US Army Corps
of Engineers
Hydrologic Engineering Center

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

Appendix K - Analysis of Historical Reservoir Operations at Folsom Dam and Development of a Stochastic Model for Simulation of Initial Reservoir Storage

September 2005

Approved for Public Release. Distribution Unlimited.

RD-48K

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
September 2005	Research Document	

4. TITLE AND SUBTITLE	
Stochastic Modeling of Extreme Floods on the American River at Folsom Dam Appendix K - Analysis of Historical Reservoir Operations at Folsom Dam and Development of a Stochastic Model for Simulation of Initial Reservoir Storage	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)	8. PERFORMING ORGANIZATION REPORT NUMBER
US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC) 609 Second Street Davis, CA 95616-4687	RD-48K

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: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	26	19b. TELEPHONE NUMBER

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

Appendix K - Analysis of Historical Reservoir Operations at Folsom Dam and Development of a Stochastic Model for Simulation of Initial Reservoir Storage

September 2005

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-48K

ANALYSIS OF HISTORICAL RESERVOIR OPERATIONS AT FOLSOM DAM AND DEVELOPMENT OF A STOCHASTIC MODEL FOR SIMULATION OF INITIAL RESERVOIR STORAGE

December 16, 2002
Revised December 10, 2003

OVERVIEW

Information about historical reservoir operations at Folsom Dam is needed to set initial reservoir storage levels for the stochastic modeling of extreme floods on the American River. The maximum reservoir level produced by an extreme flood is, in part, dependent upon the initial reservoir level at the start of the flood. The magnitude of reservoir storage is generally lower in dry water-years and higher in wet water-years. In particular, experience at other dam and reservoir projects has shown that reservoir storage levels are often correlated with antecedent precipitation that reflects dry versus wet water-years. This relationship allows for development of a stochastic simulation procedure for generation of initial reservoir storage values at Folsom Reservoir.

This report describes the methods that were used to analyze historical reservoir operations and the procedures that were developed for the simulation of end-of-month reservoir storage. These analyses were conducted using end-of-month storage values because end-of-month conditions are used in the stochastic modeling of extreme floods for the period from end-of-October to end-of-April.

HISTORICAL RESERVOIR OPERATIONS

Four different reservoir rule curves have been used since reservoir operations began in 1956. Each evolution of the rule curve came in response to the occurrence of a drought or flood that highlighted shortcomings in the previous rule curve. These changes to the rule curve added to the complexity of the analysis of historical reservoir operations. In addition, different antecedent precipitation indices have been used for reservoir management at Folsom Reservoir and for developing a stochastic simulation model. Efforts have been made in this report to clearly identify which of the antecedent precipitation indices[2,3,7,10] is being used in a given application.

Reservoir Rule Curve 1 (1956-1976)

The original reservoir rule curve[2,3] was developed based on streamflow and flood records for the first half of the 20th century. It was intended to balance the competing needs of floodwater storage and water supply. The rule curve permitted earlier filling of the reservoir for water supply during those years when the flood potential was lower, as indicated by the 60-day Antecedent Precipitation Index (60-Day API). Reservoir Rule Curve 1 is depicted in Figure 1, where it is seen that the target maximum reservoir storage was determined based on the watershed-average precipitation that occurred during the prior 60-days (60-Day API).

<u>60-Day Antecedent Precipitation Index</u> **–** For these analyses, the 60-day antecedent precipitation index was computed using precipitation measurements at Blue Canyon, Colfax, Placerville, Repressa, Soda Springs and Twin Lakes stations. The 60-Day API was computed as the cumulative precipitation for the 60-days prior to the end-of-month of interest based on a procedure (Equation 1) developed by the Sacramento District COE[2]. This procedure essentially weights the precipitation from each station equally and adjusts the 60-day precipitation from the stations to be representative of a network of stations with an annual average precipitation of 52.7-inches. The normalizing nature of this computational procedure greatly minimizes

differences in the index value that may occur due to the choice of the stations used in computing the index.

$$60\text{-}Day\ API = \Sigma P_{60}\ (NAP_{watershed} / \Sigma NAP_{stations}) \quad (1)$$

where: P_{60} is the cumulative precipitation for the prior 60-days at a given station; $NAP_{watershed}$ is the estimated Normal Average Precipitation for the watershed (52.7-inches); and $\Sigma NAP_{stations}$ is the summation of the Normal Annual Precipitation for the six stations (300.6-inches).

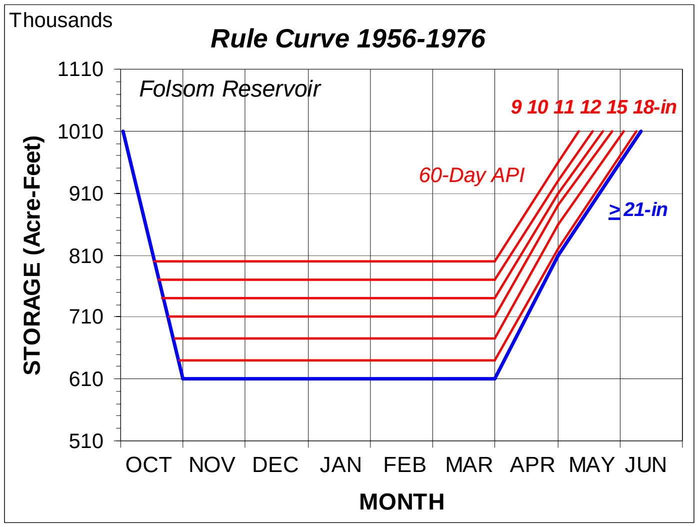

Figure 1 – Reservoir Rule Curve for Target Maximum Allowable Storage for the Period from 1956-1976 for Folsom Reservoir

Reservoir Rule Curve 2 (1977-1986)

The first revision of the rule curve was made for the start of the 1977 water-year. This revision was made[3] after experiencing four floods during the 1956-1976 period that were larger than the previous flood of record, and observing the drought of record in 1976. Three changes were implemented. A seasonal antecedent precipitation index (Seasonal API) replaced the 60-Day API; the API-based operations were delayed from mid-October to the first of January; and more flood storage was provided for a given API (Figure 2). These changes were made to provide greater flood control storage and to smooth out operations when using the API criteria[3].

Seasonal Antecedent Precipitation Index – The Seasonal API was computed using an algorithm developed by the Sacramento District COE[2]. Specifically, the value of the Seasonal API index on a given day is equal to the basin-average precipitation that occurred that day (Equation 2a) plus 97% of the index value for the prior day (Equation 2b). For these analyses, computations began at the start of the water-year and precipitation was measured at the Blue Canyon, Colfax, Placerville, Repressa, Lake Spaulding and Twin Lakes stations. The Lake Spaulding station replaced the Soda Springs station because of several periods of missing record at the Soda Springs station.

$$P_{currentday} = \Sigma P_{daily}\ (NAP_{watershed} / \Sigma NAP_{stations}) \quad (2a)$$

$$Seasonal\ API_{currentday} = P_{currentday} + 0.97(Seasonal\ API_{priorday}) \quad (2b)$$

where: $P_{currentday}$ is the estimate of the basin-average precipitation for the current day; and P_{daily} is the daily precipitation for the current day at a given station.

