US Army Corps
of Engineers
Hydrologic Engineering Center

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

Appendix H - Snowpack Characteristics and Relationship with Antecedent Precipitation for the American River Watershed

September 2005

RD-48H

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
September 2005

2. REPORT TYPE
Research Document

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Stochastic Modeling of Extreme Floods on the American River at Folsom Dam

Appendix H - Snowpack Characteristics and Relationship with Antecedent Precipitation for the American River Watershed

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
MGS Engineering Consultants, Inc.
7326 Boston Harbor Road NE
Olympia, WA 98506

5d. PROJECT NUMBER

5e. TASK NUMBER

5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER
RD-48H

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/ MONITOR'S ACRONYM(S)

11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
.

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.

15. SUBJECT TERMS
Stochastic, Precipitation, Frequency Analysis, Frequency Curve, Exceedance Probability, Temperature, Snow, Wind, Volume, Folsom, American, Corps of Engineers, MGS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
U	U	U	UU	22	19b. TELEPHONE NUMBER

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Prepared by:
MGS Engineering Consultants, Inc.
7326 Boston Harbor Road, NE
Olympia, WA 98506

For:
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

RD-48H

SNOWPACK CHARACTERISTICS AND RELATIONSHIP WITH ANTECEDENT PRECIPITATION FOR THE AMERICAN RIVER WATERSHED

January 31, 2001

OVERVIEW

Snowpack magnitude in the American River watershed varies both temporally and spatially. Temporal variability includes seasonal variability as the snowpack accumulates in the late fall, reaches a maximum during the winter period, and melts out in the spring. It also includes variability produced by the year-to-year variation at a given site due to wet or dry climatic years. All other factors being equal, heavier snowpacks would be expected in wetter years and lighter snowpacks would be expected in drier years. Snowpack spatial variability arises primarily from elevation differences between locations in the watershed that affects both temperatures and precipitation amounts.

Both temporal and spatial variability will be addressed in the stochastic model. The temporal aspects will be addressed by analyzing snowpack snow-water equivalent on a monthly basis. Snowpack will also be correlated with antecedent precipitation using a *key snowpack station* and *key precipitation station* which will allow the stochastic model to account for the variability in the snowpack due to wet and dry climatic years. Antecedent precipitation as used herein refers to the cumulative precipitation from the start of the water-year (October 1st) through the end-of-month of the month of interest. Both the deterministic and random components of the correlation relationship will be preserved in the simulations.

The spatial aspects will be addressed by analysis of snow-water equivalent at multiple sites that represent a range of mean annual precipitation and elevation zones. Sample statistics of snow-water equivalent from these sites will be used to estimate the frequency of snow-free ground, and the population means and standard deviations (natural log-space) for the various zones of mean annual precipitation and elevation. This information will be used in the stochastic simulation routines to allocate snowpack in the various zones of mean annual precipitation and elevation.

SNOW MEASUREMENT STATIONS

A large number of snow measurement stations are located within or near the American River watershed. These stations encompass a variety of measurement methods, and include snow-water equivalent (SWE) measurements at snow courses and Snotel sites, snow-on-ground measurements at NCDC cooperative stations, and measurements of snowfall at NCDC cooperative stations. Table 1 lists the 24 stations used in these analyses and the physical characteristics of the measurement sites. A surrogate station was also created at the Lake Spaulding precipitation station, which is located at 5155 feet near the upper portion of the watershed where snowpack accumulates. All winter precipitation at this site was treated as if it had fallen as snow. This was done to provide an upper limit for use in developing SWE relationships for the watershed. This surrogate station can be interpreted as a site located at an elevation sufficiently high that essentially all precipitation falls as snow. A nominal elevation of 10,000 feet was assigned to the Lake Spaulding surrogate station.

Table 1 – Snow Measurement Stations Used in Analyses of Snow-Water Equivalent for the American River Watershed

STATION ID	STATION NAME	GAGE TYPE	LATITUDE	LONGITUDE	ELEVATION (feet)	YEARS OF RECORD	MEAN ANNUAL PRECIP[9] (inch)
04-6597	Pacific House	snow on ground	38.7500	120.5000	3440	48	53.0
ATS	Antelope Springs	snow course	38.5030	120.4670	4350	55	48.0
RBP	Robbs Powerhouse	snotel	38.9030	120.3750	5150	26	48.5
BLC	Blue Canyon	snotel	39.2760	120.7080	5280	24	68.0
HIS	Ice House	snow course	38.8120	120.3750	5300	59	49.0
RBV	Robbs Valley	snow course	38.9220	120.3800	5600	42	48.0
GKS	Greek Store	snotel	39.0750	120.5580	5600	24	63.0
TBC	Talbot Camp	snow course	39.1930	120.3770	5750	30	57.0
DMN	Diamond Crossing	snow course	39.1120	120.2830	6050	31	62.5
ONN	Onion Creek	snow course	39.2750	120.3580	6100	49	58.0
MCB	Miranda Cabin	snow course	39.1200	120.3620	6200	31	52.0
WBM	Wabena Meadows	snow course	39.2270	120.4020	6300	31	53.0
HYS	Huysink	snow course	39.2820	120.5270	6600	57	62.0
HYS	Huysink	snotel	39.2820	120.5270	6600	19	62.0
VVL	Van Vleck	snotel	38.9450	120.3050	6700	26	48.0
GOL	Gold Lake	snotel	39.6750	120.6150	6750	30	77.0
WRG	Wrights Lake	snow course	38.8470	120.2330	6900	42	55.0
RDM	Red Mountain	snow course	39.3430	120.5080	7200	26	67.0
ECS	Echo Summit	snow course	38.8280	120.0370	7450	59	45.0
LCR	Lost Corner Mountain	snow course	39.0170	120.2150	7500	38	53.0
APH	Alpha	snow course	38.8050	120.2150	7600	35	45.0
ALP	Alpha	snotel	38.8050	120.2150	7600	30	45.0
SCN	Schneiders	snotel	38.7470	120.0680	8750	25	48.5
04-4713	Lake Spaulding	precipitation snow surrogate	39.3167	120.6333	10000*****	33	74.5

***** - surrogate station elevation

MAGNITUDE-FREQUENCY RELATIONSHIPS FOR SNOWPACK

The end-of-month snowpack snow-water equivalent (SWE) magnitude-frequency relationship at each snow measurement site is described by a mixed distribution[1,10]. The mixed distribution (Equation 1) is comprised of a mixing parameter (θ) that sets the frequency of time that the ground is snow-free, and a Log-Normal[1,5,10] distribution of snow-water equivalent values for those times when snow is on the ground. Typical behavior for mountainous snow measurement sites is for the mixing parameter to be relatively large at the on-set of the winter season, to be zero or near zero during the winter period, and to increase in magnitude towards the spring of the year.

