Using Multiple Methods to Estimate Frequency Hydrology for Shasta Dam

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Abstract

The Bureau of Reclamation (Reclamation) is designing a dam raise for Shasta Dam, CA. An important part of this study is providing hydrologic loadings to inform risk based design for the dam raise. The Water Resources Engineering and Management Group is using multiple methods and a phased approach to best estimate hydrologic loadings for Shasta Dam. One of the many challenging aspects of this project is an aggressive time schedule with approximately five months to provide initial hydrologic loadings to the design group.

Three somewhat independent methods are being used for this study; Expected Moments Algorithm (EMA), Risk Management Center’s Reservoir Frequency Analysis (RMC-RFA), and rainfall-runoff modeling using HEC-HMS using L-moment precipitation frequency estimates. EMA is a statistical method using an unregulated systematic record from multiple stream gages and paleoflood estimates to develop a peak discharge frequency curve for the Shasta Dam location. Initially, the EMA analysis will include available gage records and preliminary paleoflood data. The second method, RMC-RFA, uses a series of data developed from the systematic gage record available for Shasta Dam. RMC-RFA produces a reservoir stage-frequency curve with confidence bounds by utilizing a deterministic flood routing model while treating the inflow volume, the inflow flood hydrograph shape, the seasonal occurrence of the flood event, and the antecedent reservoir stage as uncertain variables rather than fixed values. In order to quantify both the natural variability and knowledge uncertainty in reservoir stage-frequency estimates, RMC-RFA employs a two looped, nested Monte Carlo methodology. The natural variability of the reservoir stage is simulated in the inner loop defined as a realization, which comprises many thousands of simulated flood events, while the knowledge uncertainty in the inflow volume frequency distribution is simulated in the outer loop, which comprises many realizations. The third method, rainfall-runoff modeling, applies a model originally developed by the U.S. Army Corps of Engineers for the Sacramento and San Joaquin River Basins Comprehensive Study. The model uses an AEP-neutral approach utilizing L-moment precipitation frequency and four historic storm templates. The model leverages parameter sensitivity and precipitation frequency uncertainty to estimate overall uncertainty. The second phase of the study will build on the results of the first phase and incorporate detailed site-specific paleoflood data into the analyses.

The strengths and weaknesses of each method within the phased multi-method framework will be discussed and used to recommend appropriate hydrologic loads for risk informed design for
Shasta Dam. Use of multiple methods and datasets allows for greater confidence in load estimates and associated uncertainty in support of risk informed design for Shasta Dam.

**Introduction**

**Objective**

The Bureau of Reclamation (Reclamation) is designing a dam raise for Shasta Dam, CA. A key component of dam design, and the focus of this paper, is the hydrologic loadings used for dam raise design and subsequent risk analysis. Reclamation utilizes a risk informed design process which allows the designers to incorporate important risk factors when considering design alternatives. For Shasta Dam an important risk factor is the high population located downstream of Shasta Dam, which is located on the Sacramento River approximately 11 miles north of Redding, CA. Flood flows would follow the Sacramento River through the entire Central Valley, through Sacramento, and into Suisun Bay near just east of San Francisco. This risk factor plays an important role in selecting an appropriate flood load for the dam raise.

There are some unusual aspects to this study that make it particularly challenging. The Pit River drainage makes up a majority of the contributing area while contributing less than a majority of the overall inflow. Characterizing the Pit River basin for extreme flood analysis and the actual contribution to the system was a complex challenge. Another challenging aspect of the project was the schedule. Work for the project began in May, 2018, based on funding availability, and due to hydrologic loadings being a critical path for final design, the completion date for inflow hydrographs was December, 2018.

**Approach**

To appropriately characterize the hydrologic hazard and uncertainty for the Shasta Dam raise project, Reclamation used a multiple methods approach. A multiple methods approach improves understanding the effects of mixed populations, non-contributing drainage areas, seasonal controls, and the range of model and data uncertainty. The analysis methodologies include:

1. Peak discharge frequency analysis using the Expected Moments Algorithm (EMA; Cohn et al., 1997). The EMA analysis was performed using the computer program PeakfqSA (Cohn and England, 2016) to compute the moments of a Log Pearson Type III distribution using a time series of systematic, historic, and paleoflood information.

2. Volume frequency analysis using HEC-SSP (Hydrologic Engineering Center – Statistical Software Package; USACE, 2017b) applied in stochastic simulation of inflow volume, hydrograph shape, seasonal occurrence, and antecedent reservoir water surface elevation using appropriate reservoir routing characteristics and antecedent reservoir conditions (Risk Management Center – Reservoir Frequency Analysis (RMC-RFA); Smith et al., 2018).