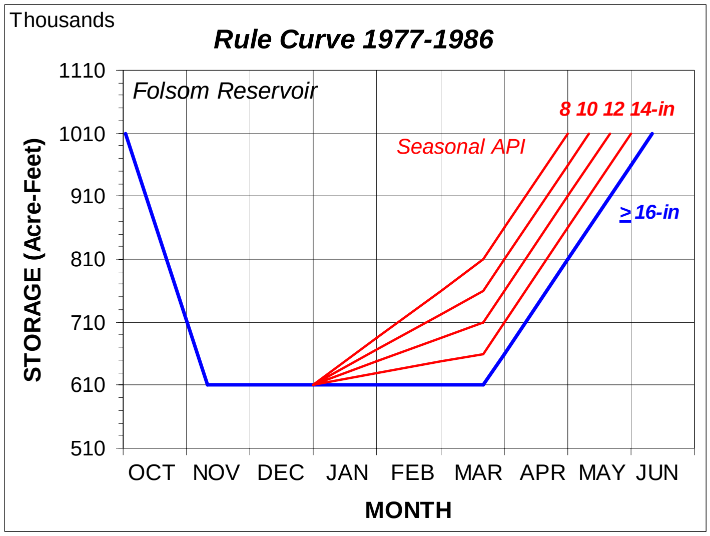

Figure 2 – Reservoir Rule Curve for Target Maximum Allowable Storage for the Period from 1977-1986 for Folsom Reservoir

Examples of the Seasonal API are shown in Figure 3 for the 1981 and 1982 water-years. The seasonal API is used for both Rule Curve 2 (Figure 2) and Rule Curve 3 (Figure 4). The relatively rapid fluctuations in the index undoubtedly added to the difficulty in operating the reservoir during periods when the API value was in the range of 8-inches to 16-inches during the winter period.

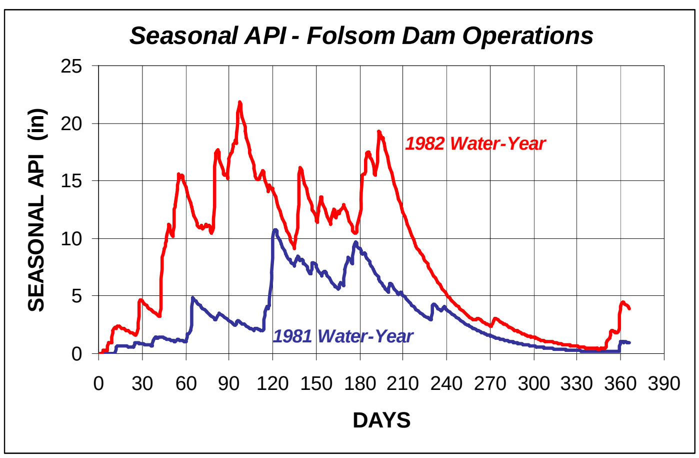

Figure 3 – Seasonal API for the 1981 and 1982 Water-Years

Reservoir Rule Curve 3 (1987-1992)
The second revision of the rule curve was made for the start of the 1987 water-year. This revision was made in response to the occurrence of the flood of record in February 1986. The changes included increasing the magnitude of storage for flood control for a given value of Seasonal API and to delay the API-based operation until later in the flood season[3]. Figure 4 depicts the new rule curve for maximum allowable reservoir storage.

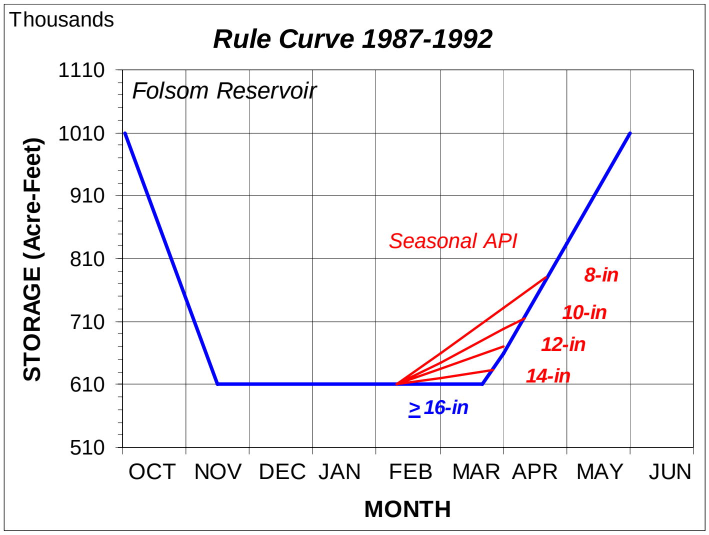

Figure 4 – Reservoir Rule Curve for Target Maximum Allowable Storage for the Period from 1987-1992 for Folsom Reservoir

Reservoir Rule Curve 4 (1993-present)

The third revision of the rule curve[3] was made for the start of the 1993 water-year. This revision was made to further increase storage for flood control. The changes included allocating more storage for flood control by purchasing storage rights from water users. In addition, the Seasonal API was replaced by a measure of the storage available in upstream reservoirs[2] as a means to better account for storage of floodwaters in the watershed (Figure 5).

Measure of Upstream Storage – Floodwater storage available at upstream reservoirs was computed as the total storage available for floodwaters at the Hell Hole, Union Valley, and French Meadows reservoirs. Table 1 lists summary statistic for end-of-month storage available at the three upstream reservoirs. A review of the summary statistics indicates that, in the majority of years, more than 200,000 acre-feet of combined storage is available in the upstream reservoirs. It should be noted that the actual storage available is not used in the procedure for reservoir operations. Instead, the storage available in a given reservoir is limited in the procedural scheme to a maximum value. This procedure is discussed in the next section.

Table 1 – Summary Statistics for End-of-Month Combined Floodwater Storage Availability for Hell Hole, Union Valley, and French Meadows Reservoirs

SUMMARY STATISTICS	END-OF-MONTH UPSTREAM STORAGE AVAILABLE (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
Mean	233500	246150	258050	243150	234700	204500	201450
Std Dev	80630	82250	93040	107700	115750	101500	99900
Skewness	0.56	-0.13	-0.79	-0.42	-0.50	-0.17	0.19

As part of the computations for upstream storage, standard procedures[2] set maximum allowable storage values of 80,000 acre-feet, 75,000 acre-feet and 45,000 acre-feet for Hell Hole, Union Valley, and French Meadows reservoirs, respectively. This results in a maximum total storage available of 200,000-acre-feet. Recomputation of available upstream storage using this constraint produces the summary statistics shown in Table 2 for the water-years from 1967-2002.

A review of Table 2 indicates that the uppermost curves for available storage (Figure 5) are used most frequently. The lower curves come into play primarily during wet water-years when storage levels in the upstream reservoirs are above average.

Table 2 – Summary Statistics for End-of-Month Combined Floodwater Storage Availability for Hell Hole, Union Valley, and French Meadows Reservoirs for 1967-2002 Water-Years where Maximum Available Storage is Limited to 200,000-acre-feet

SUMMARY STATISTICS	END-OF-MONTH UPSTREAM STORAGE AVAILABLE (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
Maximum	200000	200000	200000	200000	200000	200000	200000
Minimum	103900	10900	3500	12800	3900	2700	34500
Mean	179400	179200	177100	167200	160900	152100	155600
Std Dev	24290	35780	44830	51950	60020	56670	52710
Skewness	-1.50	-3.26	-2.69	-1.70	-1.51	-1.23	-1.07

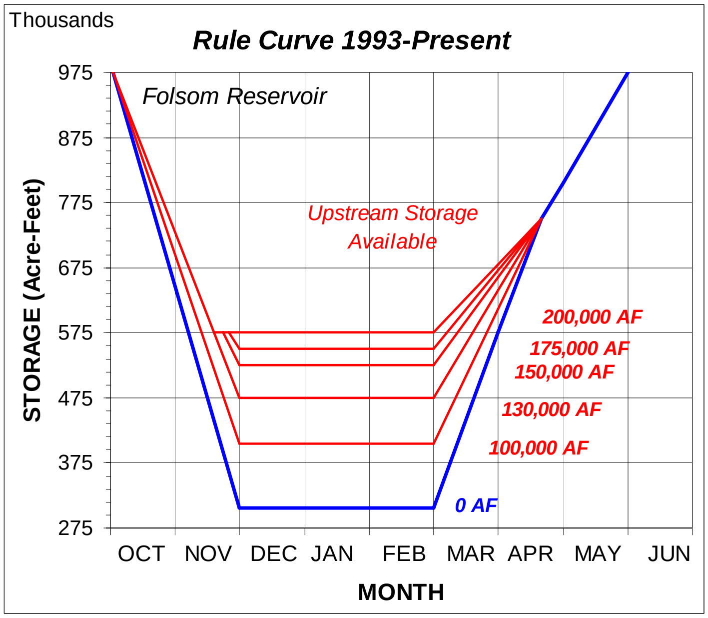

Figure 4 – Reservoir Rule Curve for Target Maximum Allowable Storage for the Period from 1987-1992 for Folsom Reservoir