The mixed probability distribution model has the form:

$$F(x) = \theta + (1-\theta)\, G(x) \qquad (1)$$

where: $F(x)$ is the cumulative distribution function for snow-water equivalent, θ is the frequency of snow-free ground, $(1-\theta)$ is the frequency of snow-covered ground, and $G(x)$ is the cumulative distribution function for snow-water equivalent when the ground is snow-covered. The two-parameter Log-Normal distribution is used for describing the cumulative distribution function $G(x)$ when the ground is snow covered. The Log-Normal distribution has location and scale parameters mu (μ) and sigma (σ), which correspond to the mean and standard deviation of the natural log-transformed values of snow-water equivalent.

The distribution parameters were estimated using the probability-plot regression[10] method. The intercept and slope parameters of the regression solution are the estimates for the distribution parameters mu (μ) and sigma (σ) of the Log-Normal distribution. This method was used in a spreadsheet application because it readily allows examination of the effect of low-outliers that can distort sample statistics. In particular, the probability-plot regression method can provide solutions that better represent the body of the SWE data.

The relationship between the distribution parameters of the Log-Normal distribution and the population moments of the distribution in real-space are:

$$mean = exp\ (\mu + \sigma^2/2) \tag{2}$$

$$variance = \mu^2\ [\ exp\ (\sigma^2) - 1\ ] \tag{3}$$

$$coefficient\ of\ variation = [\ exp\ (\sigma^2) - 1\ ]^{0.5} \tag{4}$$

where: *mean*, *variance*, and *coefficient of variation* are the population estimates in real-space.

An example probability-plot regression solution is shown in Figure 1 for the Gold Lake station at the end-of-November. It should be noted that this solution is for the data set of SWE values when there is snow on the ground at the end-of-November. The magnitude-frequency curve for the mixed distribution model is depicted in Figure 2. It incorporates the probabilities of both snow-free ground and snow-on-ground conditions and reflects a mixing parameter (θ) of 0.15, where the ground is snow-free 15% of the time at the end-of-November.

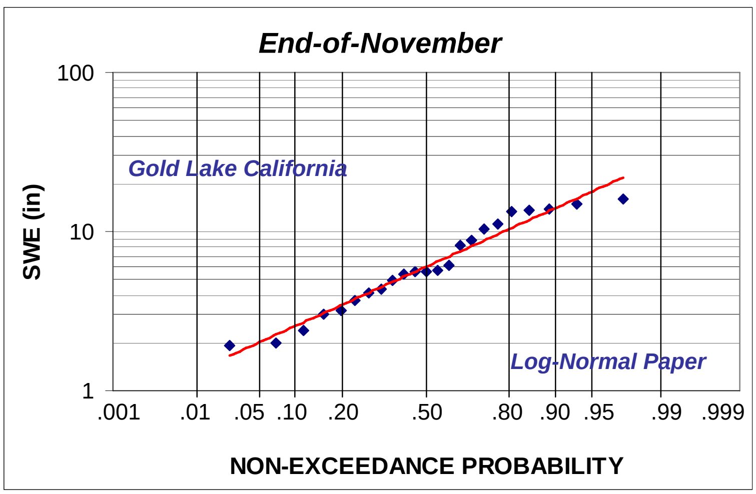

Figure 1 – Probability-Plot and Regression Solution for Snow-Water Equivalent
(Log-Normal Distribution for Condition when Ground is Snow-Covered)

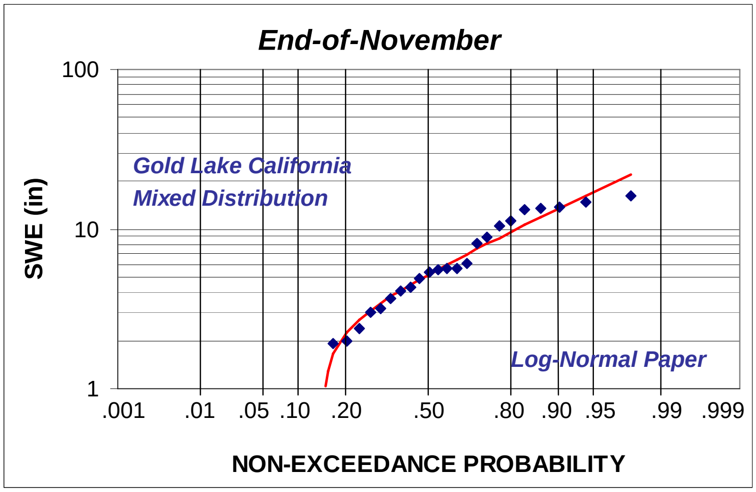

Figure 2 – Magnitude-Frequency Relationship for Snow-Water Equivalent Using a Mixed Distribution Model

Seasonal Variation of Distribution Parameters

The distribution parameters for the mixed distribution vary seasonally as the snowpack builds in the late-fall and winter season and melts out in the spring. Figure 3 depicts the seasonal variation of the mixing parameter (θ) for stations at a range of elevations, where end-of-October equates to a numeric month of 10 and end-of-January equates to a numeric month of 13. It is seen that snow-free conditions are more frequent both early and late in the snowpack season, and that stations at lower elevations have more frequent snow-free ground conditions.