3. Frequency rainfall-runoff modeling: a regional precipitation frequency analysis was developed using L-moments (Hosking and Wallis, 1997), and applied to historic storm templates to incorporate in runoff modeling and flood event analysis using the U.S. Army Corp of Engineers' (USACE) HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System; USACE, 2017a).
One of the most challenging parts of this project was the expedited schedule. The schedule did not change the overall multiple methods approach but did change how we approached each method. The focus of this paper will be on the unique challenges within each method and the steps that were taken to complete the hydrologic modeling in a timely manner.

An important aspect to highlight is that due to time constraints a phased approach was identified for final hydrologic loadings. The original scope of the study included a robust paleoflood analysis to identify and characterize historic floods and non-exceedance values. Completion of this work and incorporating the results into the hydrologic analysis was outside the possible scope for the desired completion date. Therefore a phased approach was utilized to allow an initial estimate of flood loadings to be completed using available data in the first phase of the project. A second phase of the study would incorporate paleoflood findings to verify the findings in the first phase of the study. The second phase will build on the results of the first phase and incorporate detailed site-specific paleoflood data into the analyses. A further objective of the second phase is to conduct additional data analysis, modeling, and model development needed to support the recommended hydrologic loadings from the first phase of the study. The second phase of the project will also investigate causality using a Bayesian approach to integrate results from the multiple methods.

**Watershed and Climate**

The watershed contributing to Shasta Dam (Figure 1) has a drainage area of nearly 6,600 square miles. Shasta Dam is located about 11 miles north of Redding, California. Elevation in the watershed ranges from 1,078 feet at the dam crest to 14,179 feet at the top of Mount Shasta. Vegetation is variable throughout the watershed and varies from sparse scrub to heavy coniferous forest.

Shasta Dam is located at the northern tip of California’s Central Valley, which is one of the most agriculturally productive regions in the world, and emphasizes the importance of water and water measurement in this region. Consequently, this region is data rich in hydrologic information and supports the data requirements for the various analysis methodologies presented here.

The Shasta watershed is located within a transitional climate zone where conditions vary significantly. The western portion of the basin is influenced by the Pacific Ocean and Coast Mountain Range while the eastern portion is protected from the ocean influence and is in the mountain rain shadow. Depending on altitude and local conditions, there is significant daily and seasonal temperature variability with cold/wet winters and warm/dry summers.

As with most of California, dry summers are due to the northward migration of the semi-permanent North Pacific High with most storm tracks deflected far to the north. The North Pacific High decreases in intensity in winter and moves further south, permitting storms to move into the region producing widespread rain at low elevations and snow at high elevations. Occasionally the broad-scale circulation pattern permits a series of storm centers to move into California from the southwest. This type of storm pattern (atmospheric river) is responsible for extreme precipitation events. An example of an atmospheric river extreme precipitation event was in 1955 when over 32-inches of precipitation was recorded over a 4-day period in part of the watershed.

Average annual precipitation within the watershed ranges from less than 15 inches to over 85 inches. Most precipitation occurs in the western mountainous portion of the basin with extremely
dry conditions in most of the eastern plateau areas. Annual maximum one-day precipitation events typically occur during the cool season, specifically October through April. Basin-wide average monthly high temperatures (degrees Fahrenheit) range from the upper-40s in the winter to upper-80s in summer and lows range from the mid-20s in winter to upper-40s in summer.

Figure 1. Location of Shasta Dam (gray triangle) and associated watershed, which controls runoff from ~6,590 square miles.

**Methodology**

Multiple methods were used in an attempt to fit a distribution to a relatively small sample of observed data with the intent to extrapolate that data to extremely rare annual exceedance probabilities (AEPs). Each method and its associated dataset have a credible range of extrapolation that generally is significantly limited. However, when the methods and datasets are used together, the collection of results increases the credible range of extrapolation. The methods used in the Shasta Dam study use somewhat independent datasets allowing each method to produce independent results. Trends in the magnitude and skew of each individual resulting frequency curve builds confidence in the validity of the results and extrapolation techniques used.

**Bulletin 17C Flood Flow Frequency Analysis**

A peak discharge frequency relationship was developed based on Bulletin 17C techniques (England et al., 2018) and use the Expected Moments Algorithm (EMA). The objective of EMA analyses is to utilize the longest available timeseries of instantaneous annual peak flows in which to fit with a distribution. The Shasta Dam EMA analysis is based on 137 records including one revised paleoflood record from a previous Reclamation study.
The main focus of the Shasta Dam EMA analysis was on data acquisition and validation. As stated previously, the Shasta Dam region is data rich with a large network of stream gaging stations. The stream gages utilized for the EMA analysis are shown in Figure 2. While data was not used directly from each stream gage station shown in Figure 2, data from the upstream network of gages was used to build a storyline of flows to validate observations recorded at gages representative of Shasta Reservoir inflows. Some of the largest flood events were found to have published values that conflicted depending on the source of the information. The largest flood values are critical in controlling the shape of the upper portion of a frequency curve responsible for estimating peak discharge properties for rare floods. Therefore, the validation of peak flow for the largest events was important to the overall shape of the frequency curve.