METHOD OF ANALYSIS

The existence of multiple rule curves required that a common system of measuring initial reservoir storage be employed. A system of departures was utilized to place operations on a common scale. A departure was defined as the difference between the actual reservoir storage value and the target maximum allowable storage computed using the rule curve in existence at the time of observation for a given end-of-month.

$$DS = OS - TMAS \tag{3}$$

where: DS is the departure in storage in acre-feet; OS is the observed end-of-month storage in acre-feet; and $TMAS$ is the end-of-month target maximum allowable storage in acre-feet based on the rule curve in existence at the time of observation.

Positive departures represent reservoir storage (water levels) above the target maximum allowable storage. Negative departures represent reservoir storage below the maximum allowable storage for a given end-of-month. The concept was that the target maximum reservoir level for each rule curve may be different, but the behavior of the departures about that target should be reasonably similar for the various rule curves. Thus, the magnitude and variability of departures provides information about how past operations compare to target maximum storage values.

Computation of Storage Departures

In application of the stochastic flood model, the initial reservoir storage at Folsom Dam is intended to represent conditions prior to the occurrence of extreme storms and floods. To provide compatibility between this intended usage and the method of analysis, it was necessary to examine the end-of-month reservoir storage values to confirm the dataset did not include flood-related storage values. This was accomplished by examining the record of end-of-month storage in conjunction with the record of largest 72-hour precipitation events[8] to identify end-of-months dates where the storage level might reflect an ongoing flood event. It was found that moderate to large floods were ongoing for the end-of-month dates for Jan 1967, Dec 1981, Dec 1982, Dec 1983, and Dec 1996. The storage values on these end-of-month dates were replaced by a storage value representative of conditions prior to the flood event. After these adjustments were made, departures were computed as described in Equation 3 for end-of-month storage at Folsom Reservoir.

Figure 6a depicts departures in reservoir storage for the period in each water-year from the end-of-October through the end-of-April. Departures from Mean Annual Precipitation at the Lake Spaulding precipitation station were also computed (Figure 6b) in order to place the storage departures in perspective relative to the occurrence of wet and dry years. Comparison of these two figures indicates that departures from maximum allowable reservoir levels vary with the magnitude of annual precipitation. The 1976-1977 drought and the sequence of dry years from 1988-1992 are clearly reflected in unusually large negative departures in reservoir storage. Conversely, the wet-years from 1982-1984 are seen to have small departures in reservoir storage.

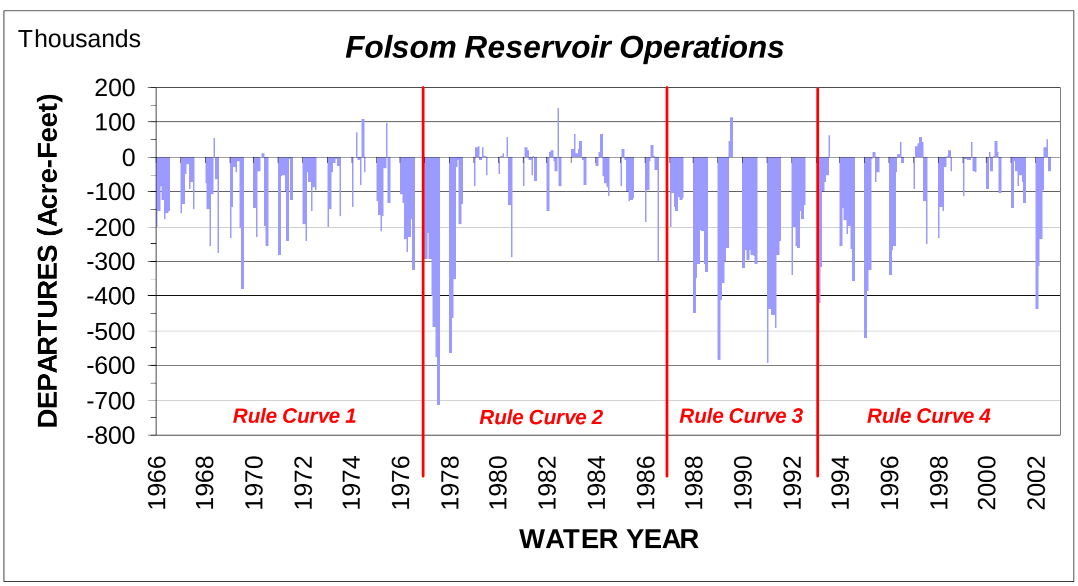

Figure 6a – Departures from Target Maximum Allowable Reservoir Operating Levels at Folsom Reservoir

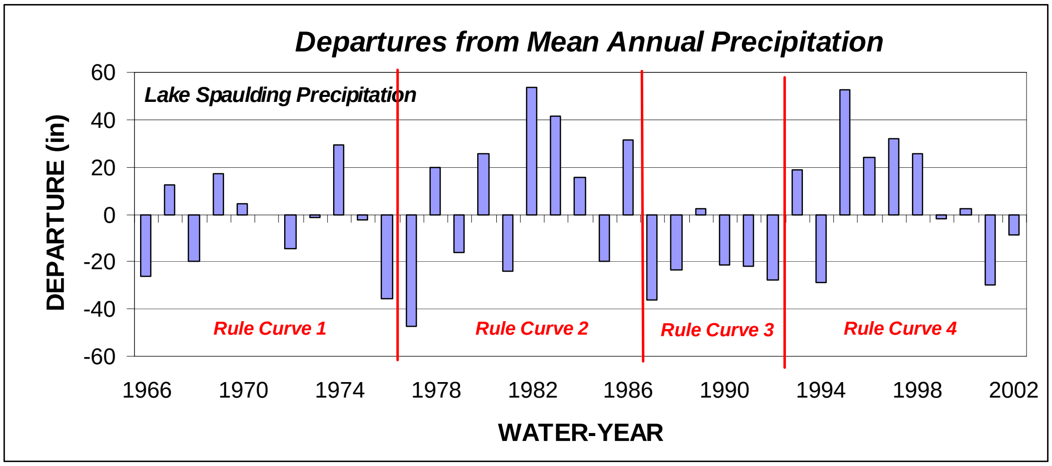

Figure 6b – Departures from Mean Annual Precipitation at Lake Spaulding Precipitation Station

STORAGE DEPARTURE DATA REPRESENTATIVE OF CURRENT OPERATIONS

The findings of analyses of storage departures are used to develop a stochastic model for simulation of end-of-month reservoir storage at Folsom Dam. Therefore, it is desirable to use as much of the historic reservoir departure data as possible to provide for the description of reservoir operations over a wide range of climatic conditions. However, the existence of four separate rule curves raised questions about the appropriateness of combining storage departure data from the four periods for analysis. One perspective is that all four rule curves represent maximum allowable storage levels and that operators/managers would have attempted to be near but below these target values for all rule curves. However, this perspective does not account for the changing priorities that have occurred over time in operating the reservoir for the competing goals of flood control, water supply, fisheries, and recreation.