Figure 4 depicts the seasonal variation of mean values of snow-water equivalent for stations at various elevations. The mean values were computed based on Equation 2 and then rescaled to be representative of SWE values for a site with 50 inches of annual precipitation. This rescaling allows more direct inferences to be made of the effect of elevation in conversion of liquid precipitation to snowpack.

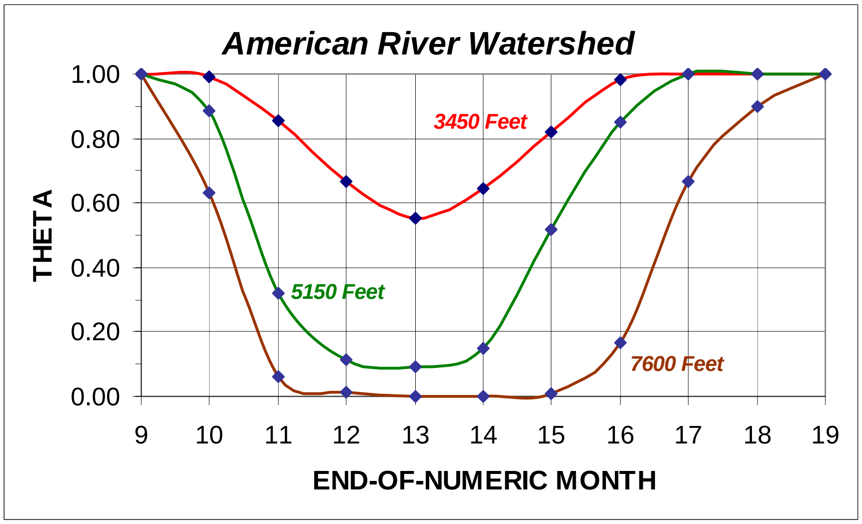

Figure 3 – Seasonal Variation of Mixing Parameter (θ) for Frequency of Snow-Free Ground Conditions at Various Elevations in the American River Watershed

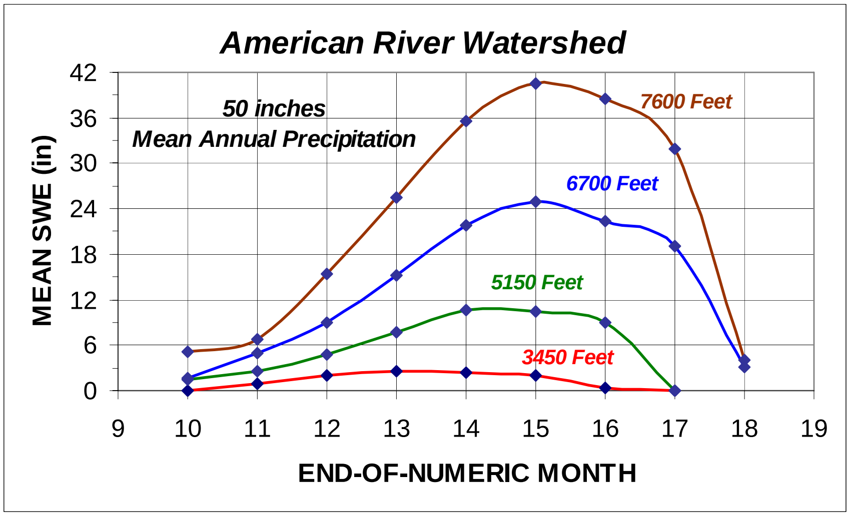

Figure 4 – Seasonal Variation of Mean Values of Snow-Water Equivalent for Various Elevations in the American River Watershed

Estimation of Basin-Wide Distribution Parameters for Snow-Water Equivalent
The magnitude of end-of-month SWE at a given location is primarily governed by two factors, precipitation supply and the frequency of below-freezing air temperature. The supply of precipitation, comprised of the late-fall, winter, and early-spring component of annual precipitation, represents the potential amount of liquid precipitation that can be converted to snow. Air temperature decreases with elevation, and elevation at a site can be used as an indicator of the efficiency, or proportion of liquid precipitation that can be converted into snow. For a given magnitude of annual precipitation, the proportion that will fall as snow and become part of the snowpack will increase with increasing elevation. This behavior is clearly seen in Figures 3 and 4.

Prior studies[9] have shown that sites within the American River watershed have essentially the same monthly distribution of annual precipitation. In addition, it is known that inter-site correlation of antecedent precipitation (multi-month precipitation) decays slowly with distance for lowland and mountain areas on the west coast of the United States[7,8,11,12]. Thus, the snowpack magnitude at two distant sites at the same elevation within the watershed would be expected to have SWE values in the same proportion as the ratio of the cumulative precipitation over the late-fall, and winter period. Based on the foregoing discussion, a reasonable regression solution for estimation of basin-wide SWE distribution parameters can be developed using elevation and mean annual precipitation as explanatory variables.

***Mixing Parameter* –** The end-of-month SWE data were analyzed for the 24 stations. The mixing parameter (θ) was found to be well described by the elevation of the measurement site. Figure 5 depicts the regional regression solution for the variation of the mixing parameter with elevation for the end-of-January. Similar regression solutions were obtained for other months.

Mean of Log-Transformed SWE – Mean values of end-of-month SWE were found to vary with both elevation and mean annual precipitation. This was expected based on the prior findings depicted in Figure 4, and for the reasons discussed in the previous paragraphs. One approach would be to conduct multiple regression analyses with both mean annual precipitation and elevation as explanatory variables. A simpler approach was obtained by first rescaling the computed end-of month natural log-transformed mean values (μ) to values representative for a site with 50 inches mean annual precipitation. Regression analyses were then conducted using elevation as an explanatory variable. The rescaling of the distribution parameter μ was accomplished as:

$$\mu_{50} = \mu + LN\,(50) - LN\,(MAP) \qquad (5)$$

where: μ_{50} is the distribution parameter applicable to a site with 50 inches mean annual precipitation, μ is the distribution parameter obtained from the probability-plot regression for a particular station for a given end-of-month, and *MAP* is the mean annual precipitation[2,6] for the station.