Similarly, Reclamation uses paleoflood data as an additional important basis for extending the flood frequency curve. Paleofloods are floods estimated from geologic and geomorphological information combined with hydraulic modeling. Paleoflood studies also try to identify ranges of non-exceedance data representing a period when flow values have not been exceeded at a given location. The data is used to extend the timeseries of available annual peak flows. EMA incorporates the paleoflood and non-exceedance data as a single value or a range of values. Previous paleoflood and non-exceedance estimates were developed for Shasta Dam in 2007. The data were revisited for this study using carbon dating and one-dimensional hydraulic modeling that was not completed during the prior study. The updated paleoflood analysis helped to refine the data for incorporation to the EMA model.

The EMA analysis resulted in a peak discharge frequency curve developed from 137 years of concurrent annual peak flows and a paleoflood with an age greater than 680 years before present time.
Reservoir and Volume Frequency Analysis

The reservoir frequency analysis is an iterative analysis and includes a two-step process consisting of, (1) volume frequency analysis, and (2) reservoir frequency analysis (RFA) that is informed with the volume frequency analysis in addition to other inputs such as seasonality, critical duration, reservoir stage and stage-storage-discharge relationships. The objective of the RFA analysis is to use a combination of daily flows, historic reservoir operations, and sub-daily inflow hydrographs to better understand the probability of the reservoir reaching a stage of interest.

Figure 2. Location of stream gages used to develop annual peak flow timeseries.
Daily unregulated inflows are one of the most important pieces of data needed to develop volume frequency for an RFA analysis. A long record of unregulated inflow is difficult to acquire for a heavily regulated watershed like the one for Shasta Dam. Fortunately, an extensive 93 year dataset of daily unregulated inflows to Shasta Dam was available based on reanalysis performed by the USACE during the 2002 Sacramento and San Joaquin River Basins Comprehensive Study (USACE 2002). The dataset has been reviewed and used extensively within basin studies and was appropriate for use in the RFA analysis for Shasta Dam.

An important focus of the RFA analysis is understanding and developing the model around the seasonality of the system. While the dominant storms occur during the winter and early spring, the reservoir is operated to have the most flood storage available during the same season. Maximum reservoir stage is reached following the dominant storm season to reduce the probability of flooding while maximizing storage for irrigation season. Therefore, a critical analysis period for RFA modeling is the shoulder season when large floods are still possible but reservoir storage is increasing. Much effort was spent identifying possible scenarios that would result in the greatest reservoir stage.

Again, due to the data rich aspect of the region, several sub-daily hydrographs were available from the USGS through direct contact and within water supply papers. Real hydrographs are critical to characterize the shape and volume of inflow representative of big floods at Shasta Dam.

**Rainfall-Runoff Modeling**

An AEP-neutral approach (AEP is annual exceedance probability) to rainfall-runoff modeling was used to develop Shasta Dam flood loadings. AEP-neutrality assumes the AEP of the flood is equal to the AEP for the rainfall input. Proper modeling of the precipitation and basin runoff need to reach to validate this assumption. In the current study, precipitation frequency estimates and historic storm templates were developed for application in the rainfall-runoff model. Following calibration of the hydrologic model, precipitation totals in the storm templates were scaled to match specific precipitation magnitudes sampled from the precipitation frequency relationship. The frequency-based templates were routed through the model to simulate flood conditions under rare conditions. Sensitivity analyses were used within the rainfall runoff model varying sensitive runoff parameters as well as the temporal and spatial distribution of precipitation for each storm template. Understanding the full range of resulting flows for each precipitation frequency helped to estimate the AEP neutral results.

**Regional Precipitation Frequency Analysis:** A basin-average precipitation frequency relationship was developed by applying the regional frequency method (L-moments) of Hosking and Wallis (1997) to historical point precipitation observations in the meteorological region of interest. The precipitation frequency analysis is highly dependent on seasonality and duration. The seasonality is based on the time of year when large precipitation events, atmospheric river events (e.g., Ralph and Dettinger, 2011; Dettinger, 2013; Rutz et al., 2014), occur for the Shasta Dam watershed. Historically, atmospheric river events have produced heavy precipitation totals and flooding in the region. Precipitation-frequency duration is based on understanding the number of precipitating days during heavy precipitation events in the watershed. For the Shasta
Dam basin, 4-day annual maximum precipitation events occur between late-fall and late-spring, specifically October through April, were used.