For example, it is likely that operations under Rule Curve 2 were biased in favor of reservoir filling for water supply after experiencing the severe drought of 1976-1977. The smallest negative departures in the 36-year period are seen to occur under Rule Curve 2. This is partially explained by this being a generally wetter than average period, however the departures are still smaller here than in other similarly wet periods. The bias towards water supply appears to end after experiencing the February 1986 flood. The negative departures under Rule Curve 3 are the largest for any of the rule curves, as there now appears to be a bias towards assuring adequate storage for flood control. Operations under Rule Curve 3 also coincide with one of the drier periods in the record, which makes it more difficult to attribute what portion of the departures are due to a possible flood control bias and what portion are due to below average precipitation/runoff.
In short, all of these factors add to the complexity of determining/selecting the departure data that are representative of current operating conditions.

As a starting point, operations under Rule Curve 4 represent current operational procedures and priorities and are an obvious choice for characterizing future operational procedures. The question can then be framed as – what storage departure data from Rule Curves 1, 2 or 3 can be grouped with departures for Rule Curve 4 for analysis? This question was addressed in several steps. First, summary statistics for storage departures were examined in each of the periods governed by the remaining three rule curves. A review of Tables 3a,b shows high variability in the sample means and standard deviations for storage departures for the various rule curves. Statistical tests were conducted for the hypothesis of equal variances with Rule Curve 4 against the two-sided alternative of unequal variances with the other three rule curves for the various months. Statistical tests were also conducted for the hypothesis of equal mean values with Rule Curve 4 against the two-sided alternative of unequal means with the other three rule curves for the various months. The null hypothesis of equal variances and equal mean values was rejected at the 95% significance level for several months for the various rule curves as indicated by the yellow highlighted cells in Tables 3a,b.

Table 3a – Mean Values of End-of-Month Departures for Rule Curves 1, 2, 3 and 4

RULE CURVE	MEAN VALUES OF END-OF-MONTH DEPARTURES (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
#1 (1966-1976)	-169955	-141636	-88909	-84527	-87118	-70927	-190545
#2 (1977-1986)	-149490	-59840	-51060	-55640	-65810	-101160	-194510
#3 (1987-1992)	-414677	-295070	-304248	-274991	-252995	-186842	-170651
#4 (1993-2002)	-279142	-164627	-151963	-52380	-13367	-49873	-96191

Table 3b – Standard Deviation of End-of-Month Departures for Rule Curves 1, 2, 3 and 4

RULE CURVE	STANDARD DEVIATION OF END-OF-MONTH DEPARTURES (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
#1 (1966-1976)	59320	67299	101875	82142	100969	110424	103700
#2 (1977-1986)	170545	163605	145255	125980	159032	190632	201809
#3 (1987-1992)	155829	128859	103332	102224	133607	135071	163479
#4 (1993-2002)	179446	171434	132070	76465	75788	94755	121745

A second analysis of storage departure data was made by examining the relationship between the magnitude of departures and the occurrence of wet and dry water-years. Figure 7 depicts a scatterplot of storage departures versus antecedent precipitation for the Lake Spaulding precipitation station. The Lake Spaulding precipitation station was chosen because it is used in the stochastic flood model as an explanatory variable for simulation of several of the hydrometeorological inputs. Antecedent precipitation in this application is cumulative precipitation from the start of the water-year through the end-of-month of interest[7]. It should be noted that this definition of antecedent precipitation is different from the 60-Day API and Seasonal API used for reservoir regulation. This definition of antecedent precipitation will be used throughout the remainder of this report.

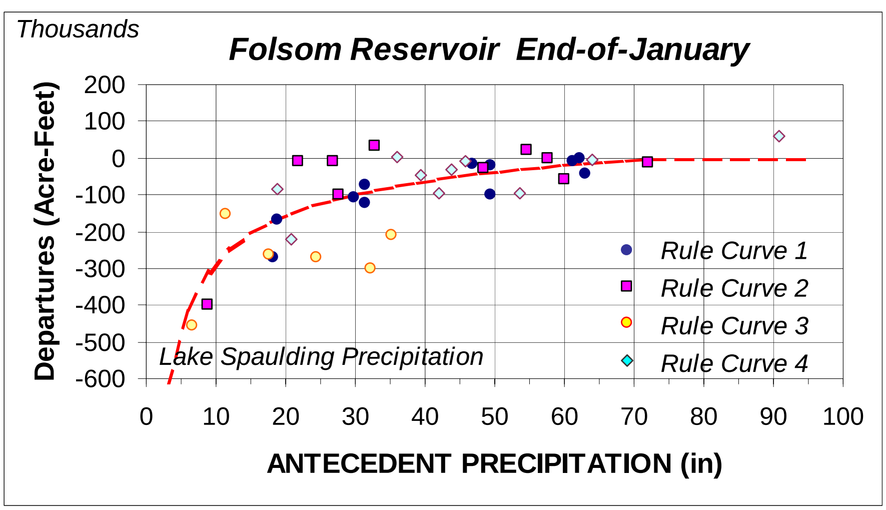

Figure 7 – Scatterplot of Storage Departures for End-of-January versus Antecedent Precipitation at Lake Spaulding Precipitation Station

A review of Figure 7 shows the storage departures are correlated with antecedent precipitation. Thus, some of the variability in storage departures seen in Tables 3a,b is attributable to the occurrence of wet or dry years. There is a reasonable grouping of the departure data about the general trend line except for the data from Rule Curve 2, which have mostly near-zero departures and reside predominately at or above the general trend line. These results support the conclusion that operations under Rule Curve 2 were biased towards assuring adequate water supplies following the 1976-1977 drought.

Interpretation of Behavior of Storage Departure Data

The results from the analyses described above were interpreted as follows. Early in the water-year, the magnitude of storage departures primarily reflects carryover storage and limited runoff for refilling. As the water-year progresses into winter and early-spring, the magnitude of departures reflect reservoir management priorities in attempting to balance competing goals of reserving storage for flood control, filling to provide for irrigation water supply, releases for power production, releases for maintaining in-stream flows for fisheries, and reservoir filling for the summer recreation season.

Rule Curve 1 – There are large differences between the standard deviations of storage departures for Rule Curves 1 and 4 for the months of October and November. This is indicated by rejection of the null hypothesis of equal variances for these months (Table 3b). Carryover storage from the prior water-year is the dominant factor in the resultant storage departures for these months. This suggests possible broad-based differences in reservoir management between Rule Curve 1 and 4. Much has changed between 1956 and the present time with regard to sensitivities and priorities for flood control, water supply, fisheries and recreation. Given the large time gap between Rule Curves 1 and 4 and the evolution of reservoir management priorities, there are questions about the appropriateness of combining storage departure data from these two periods. However, there is nothing in the summary statistics or behavior of the storage departure datasets for the months of December through April that would warrant removal of these data from analysis. Based on the foregoing, storage departure data from the Rule Curve 1 period were treated as follows. Data from the months of October and November were not combined with data from the Rule Curve 4 period. Data from the months of December through April were combined with data from the Rule Curve 4 period.

Rule Curve 2 – As discussed previously, storage departure data for the Rule Curve 2 period appear to be biased towards assuring adequate water supply and were judged not to be representative of the current approach to reservoir management. Thus, storage departure data from the Rule Curve 2 period were not combined with data from the Rule Curve 4 period.

Rule Curve 3 – There are large differences between the mean values of storage departures for Rule Curves 1 and 3 for the months of December, January and February, which resulted in rejection of the null hypothesis of equal mean values for these months (Table 3a). However, these differences in storage departures are largely attributable to the differences in precipitation/runoff in these two short periods. Specifically, the 1987-1992 period for Rule Curve 3 can be described as a multi-year sequence of below-average precipitation/runoff and the current period for Rule Curve 4 contains a majority of years with above-average precipitation/runoff (Figure 6b). General compatibility of these two datasets with the general trend line can be seen in Figure 7. Based on these findings, combining of storage departure data from the Rule Curve 3 period with the Rule Curve 4 period was judged to be acceptable.