It was also recognized that the log-transformed SWE mean values would approach a limiting value as a greater proportion of the precipitation supply was converted to snow. This convergence to a limiting condition is seen in Figure 6 as the elevation of the measurements sites approaches 10,000 feet.

Standard Deviation of Log-Transformed SWE – Values of the distribution parameter σ for end-of-month SWE were also found to vary with elevation. Figure 7 depicts the variation of σ with elevation for end-of-January SWE. Referring to Equation 4, it is seen that the coefficient of variation in real-space is a function of σ. Figure 7 may be interpreted as demonstrating that higher elevation sites have smaller coefficients of variation, and lower elevation sites have larger coefficients of variation and experience greater year-to-year variation in snowpack. This behavior was exhibited by all datasets.

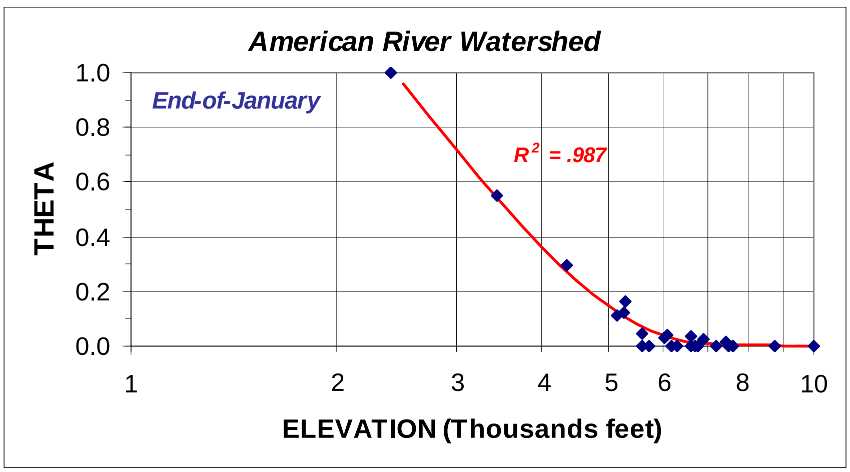

Figure 5 – Regression Solution of Mixing Parameter Theta for End-of-January as a Function of Elevation for the American River Watershed

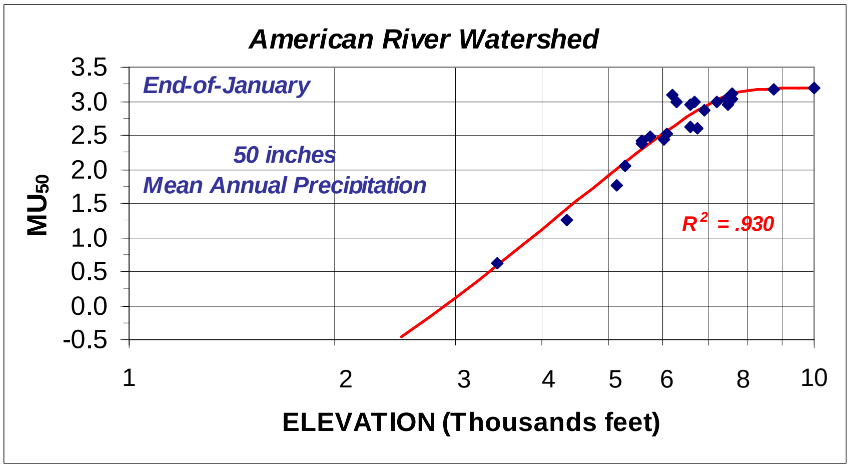

Figure 6 – Regression Solution of Mean (μ_{50}) of Natural Log-Transformed SWE for End-of-January as a Function of Elevation for Sites with Mean Annual Precipitation of 50 Inches

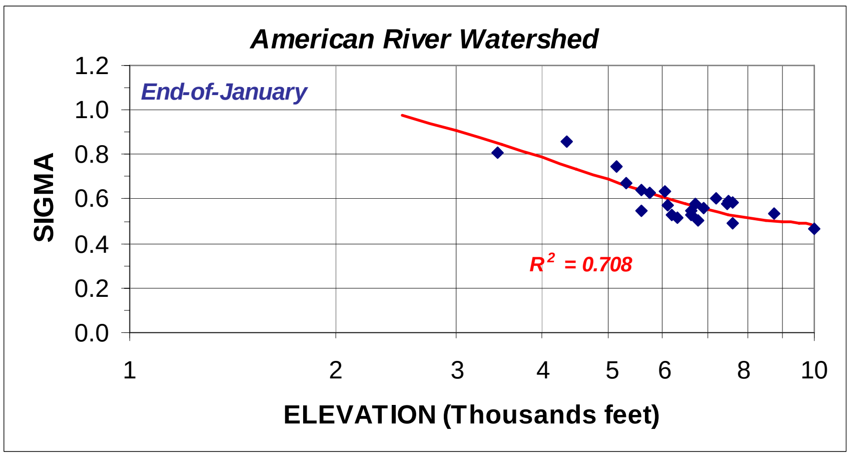

Figure 7 – Regression Solution of Sigma (σ) of Natural Log-Transformed SWE for End-of-January as a Function of Elevation for the American River Watershed

ELEVATION ZONES FOR ALLOCATION OF SNOWPACK

The spatial allocation of snowpack requires that the watershed be subdivided into zones of mean annual precipitation and zones of elevation. Mean annual precipitation[2,6] varies from about 25-inches to 75-inches in the American River watershed with a basin-average near 50-inches. Elevation in the watershed varies from near 1,000 feet to over 10,000 feet, with snowpack accumulation occurring primarily above 5,000 feet. The zones of mean annual precipitation and elevation should be selected sufficiently narrow to provide for adequate resolution in allocation of snowpack. This is particularly important in the elevation zones above 5,000 feet where the winter snowpack typically develops. It is also important in the lower elevation zones where there is high year-to-year and month-to month variability in snow-on-ground.