The Generalized Extreme Value (GEV) distribution best characterizes the seasonal maximum precipitation observations within the meteorological region of interest. The basin-average precipitation frequency relationship was developed by scaling the GEV distribution fit to the point observation data (in the form of a unitless regional growth curve) by an at-site mean (ASM) precipitation total and an areal-reduction factor (ARF) for the Shasta Dam watershed. An uncertainty analysis providing 5th and 95th percent confidence limits was performed using a bootstrap resampling approach.

**Storm Templates:** HEC-HMS storm template files were generated using output from a numerical weather prediction model, the Weather, Research, and Forecasting (WRF) model. The WRF model is designed to solve the governing equations (e.g., conservation of mass, conservation of momentum, conservation of energy) based on initial and transient conditions provided at domain boundaries. Initial and transient boundary conditions were provided by the Climate Forecast Reanalysis System (CFSR; Saha et al., 2010) at six-hour intervals during each 15-day simulation. Four historical precipitation events were simulated in the WRF model—modeled events began in February 1986, March 1995, December 1996, and February 2004.

Output from WRF was used to develop two types of storm template files—best-estimate and frequency-based estimates. Best-estimate storm templates were based on raw WRF output. Specifically, sub-basin-average precipitation, 2 m air temperature, and 10 m wind speed time series were computed during each hour by averaging each field across each sub-basin. Frequency-based storm templates were based on scaling WRF precipitation output by a frequency-based ratio. The frequency-based ratio, which varies by event and return period, was computed as the ratio of basin-average precipitation sampled from a basin-average precipitation-frequency relationship to basin-average precipitation from WRF. The frequency-based storm templates only include changes to precipitation; all other variables remain the same.

**Runoff Modeling:** Storm templates and the basin-average precipitation frequency relationship were used to develop inputs to a rainfall-runoff model (HEC-HMS) to simulate the hydrologic response of the Shasta Dam watershed. To conduct this analysis, the precipitation was spatially and temporally distributed throughout the basin according to historic storm patterns (i.e., output from WRF). The four selected historic events, identified here by water year as 1986, 1995, 1997, and 2004, were used to represent a range of precipitation events that impacted the watershed.

The Upper Sacramento River HEC-HMS model originally developed by the USACE (Dunn et al., 2001; USACE, 2002) was adapted and used in this study for rainfall-runoff modeling. The original model developed for the 2002 USACE Sacramento and San Joaquin River Basins Study has been extensively reviewed and used since its development.

The original HEC-HMS model was modified allow data inputs developed specifically for the Shasta Dam hydrology study. Similarly, the model was recalibrated and validated using the four historic precipitation events used for storm template development (1986, 1995, 1997, and 2004).
Results

Results from the multiple methods analysis were used to build a case for recommending the most representative frequency flood inflows to Shasta Dam. The independent nature of each of the methods lead to unique results representative of different flood properties. The EMA analysis results in a peak discharge frequency curve, RFA results in a volume and stage frequency curves, and the rainfall-runoff modeling results in hydrographs representative of the precipitation frequency. In order to compare the results in a trend analysis they needed to be converted to describe similar metrics. Trends were explored based on peak inflow and 7-day volume.

Peak inflow was estimated for the RFA model results using the peak of the representative scaled hydrograph corresponding to specific frequencies. Peak inflow is a direct output from the EMA and rainfall runoff methods. The peak discharge from all three methods resulted in a similar skew. The magnitudes of the peak inflow varied between the methods with the EMA method producing the lowest peak inflows, the rainfall runoff method producing the highest peak inflows, and the RFA method having results somewhere in between.

To compare 7-day volume, the EMA results were scaled to the peak discharge of the 1940 historic hydrograph. Similar to the peak discharge results, the 7-day volume from the multiple methods had a similar skew but varied in magnitude, with the EMA method producing the lowest 7-day volumes and the rainfall runoff producing the highest 7-day volume.

A positive aspect of the results were the similar trends in skew between the results of the independent methods. The similar trend in the skew could be associated with how the results are being extrapolated. If the skew varied between the methods, the difference in the values could increase greatly for rarer events. Or the curves could cross at some point. Having frequency curves with similar skew results in somewhat parallel frequency curves that gives more confidence that the data is being extrapolated appropriately. Similarly, it builds confidence that similar hydrologic processes are being captured by the independent datasets.

While the results had similar shapes, the magnitudes varied, making it challenging to recommend specific frequency results and set of hydrographs to be used for hydrologic loadings. All of the results are supported with historic observations, calibrated modeling, and current state-of-the-practice methodologies. Therefore, a combination and weighting approach was used with the recommended results representing a range of uncertainty based on the median values from each method.

References