Situations where Past and Present Operations were Judged to be Similar – There are two situations where similarity of reservoir operations can be expected for all rule curves. During extreme dry-periods, there is insufficient runoff for significant reservoir filling and reservoir management priorities would be to conserve water and to maximize reservoir filling. During very wet water-years, there is more than enough runoff for reservoir filling and operational decisions must be made to hold the reservoir storage at, or below, the target maximum reservoir storage level for flood control reservation. Recognizing the commonality of reservoir management priorities in these two situations, storage departure data from extreme wet and dry periods from Rule Curves 1, 2 and 3can be combined with storage departure data from the Rule Curve 4 period. In these situations, an extreme wet or dry period was defined as one where the antecedent precipitation for the end-of-month of interest was either greater than (wet period) or less than (dry period) the end-of-month mean of antecedent precipitation at Lake Spaulding by more than 1.25 standard deviations[7].

Augmenting the Dataset of Storage Departures – The data selection decisions discussed above produced a relatively small dataset for use in development of a computer routine for stochastic simulation of end-of-month reservoir storage. It was decided to augment this data by inclusion of storage departure data from the 1992-2002 Rule Curve 4 period for the months prior and posterior to the end-of-month of interest. The premise is that these data generally represent conditions drier than (prior month) and wetter than (posterior month) the month of interest under the current reservoir management priorities. In particular, these data help to further define the relationship between storage departure data and antecedent precipitation for a broader range of climatic conditions.

DEVELOPMENT OF A STOCHASTIC MODEL FOR RESERVOIR STORAGE

The stochastic model for simulation of end-of-month reservoir storage at Folsom Reservoir was developed using the datasets of storage departures described in the previous section. Antecedent precipitation at the Lake Spaulding precipitation station (October 1st to end-of-month of interest) is used in the stochastic flood model as an explanatory variable for several hydrometeorological inputs. It was also used here for developing a stochastic model that preserves the historical trend as well as the unexplained variance in the relationship between storage departures and antecedent precipitation.

Formulation of the Stochastic Model for Simulating Storage in Folsom Reservoir

A stochastic simulation model using information from a linear regression solution[4,6] takes the following general form:

$$y = \alpha + \beta x + \sigma_r Z_n \tag{4a}$$

$$\sigma_r = \sigma_y [1 - \rho^2]^{1/2} \tag{4b}$$

where: y is the response variable; x is the explanatory variable; α is the intercept regression parameter; β is the slope regression parameter; σ_r is the standard deviation of the residuals for the unexplained variance of the regression solution; Z_n is a standardized variate drawn from the standardized Normal distribution N[0,1]; ρ is the correlation coefficient; and σ_y is the standard deviation of the response variable y.

A linear regression model provides the basic framework for the stochastic model, however transforms are needed to yield a linear relationship. A review of Figure 7 shows the relationship between antecedent precipitation and storage departures to be non-linear and the variance of the storage departure data is heteroscedastic. Specifically, the variance of storage departures is greatest for dry years with low antecedent precipitation and smallest for wet years when there is sufficient precipitation and runoff to fill the reservoir to the target maximum allowable storage level.

These issues were addressed as follows. Log-log regression was used to establish the relationship between antecedent precipitation and storage departures. This produced a linear relationship in log-space and eliminated the heteroscedasticity. Since the majority of storage departure data are negative, a transform was necessary that provided a translation and sign change of the storage departure data. Specifically:

$$w = -(DS - 200000) \quad (5)$$

where: w is the translated storage departure value (acre-feet); and DS is the departure in storage (acre-feet).

Substitution of the transforms described above into Equations 4a yields the deterministic component of the regression solution:

$$LN(w) = \alpha + \beta LN(AP_{LS}) \quad (6)$$

where: α is the intercept regression parameter; β is the slope regression parameter; and AP_{LS} is the antecedent precipitation (inches) for the Lake Spaulding precipitation station for the end-of-month of interest.

Figure 8 presents an example correlation relationship of transformed storage departures with antecedent precipitation at Lake Spaulding for the end-of-January. Appendix A contains log-log regression plots for each of the end-of-months from October through April. Table 4 lists the results of the log-log regression analyses and the regression parameters and statistics necessary for development of a stochastic model for initial reservoir storage for each end-of-month.

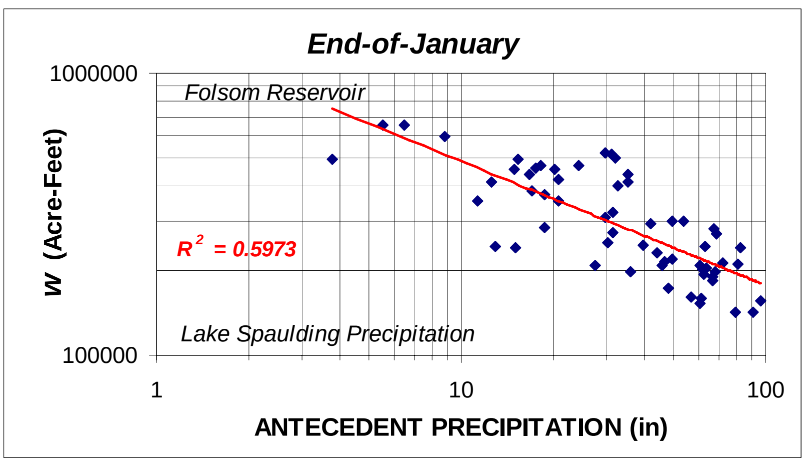

Figure 8 – Relationship of Transformed Storage Departures (w) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-January

Implicit in the formulation of the regression model is the condition that the residuals are Normally distributed about the regression solution. In the case of simulation of reservoir storage, constraints imposed by rule curves and management decisions may invalidate the assumption and use of Normally distributed residuals. This is the case at Folsom Reservoir where operational decisions are routinely made to attain compliance with the rule curve and to be below the target maximum allowable storage for non-storm/flood related periods. Specifically, regulation of reservoir levels and the frequency of management decisions and actions increase as the reservoir level approaches the target maximum allowable storage level. When the reservoir level exceeds the target maximum level, specific actions are required to bring the reservoir level below the target within a reasonable amount of time. These regulatory constraints have the effect of limiting the natural fluctuation of the reservoir during extreme dry and wet years that might otherwise be described by the use of Normally distributed residuals.

Table 4 – Log-Log Regression Solutions for Storage Departures for Folsom Reservoir based on the Regression Form of Equation 6

END-OF-MONTH	SAMPLE SIZE	LOG-LOG REGRESSION PARAMETERS			STANDARD DEVIATION LN (RESIDUALS) LN (σ_r)
		INTERCEPT (α)	SLOPE (β)	CORRELATION COEFFICIENT (ρ)	
OCTOBER	25	13.149	-0.1652	-0.528	0.3345
NOVEMBER	39	13.260	-0.2181	-0.534	0.3065
DECEMBER	54	13.556	-0.2975	-0.578	0.3340
JANUARY	60	14.108	-0.4394	-0.773	0.2370
FEBRUARY	51	14.392	-0.4907	-0.748	0.2555
MARCH	44	14.816	-0.5707	-0.711	0.2780
APRIL	31	15.408	-0.6965	-0.701	0.3420

Recognizing the effects of reservoir regulation on the residuals, the stochastic model must be reformulated to accommodate these constraints. The adopted approach was to use the four-parameter Beta distribution[1,10] for describing the random scatter about the regression solution. The Beta distribution has the advantage of providing a lower and upper bound for the storage departures. Use of a lower bound is consistent with the physical limit of an empty reservoir and management intervention to preserve some minimum conservation pool during protracted dry periods. Use of an upper bound is consistent with reservoir operations that employ rule curves to limit maximum reservoir levels.