Lower Elevation Limit of Winter Snow Line

A determination of the lower elevation limit of the winter snow line is needed for setting the bounds for the elevation zones. This determination was made by examination of snowfall data. Snowfall data is measured as the depth of snow that falls each day. Freshly fallen snow is generally taken to have a snow density of 0.10 where each inch of snowfall is taken to have a snow-water equivalent of 0.10 inch. At low-elevation stations, the snow rarely remains on the ground for long periods, so it is difficult to make inferences how daily, monthly, and seasonal snowfall values translate to snow-on-ground and snow-water equivalent values. Nonetheless, snowfall data is useful for assessing the elevation band where snow-on-ground can be reasonably expected in most years.

Figure 8 depicts the typical variability of winter snowfall for stations within and near the American River watershed. The data have been standardized to be equivalent to a zone of 50 inches of annual precipitation to minimize variability due to differences in annual precipitation. It is seen that at elevations above approximately 3,000 feet, that annual snowfall is sufficiently large to expect that snow-on-ground is fairly common in the mid-winter months in most years. This is corroborated by the snow-on-ground data for Pacific House, located at an elevation of 3,440 feet, where some snow-on-ground is common from the end-of-December to end-of-March. It should be recognized that at these lower elevations, snow-on-ground is an intermittent occurrence and the ground would not be expected to be covered by snow from late-December through the end-of-March.

A review of Figure 8 also indicates that below 2,000 feet, snowfall is so small as to be considered negligible. Based on these considerations, it was determined that an elevation of 2,400 feet would be used as the lower bound for the elevation zone below which there is no need to consider snow-on-ground. Annual snowfall at the 2,400 foot elevation corresponds to a typical value of about 15 inches (1.5 inches SWE), with a historical (40-year) maximum snowfall of about 50 inches (5.0 inches SWE) for the entire winter season. These values are just large enough to warrant consideration in the flood analyses, although they are minimal when compared to the snowpack magnitudes that develop over much of the upper watershed.

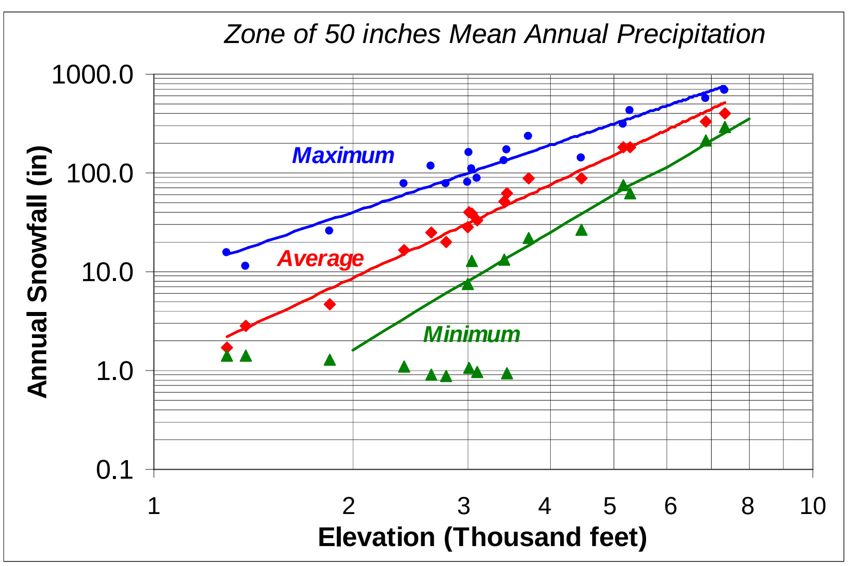

Figure 8 – Relationship between Annual Snowfall and Elevation for the American River Watershed

Selection of Elevation Zones For Allocation of Snowpack

Based on the foregoing, thirteen zones of mean annual precipitation, and nine elevation zones are proposed to achieve the desired high resolution in the spatial allocation of snowpack. Table 2 lists the proposed zones of mean annual precipitation, and Table 3 lists the proposed elevation zones to be used for subdivision of the watershed.

Table 2 – Proposed Subdivision of American River Watershed into Zones of Mean Annual Precipitation

ZONES OF MEAN ANNUAL PRECIPITATION (inches)													
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Range	20-28	28-32	32-36	36-40	40-44	44-48	48-52	52-56	56-60	60-64	64-68	68-72	72-80
Median	26 in	30 in	34 in	38 in	42 in	46 in	50 in	54 in	58 in	62 in	66 in	70 in	74 in

Table 3 – Proposed Subdivision of American River Watershed into Elevation Zones

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

DISTRIBUTION PARAMETERS FOR BASIN-WIDE ALLOCATION OF SNOWPACK

Spatial allocation of snowpack using stochastic simulation requires that distribution parameters theta (θ), mu$_{50}$ (μ_{50}) and sigma (σ) be determined for each of the elevation zones identified in Table 3. The distribution parameters were determined using the findings of the regression analyses presented in the previous sections. The resultant distribution parameter sets for the mean annual precipitation zone of 50 inches are contained in Appendix A, and the parameter set for the end-of-January is listed in Table 4. Quantile estimates of snow-water equivalent are also shown in Table 4 for selected exceedance probabilities to provide a perspective on snowpack variability.

