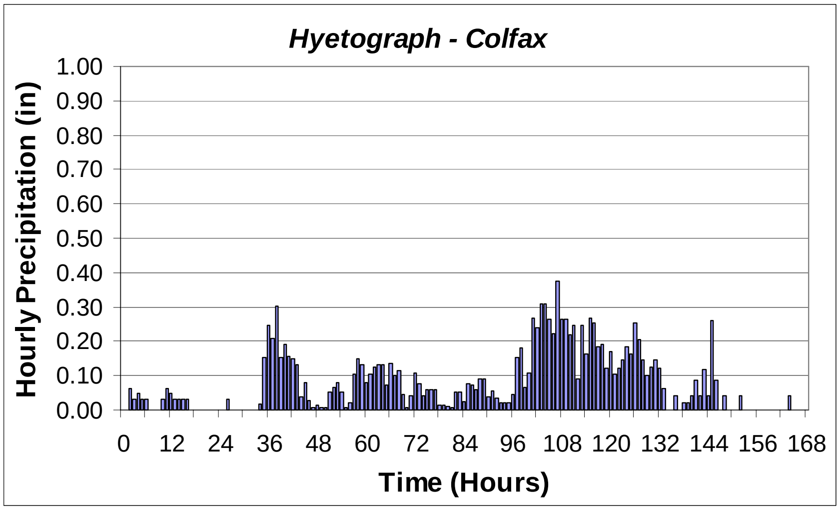


Figure 5 – Scaled Hourly Incremental Precipitation Pattern
for Storm of Dec 28, 1996 to Jan 3, 1997 at Colfax Daily Gage

<u>Task 3: Transform All 72-Hour Maxima at Precipitation Gages using 72-Hour Index Value</u>

a) Transformed all 72-hour precipitation maxima at hourly and daily gages by division by the 72-hour mean annual maxima (index value) applicable to the grid cell where the gage resides. Used the gridded 72-hour mean annual maxima provided through analyses conducted by Oregon Climate Service of 72-hour at-site means from regional precipitation-frequency study[11].

<u>Task 4: Determine Spatial Distribution of 72-Hour Transformed Values</u>

a) Used inverse distance weighting algorithm to interpolate between all gages and estimate the transformed value applicable to each grid cell. Used weighting exponent (*n*) equal to 1 for computing weights for inverse distance weighting algorithm ($1/d^n$). Examples of this process are depicted in Figures 1a,b.

- Yields spatial distribution/isopercental map for <u>transformed</u> 72-hour precipitation maxima

b) The rarity and variation of at-site precipitation amounts for a given storm over the American River watershed could then be determined from the spatial distribution. Table 2 lists ratios of 72-hour mean annual maxima and corresponding annual exceedance probabilities[11].

Table 2 – Listing of Ratios of 72-Hour Mean Annual Maxima
and Corresponding Annual Exceedance Probabilities
for 72-Hour Precipitation for American River Watershed

ANNUAL EXCEEDANCE PROBABILITY											
.900	.700	.500	.300	.200	.100	.040	.0100	.0032	.0010	.00032	.00010
0.58	0.77	0.92	1.12	1.26	1.50	1.83	2.35	2.82	3.32	3.87	4.47
RATIO TO 72-HOUR MEAN ANNUAL MAXIMA											

Task 5: Transform Spatial Distribution Back to 72-Hour Precipitation Values

a) Used 72-hour mean annual maxima value for each grid cell to convert transformed values back to 72-hour precipitation values. This was accomplished by multiplying the transformed value for each grid cell by the 72-hour mean annual maxima for that grid cell to obtain the estimated value of the 72-hour maximum precipitation for that grid cell. Examples of this process are depicted in Figures 1c,d.

Task 6: Compute 72-Hour Precipitation Maxima for Each of 33 Sub-basins

a) Computed 72-hour precipitation maxima for each of 33 sub-basins in watershed by areally averaging grid-cell values of 72-hour maxima (Step 5a) for each sub-basin.

Task 7: Develop Storm Mass Curve and Temporal Pattern for each of 33 Sub-basins

a) Assigned each of the 33 sub-basins in the American River watershed to the nearest and most representative precipitation gage. Scaled the dimensionless storm mass curve from the representative precipitation gage (Step 1a or 2b) by the 72-hour precipitation maxima for the sub-basin determined in Step 6a. Computed incremental precipitation pattern (temporal pattern) from scaled storm mass curve.

   - Yields storm-specific mass curve and hyetograph/temporal pattern for each sub-basin

Task 8: Compute 72-Hour 1860-mi^2 Watershed-Average Precipitation

a) Used the hourly incremental precipitation pattern and area (mi^2) for each of the 33 sub-basins to determine the 72-hour period during which the total precipitation over the watershed is a maximum.

   - Yields the 72-hour 1860-mi^2 watershed-average precipitation value

List of Tasks for Creating Storm Templates for Each Storm for Use in Stochastic Storm Resampling

Task 9: Spatial Template for 72-Hour Precipitation Maxima

a) The spatial template for each storm is comprised of the gridded dataset of 72-hour precipitation values.

   - Yields spatial template of 33 sub-basin 72-hour precipitation maxima that sum to a watershed-average for the 1860-mi^2 watershed.

Task 10: Temporal Template for Each Sub-basin

a) The temporal template for each storm is comprised of the dimensionless storm mass curves, one per sub-basin, developed in Step 7a.

- Yields one temporal template per storm comprised of 33 dimensionless mass-curves per template.

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