A review of the 1967-2002 record for greatest negative storage departures indicates a practical lower limit of –500,000 acre-feet for storage departures for use with Rule Curve 4 for most months. A similar review of maximum positive storage departures during the 1992-2002 period indicates a reasonable upper limit of 60,000 acre-feet for storage departures. Only the later 1992-2002 period was used for estimating the upper bound because it better reflects the current attitudes and operational procedures when the reservoir level exceeds the target storage level. Table 5 lists the lower and upper bounds that were adopted for use with the stochastic model.

Table 5 – Adopted Values of Lower and Upper Bounds for Storage Departures for use with the Stochastic Model for Initial Reservoir Storage at Folsom Reservoir

BOUNDS	END-OF-MONTH STORAGE DEPARTURES (*DS*) (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
LOWER	-550,000	-500,000	-500,000	-500,000	-500,000	-550,000	-600,000
UPPER	60,000	60,000	60,000	60,000	60,000	60,000	60,000
BOUNDS	**TRANSLATED END-OF-MONTH STORAGE DEPARTURES (*w*) (Acre-Feet)**						
	OCT	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**
LOWER	140,000	140,000	140,000	140,000	140,000	140,000	140,000
UPPER	750,000	700,000	700,000	700,000	700,000	750,000	800,000

Lastly, the extreme upper ends of the regression solutions were modified to include an asymptote. The asymptote represents the expected value of the storage departure for those situations where there is more than sufficient runoff for filling to the target maximum allowable storage value. The asymptotic behavior of the storage departure data can be seen at the upper end of the storage departure curve in Figure 7. Analysis of the storage departure data indicates a reasonable value for the asymptote to be –5,000 acre-feet. The effect of the asymptote can be seen in the simulations depicted in Figures 9a where the trend line for the deterministic component of the regression solution converges to a storage departure of –5,000 acre-feet.

Incorporation of the all of the above considerations into the stochastic model for simulation of initial reservoir storage for Folsom Reservoir results in the following:

$$FolsomStorage_{initial} = TMAS + DS \qquad (7a)$$

where the storage departure for the month of interest is simulated using a four-parameter Beta distribution[1,10] with upper and lower bounds as described above and transformed by Equation 5, a standard deviation of the residuals equal to σ_r, and a mean (μ_{ds}) of:

$$\mu_{ds} = \alpha + \beta \, LN\,[AP_{LS}] \qquad (7b)$$

$$\sigma_r = \sigma_{LNw}\,[1 - \rho^2\,]^{1/2} \qquad (7c)$$

Monte-Carlo selection[5,6,10] of a variate from the four-parameter Beta distribution yields a log-transformed w_i value that can be converted to the desired storage departure by:

$$DS = 200000 - EXP[\,w_i\,] \qquad (7d)$$

where: $FolsomStorage_{initial}$ is the storage (acre-feet) in Folsom reservoir at the start of the storm/flood simulation for a given end-of-month; $TMAS$ is the end-of-month target maximum allowable storage (acre-feet) based on Rule Curve 4; DS is the departure in storage (acre-feet); α is the intercept regression parameter; β is the slope regression parameter; AP_{LS} is the antecedent precipitation for the Lake Spaulding precipitation station (inches) for the end-of-month of interest; σ_r is the standard deviation of the residuals for the unexplained variance of the log-log regression solution; ρ is the logarithmic correlation coefficient; and σ_{LNw} is the standard deviation of the log-transformed w variable.

Overview of Simulation Procedure for Folsom Initial Reservoir Storage

The procedures for stochastic simulation of initial reservoir storage at Folsom Reservoir can be described as follows:

1. The end-of-month of occurrence of the extreme storm, the magnitude of antecedent precipitation at the Lake Spaulding precipitation station, and the storage available in the three largest upstream reservoirs would have been selected prior to executing the stochastic model for storage in Folsom Reservoir.
2. The expected value (μ_{ds})of the transformed storage departure variable *w* is computed from Equation 7b using the regression parameters from Table 4 for the selected end-of-month.
3. The standard deviation (σ_r) of the log-transformed residuals would be obtained from Table 4 for the selected end-of-month.
4. The variate w_i is generated based on standard Monte Carlo procedures using the four-parameter Beta distribution using the mean and standard deviation from Steps 2 and 3. The lower and upper bounds of the Beta distribution would be set as LN(*w*) based on translated storage departure values listed in Table 5.
5. The storage departure (*DS*) is computed from Equation 7d using the value of w_i obtained from Step 4.
6. The target maximum allowable reservoir storage (*TMAS*) would be obtained from Rule Curve 4 based on the selected end-of-month and the magnitude of storage available in the three upstream reservoirs.
7. The initial reservoir storage at Folsom Reservoir would be obtained from Equation 7a based on the values of the storage departure (*DS*) and target maximum allowable reservoir storage (*TMAS*) obtained from Steps 5 and 6, respectively.

The results of a 500 sample simulation of the stochastic model for storage departures, as described by Equations 7a-d for the end-of-January, are shown in Figure 9a. The results of the simulation for reservoir storage at Folsom Reservoir are depicted in Figure 9b for the case where the target maximum allowable storage is 575,000 acre-feet (see Rule Curve 4). A review of historical storage departures (Figure 6a) and simulated departures (Figure 9a) shows a relatively high level of variability can be expected in the reservoir storage that will be present prior to the occurrence of an extreme storm and flood. Similar simulation results are obtained for the months from end-of-October through end-of-April.

Table 6a lists the summary statistics obtained from simulation of storage departures with a sample size of 5000 for each end-of-month. In general, the mean value of storage departures tends to approach the target maximum allowable storage as the water-year progresses and antecedent precipitation increases. Also, there is an increase in the percentage of positive departures as the water-year progresses.

Table 6a – Summary Statistics from Stochastic Simulation of Storage Departures for Folsom Reservoir

MEASURE	SUMMARY STATISTICS FOR SIMULATED STORAGE DEPARTURES (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
Mean	-263,900	-162,850	-136,750	-101,600	-93,200	-99,100	-117,900
Standard Deviation	159,000	126,200	133,300	108,100	103,900	120,300	152,800
Skewness	-0.2	-0.6	-0.8	-1.2	-1.2	-1.3	-1.2
Positive Departures	2.4%	6.4%	15.0%	15.9%	17.7%	21.7%	25.4%

Table 6b lists the summary statistics for the 5000 simulation sample sets for end-of-month storage in Folsom Reservoir.

Table 6b – Summary Statistics from Stochastic Simulation of End-of-Month Storage in Folsom Reservoir

MEASURE	SUMMARY STATISTICS FOR SIMULATED RESERVOIR STORAGE (Acre-Feet)						
	OCT	NOV	DEC	JAN	FEB	MAR	APR
Mean	461,100	412,200	438,200	473,400	481,800	580,900	682,100
Standard Deviation	159,000	126,200	133,300	108,100	103,900	120,300	152,800
Skewness	-0.2	-0.6	-0.8	-1.2	-1.2	-1.3	-1.2

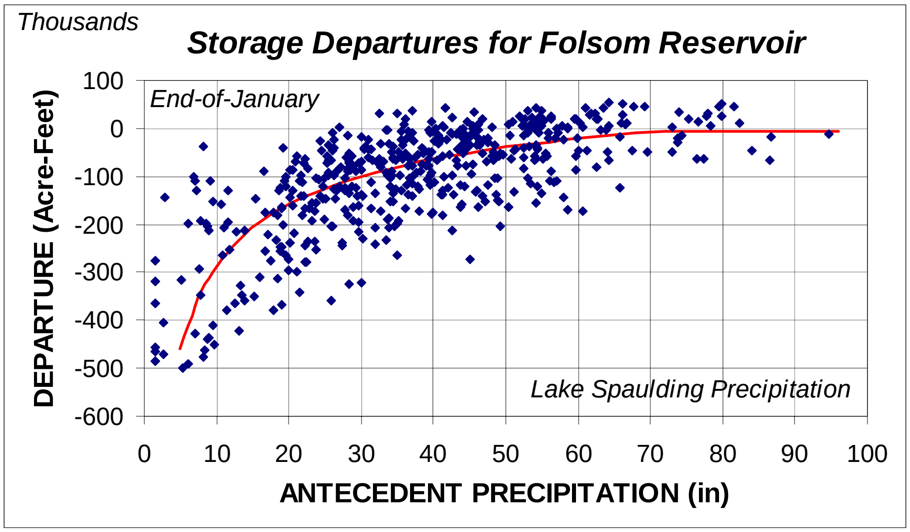

Figure 9a – Example Simulation of Storage Departures (*DS*) for End-of-January for Folsom Reservoir