Table 4 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-January

	DISTRIBUTION PARAMETERS								
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	0.808	0.486	0.262	0.120	0.044	0.015	0.000	0.000
MU$_{50}$		-0.108	0.731	1.450	2.048	2.525	2.881	3.117	3.180
Sigma		0.937	0.835	0.746	0.671	0.609	0.561	0.515	0.507
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	4.1	7.8	8.5
90%	0.0	0.0	0.0	0.0	0.0	4.8	8.3	11.7	12.6
50%	0.0	0.0	0.4	3.0	6.9	12.1	17.6	22.6	24.0
10%	0.0	0.9	4.3	9.7	17.4	26.8	36.4	43.7	46.0
2%	0.0	2.9	9.1	18.0	29.8	43.4	56.6	65.3	68.5

CORRELATION OF SNOWPACK WITH ANTECEDENT PRECIPITATION

The temporal variability of snowpack due to year-to-year and month-to-month variability resulting from wet or dry climatic years is accounted for by correlation with antecedent precipitation. The Lake Spaulding station was selected as the key precipitation station for use in developing the relationship between antecedent precipitation and snowpack. It has a long, high-quality record, is a high-elevation gage (5155 feet), and is located near the upper portion of the watershed where snowpack accumulates.

Standard log-log regression analyses[3] were conducted between antecedent precipitation at the Lake Spaulding station and end-of-month snow-water equivalent at several snotel sites. Regression analyses for the Alpha, Gold Lake, and Huysink snotel stations produced similar results with correlation coefficients increasing to a maximum in mid-winter and decaying in the early-spring (Figure 9a). The Alpha snotel station was selected as the key snowpack station (Figure 9b) because it is more centrally located within the watershed, is at the highest elevation of the three stations, and is generally more representative of the basin-wide snowpack characteristics.

The Lake Spaulding station and Alpha snotel stations exhibit strong correlation (Figure 9b) through the winter snowpack season despite being 42 miles apart. This high level of correlation is primarily due to the fact that the correlation of multi-month precipitation decays slowly with distance in mountain areas on the west coast of the United States and the Alpha snotel site is at a high elevation (7,600 feet) where much of the precipitation occurs as snowfall.

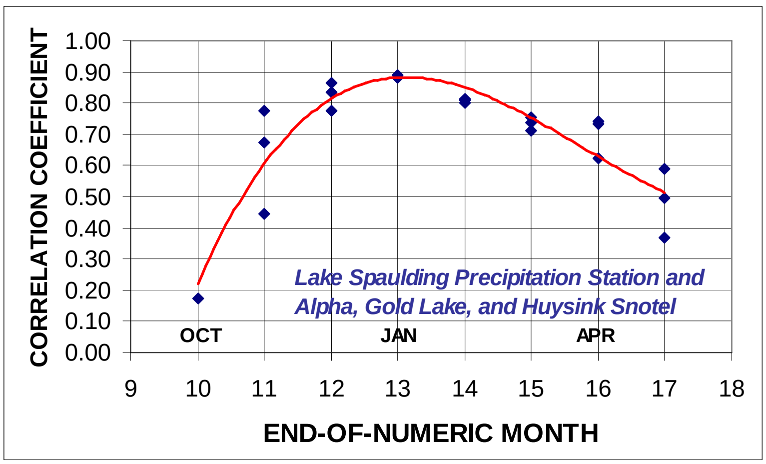

Figure 9a – Seasonal Variation of Correlation Coefficients for Log-Log Regression of Snow-Water Equivalent at Alpha, Gold Lake and Huysink Snotel Sites with with Lake Spaulding Antecedent Precipitation

The end-of-month regression parameters for the relationship between Lake Spaulding antecedent precipitation and the Alpha snotel site are listed in Table 5, where α is the intercept, β is the slope, and ρ is the correlation coefficient for log-log regression. A typical regression solution is shown in Figure 10 for the end-of-January.

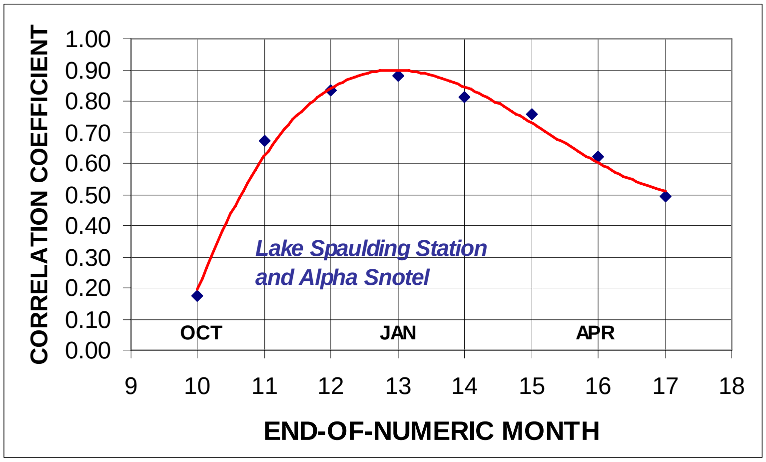

Figure 9b – Seasonal Variation of Correlation Coefficient for Log-Log Regression of Alpha Snotel Snow-Water Equivalent with Lake Spaulding Antecedent Precipitation

Table 5 – Log-Log Regression Parameters for Relationship Between Antecedent Precipitation at Lake Spaulding Station and Snow-Water Equivalent at Alpha Snotel Station

REGRESSION PARAMETERS								
PARAMETERS	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**
Intercept (α)	-0.280	-1.156	-1.109	0.119	0.400	0.100	-2.594	-2.562
Slope (β)	0.229	1.029	1.112	0.818	0.773	0.836	1.381	1.266
Correlation Coefficient (ρ)	0.173	0.664	0.833	0.880	0.820	0.753	0.604	0.494
Standard Deviation SWE	0.973	0.999	0.957	0.558	0.479	0.476	0.813	0.812