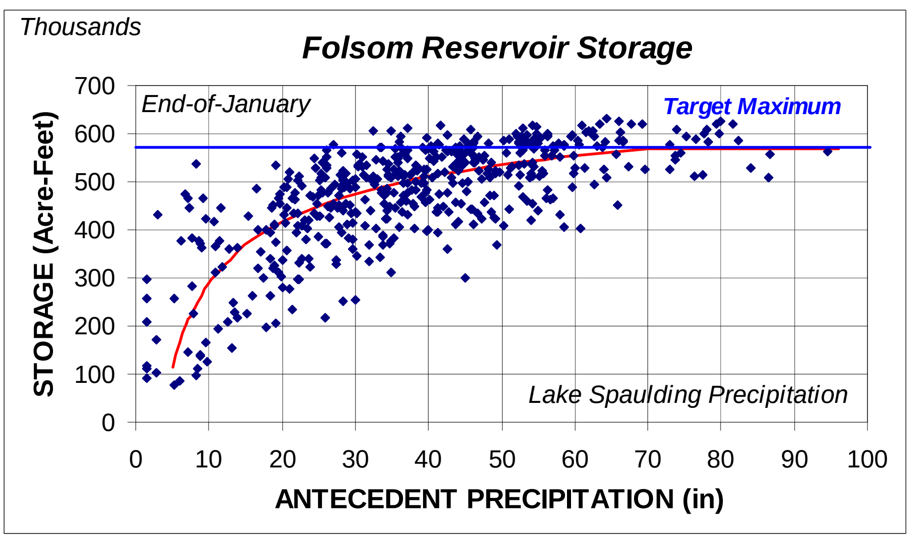

Figure 9b – Example Simulation of Folsom Reservoir Storage for End-of-January for the Case of a Target Maximum Allowable Storage of 575,000 Acre-Feet

REFERENCES

1. Benjamin JR and Cornell CA, Probability, Statistics and Decision for Civil Engineers, McGraw-Hill, 1970.
2. Bond MV and Harris DJ, Personal Communication Regarding Computation of Antecedent Precipitation Indices (API) for Folsom Dam Operations, Sacramento District Corps of Engineers and Hydrologic Engineering Center, Davis CA, November 2002.
3. Davis DW and Feldman AD, Water Control Management of Corps Reservoirs for Climate and Other Variations, Hydrologic Engineering Center, Davis CA.
4. Helsel DR, and Hirsch, RM, Statistical Methods in Water Resources, Studies in Environmental Science 49, Elsevier, 1992.
5. Jain R, The Art of Computer Systems Performance Analysis, John Wiley and Sons, 1991.
6. Salas JD, Delleur JW, Yevdjevich Y, and Lane WL, Applied Modeling of Hydrologic Time Series, Water Resources Publications LLC, 1980.
7. Schaefer MG, and Barker BL, Antecedent Precipitation Characteristics for the American River Watershed, MGS Engineering Consultants Inc, prepared for Hydrologic Engineering Center, US Army Corps of Engineers, December 2000.
8. Schaefer MG, Catalog of Storms for the Spatial Analysis of Storms for the American River Watershed, MGS Engineering Consultants, Inc., prepared for US Army Corps of Engineers Hydrologic Engineering Center, February 2000.
9. Stedinger JR, Vogel RM, and Foufoula-Georgiou, E, Frequency Analysis of Extreme Events, Chapter 18, *Handbook of Hydrology*, McGraw Hill, 1992.
10. SEFM, Stochastic Event Flood Model and Users Manual, MGS Engineering Consultants Inc, developed for the US Bureau of Reclamation, Flood Hydrology Group, 1998.

Appendix A

SCATTERPLOTS FOR REGRESSION ANALYSES OF STORAGE DEPARTURES AT FOLSOM RESERVOIR WITH ANTECEDENT PRECIPITATION AT LAKE SPAULDING PRECIPITATION STATION

SCATTERPLOTS FOR REGRESSION ANALYSES OF STORAGE DEPARTURES AT FOLSOM RESERVOIR WITH ANTECEDENT PRECIPITATION AT LAKE SPAULDING PRECIPITATION GAGE

December 16, 2002

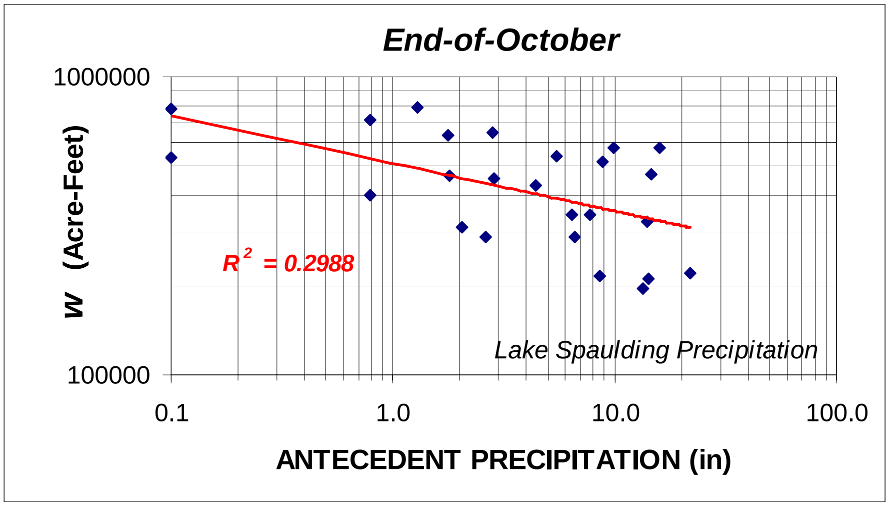

Figure A1 – Relationship of Transformed Storage Departures (*w*) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-October

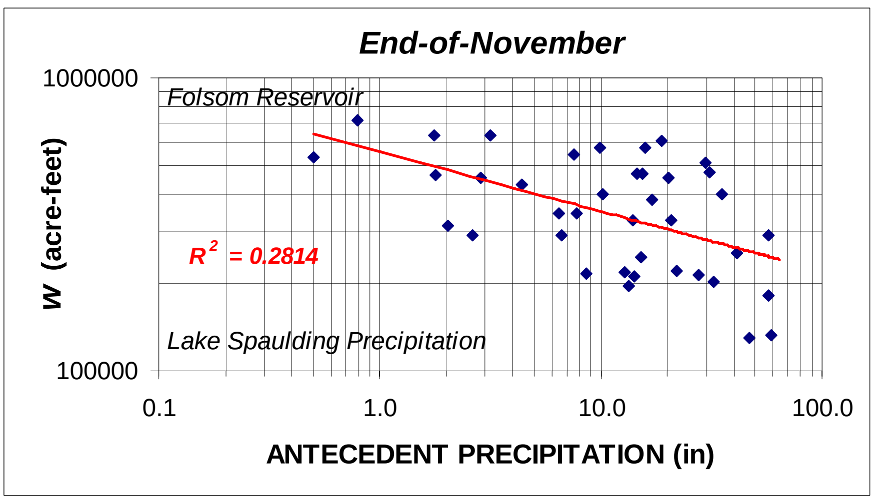

Figure A2 – Relationship of Transformed Storage Departures (*w*) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-November