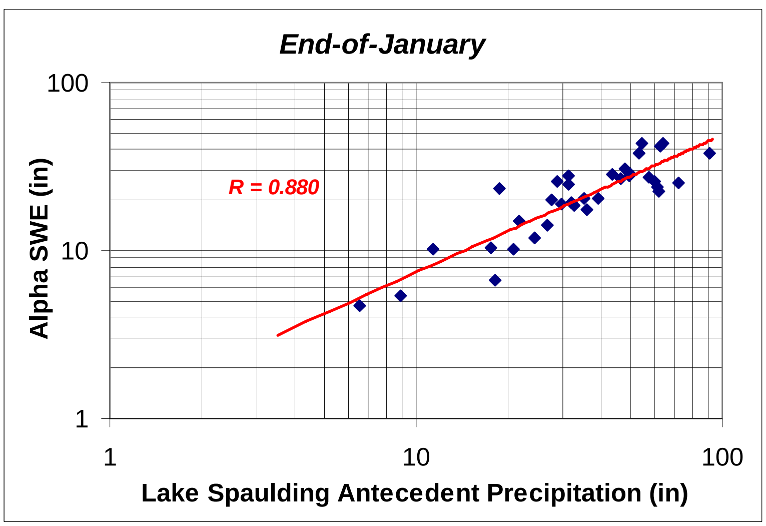

Figure 10 – Log-Log Regression of Alpha Snotel Snow-Water Equivalent with Lake Spaulding Antecedent Precipitation for End-of-January

STOCHASTIC SIMULATION OF SNOWPACK SNOW-WATER EQUIVALENT

For each simulation, a snowpack snow-water equivalent value is needed for locations within each zone of elevation and mean annual precipitation. This will be accomplished in four steps.

Step 1 – Determine snow-water equivalent at key snowpack station (Alpha snotel site)

A value of snow-water equivalent for the key snowpack station (Alpha snotel site) is determined based upon the value of antecedent precipitation that is selected for the key precipitation station (Lake Spaulding precipitation station) and the logarithmic correlation relationship between the two key stations:

$$LN\,(y) \;=\; \alpha \;+\; \beta\, LN\,(x) \;+\; \varepsilon \qquad (6)$$

$$SWE \;=\; EXP\;[LN\,(\,y\,)\,] \qquad (7)$$

where: y is the end-of-month snow-water equivalent, x is the end-of-month antecedent precipitation, alpha (α) and beta (β) are intercept and slope parameters, ε is a Normally distributed error term that accounts for the unexplained variance, and *SWE* is the snow-water equivalent at the key snowpack station.

Step 2 – Compute exceedance probability of snow-water equivalent at key snowpack station

The exceedance probability of the value of snow-water equivalent from step 1 is computed for the key snowpack station based on the mixed distribution (Equation 1) and the distribution parameters for the key snowpack station.

Step 3 – Assemble distribution parameters needed for all elevation zones

Retrieve the distribution parameters from Appendix A for each of the 9 zones of elevation. For each elevation zone, use Equation 5 to rescale the mean (μ_{50}) applicable to a zone of 50 inches mean annual precipitation to the mean value (μ) applicable to each of the 13 zones of mean annual precipitation. This represents 117 (13x9) parameter sets.

Step 4 – Spatially allocate the snowpack snow-water equivalent

Determine the snowpack snow-water equivalent applicable to each of the 117 combinations of mean annual precipitation and elevation zones using the parameter sets from step 3 and the exceedance probability for the key snowpack station computed in step 2. Spatially allocate the snowpack throughout the watershed based on the area within each subbasin that corresponds to the various combinations of the zones of mean annual precipitation and elevation.

This procedure is an adaptation of the methodology used in the Stochastic Event Flood Model (SEFM)[11]. It preserves the historical seasonal basin-wide snowpack magnitude-frequency characteristics, and the historical seasonal relationships between antecedent precipitation and snow-water equivalent. The spatial allocation algorithm utilizes the same exceedance probability for snow-water equivalent at all sites in the watershed.

For the algorithm proposed here, this infers that the correlation coefficients between snow-water equivalent values for sites within the watershed are near unity – particularly in the upper elevations of the watershed were the majority of the snowpack occurs. Figure 11 depicts the average inter-site correlation between the Alpha, Gold Lake and Huysink snotel sites. These sites have inter-site distances of 60-miles, 37-miles, and 24-miles, for an average of about 40-miles. It is seen in Figure 11 that there is a very high level of correlation for these stations that are representative of the primary snowpack accumulation zones within the watershed. Thus, the proposed algorithm is a practical approach for spatial allocation of snowpack.

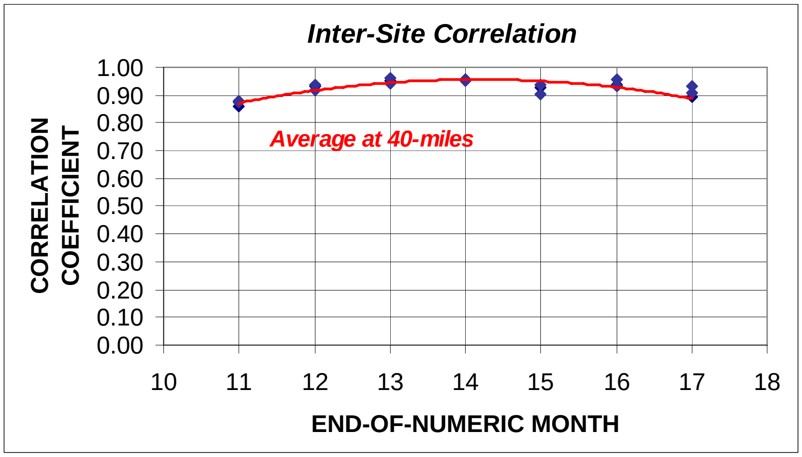

Figure 11 – Seasonal Variation of Inter-Site Correlation of Snow-Water Equivalent Values for Alpha, Gold Lake and Huysink Snotel Sites

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APPENDIX A

DISTRIBUTION PARAMETERS FOR SNOW-WATER EQUIVALENT FOR ELEVATION ZONES IN AMERICAN RIVER WATERSHED

DISTRIBUTION PARAMETERS FOR BASIN-WIDE ALLOCATION OF SNOWPACK

Spatial allocation of snowpack snow-water equivalent (SWE) using stochastic simulation requires that distribution parameters theta (θ), mu$_{50}$ (μ_{50}) and sigma (σ) be determined for each of the nine elevation zones. The distribution parameters were determined using the findings of the regression analyses for snow-water equivalent. The distribution parameter sets for end-of-month SWE for the mean annual precipitation zone of 50 inches are listed below. Quantile estimates of snow-water equivalent are also shown for selected exceedance probabilities to provide a perspective on snowpack variability.

Table A1 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-October

	DISTRIBUTION PARAMETERS								
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	1.000	1.000	0.936	0.862	0.799	0.743	0.694	0.649
MU$_{50}$				-0.430	-0.135	0.118	0.339	0.535	0.712
Sigma				0.650	0.650	0.650	0.650	0.650	0.650
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10%	0.0	0.0	0.0	0.0	0.6	1.1	1.7	2.3	2.9
2%	0.0	0.0	0.0	0.9	1.7	2.6	3.5	4.6	5.7

Table A2 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-November

	DISTRIBUTION PARAMETERS								
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	0.929	0.709	0.520	0.362	0.235	0.138	0.072	0.036
MU$_{50}$		-0.333	0.135	0.508	0.819	1.085	1.318	1.525	1.711
Sigma		1.102	1.025	0.964	0.913	0.869	0.830	0.796	0.765
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.7
50%	0.0	0.0	0.0	0.0	1.1	2.1	3.2	4.3	5.3
10%	0.0	0.0	1.7	3.6	5.7	7.8	10.1	12.3	14.5
2%	0.0	1.4	5.3	8.9	12.5	16.1	19.7	23.2	26.5

Table A3 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-December

DISTRIBUTION PARAMETERS									
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	0.838	0.514	0.287	0.138	0.053	0.013	0.001	0.000
MU_{50}		-0.108	0.604	1.118	1.559	1.928	2.225	2.451	2.604
Sigma		0.921	0.869	0.827	0.792	0.762	0.736	0.712	0.691
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	1.5	2.6	3.3
90%	0.0	0.0	0.0	0.0	0.0	2.0	3.4	4.6	5.6
50%	0.0	0.0	0.0	2.0	4.1	6.5	9.2	11.6	13.5
10%	0.0	0.7	3.7	7.5	12.2	17.8	23.6	28.9	32.8
2%	0.0	2.6	8.3	14.9	23.2	32.6	42.1	50.4	56.3

Table A4 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-January

DISTRIBUTION PARAMETERS									
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	0.808	0.486	0.262	0.120	0.044	0.015	0.000	0.000
MU_{50}		-0.108	0.731	1.450	2.048	2.525	2.881	3.117	3.180
Sigma		0.937	0.835	0.746	0.671	0.609	0.561	0.515	0.507
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	4.1	7.8	8.5
90%	0.0	0.0	0.0	0.0	0.0	4.8	8.3	11.7	12.6
50%	0.0	0.0	0.4	3.0	6.9	12.1	17.6	22.6	24.0
10%	0.0	0.9	4.3	9.7	17.4	26.8	36.4	43.7	46.0
2%	0.0	2.9	9.1	18.0	29.8	43.4	56.6	65.3	68.5

Table A5 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-February

DISTRIBUTION PARAMETERS									
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	0.849	0.537	0.308	0.149	0.049	0.005	0.000	0.000
MU_{50}		-0.466	0.621	1.540	2.291	2.874	3.289	3.370	3.430
Sigma		1.183	0.967	0.786	0.641	0.532	0.458	0.450	0.450
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	9.9	11.5	12.2
90%	0.0	0.0	0.0	0.0	0.0	7.5	14.7	16.3	17.3
50%	0.0	0.0	0.0	2.9	8.6	17.1	26.7	29.1	30.9
10%	0.0	0.4	4.0	10.7	21.1	34.4	48.1	51.8	55.0
2%	0.0	2.3	9.8	20.8	35.5	52.4	68.9	73.6	78.2

Table A6 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-March

DISTRIBUTION PARAMETERS									
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	0.853	0.678	0.542	0.358	0.044	0.000	0.000	0.000
MU_{50}		-0.543	0.576	1.528	2.312	2.930	3.381	3.520	3.630
Sigma		1.270	1.049	0.860	0.703	0.579	0.487	0.450	0.425
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	10.8	13.4	15.7
90%	0.0	0.0	0.0	0.0	0.0	7.5	15.8	19.0	21.9
50%	0.0	0.0	0.0	0.0	5.9	18.1	29.4	33.8	37.7
10%	0.0	0.3	3.0	9.0	20.5	38.7	54.8	60.1	65.0
2%	0.0	2.3	8.9	20.1	37.7	61.2	80.2	85.5	90.7

Table A7 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-April

DISTRIBUTION PARAMETERS									
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	1.000	1.000	0.950	0.800	0.400	0.125	0.080	0.060
MU_{50}				0.627	1.737	2.606	3.233	3.450	3.620
Sigma				1.071	0.943	0.829	0.727	0.638	0.561
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.6	14.2
50%	0.0	0.0	0.0	0.0	0.0	6.1	22.3	29.4	35.7
10%	0.0	0.0	0.0	0.0	5.7	30.1	60.8	69.1	75.1
2%	0.0	0.0	0.0	2.4	19.0	62.3	109.1	114.8	117.2

Table A8 – Distribution Parameters and Quantile Estimates for Snow-Water Equivalent for End-of-May

DISTRIBUTION PARAMETERS									
ELEVATION ZONE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MEDIAN ELEVATION	**2000 ft**	**2800 ft**	**3600 ft**	**4400 ft**	**5200 ft**	**6000 ft**	**6800 ft**	**7600 ft**	**8400 ft**
Theta	1.000	1.000	1.000	1.000	0.950	0.679	0.529	0.396	0.275
MU_{50}					-0.595	1.272	2.658	3.250	3.450
Sigma					1.223	1.050	0.899	0.764	0.643
Exceedance Probability	**SNOW-WATER EQUIVALENT (INCHES)**								
98%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.6	22.9
10%	0.0	0.0	0.0	0.0	0.0	6.0	29.2	54.1	63.4
2%	0.0	0.0	0.0	0.0	0.8	18.0	67.5	105.6	108.7