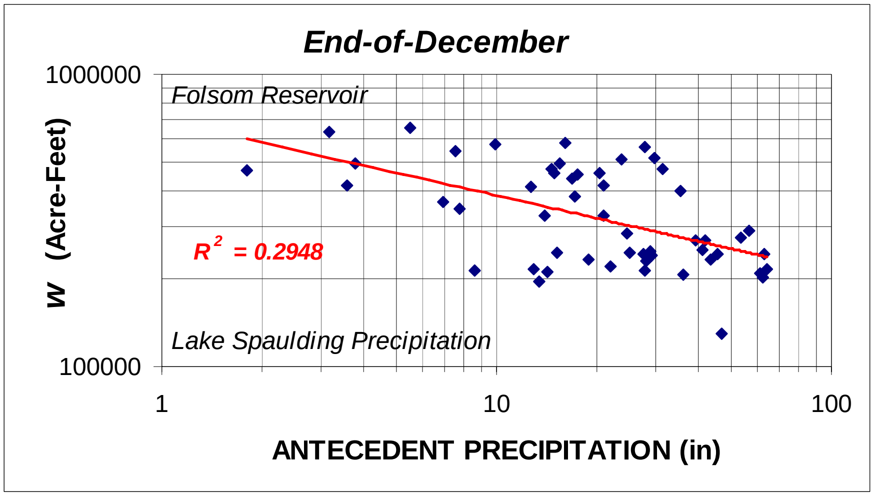

Figure A3 – Relationship of Transformed Storage Departures (*w*) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-December

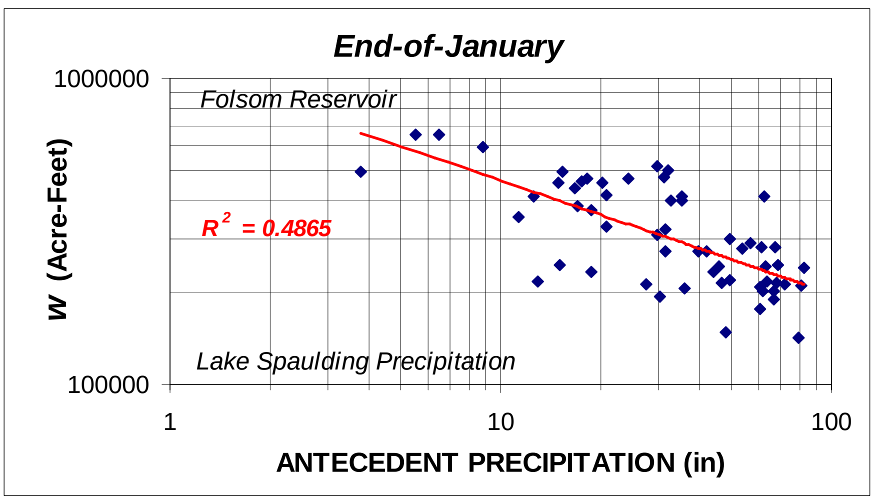

Figure A4 – Relationship of Transformed Storage Departures (*w*) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-January

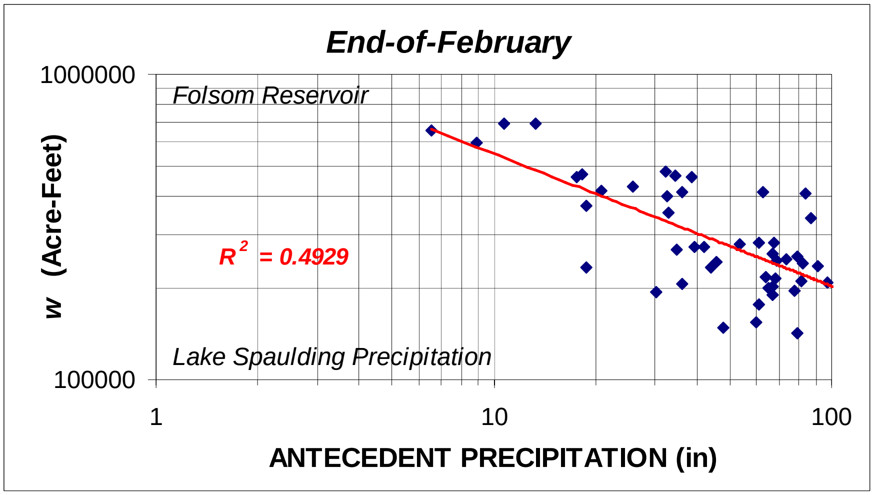

Figure A5 – Relationship of Transformed Storage Departures (*w*) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-February

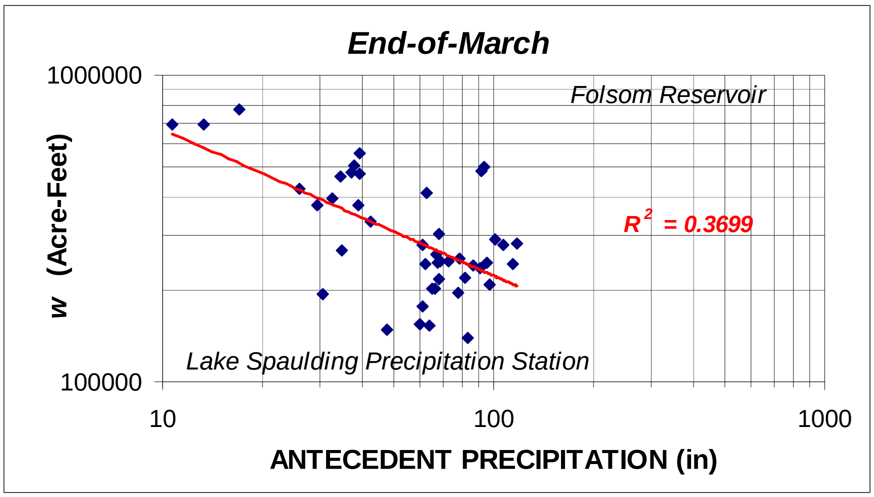

Figure A6 – Relationship of Transformed Storage Departures (*w*) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-March

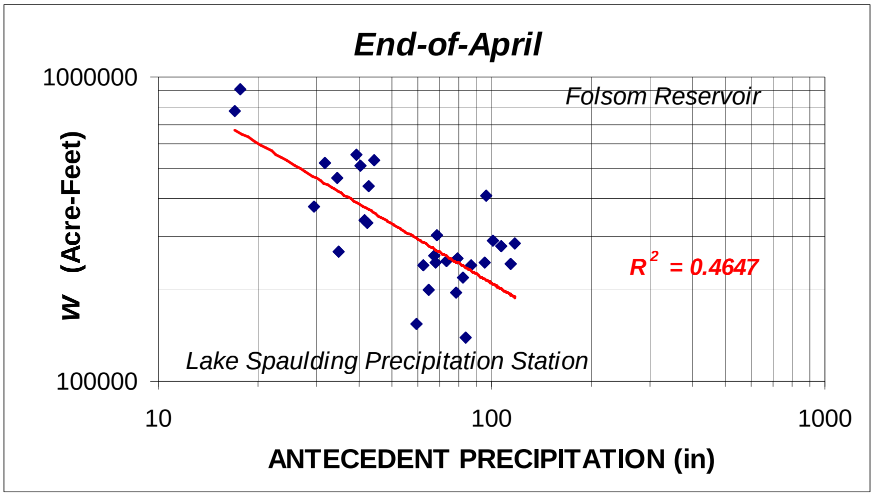

Figure A7 – Relationship of Transformed Storage Departures (*w*) at Folsom Reservoir with Antecedent Precipitation at Lake Spaulding Precipitation Station for End-of-April