Estimation of Flow, Volume, and Stage-Frequency for use in Dam and Levee Safety Studies within HEC-SSP and HEC-HMS

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ABSTRACT

Current U.S. Army Corps of Engineers (USACE) guidance requires the development of a "hydrologic hazard curve" when evaluating the hydrologic risk for dams and levees. The hydrologic hazard curve provides magnitudes and probabilities for the entire range of peak flows, flow durations, and stages. These variables are used when assessing potential failure modes as part of risk assessments. For instance, the probability of failure is often conditional on the magnitude of stage.

Due to the age of most USACE projects, there is usually not enough observed data to directly estimate a stage-frequency relationship for relatively remote annual chances of exceedance (ACE). In order to provide adequate information for use in risk analyses, extrapolation of stage-frequency curves to remote ACE is often needed. Balanced hydrographs can be used as a means to inform pool stage-frequency curves (dams) and river stage-frequency curves (levees) for remote ACE.

New tools are under development at the Hydrologic Engineering Center (HEC) that can better estimate stage-frequency relationships and hydrologic hazard curves. Version 2.1 of the Statistical Software Package (HEC-SSP) contains features that can fit the Log Pearson Type III distribution to annual maximum flows using Bulletin 17C procedures as well as quickly develop multiple balanced hydrographs. Version 4.2 of the Hydrologic Modeling System (HEC-HMS) contains features that can then efficiently route these balanced hydrographs. In this way, more informative stage-frequency relationships can be developed for use in dam and levee risk analyses.

INTRODUCTION

When a dam impounds water upstream of a populated area, a distinct hazard to that area from a possible failure of the dam is created. The USACE Dam Safety Program is predicated upon the use of risk-informed decision making processes. These processes help to properly allocate limited resources to appropriately manage the wide range of projects contained within the USACE portfolio. When assessing the risk posed by high hazard dams, reservoir stage is the primary loading parameter used when evaluating a potential failure mode.

Appropriately defining the probability of equaling or exceeding a defined reservoir stage, hereafter referred to as stage-frequency, is a crucial consideration when performing a risk analysis. A generalized risk equation used within the USACE Dam Safety Program is defined as:

$$Risk = P(Hazard) \times P(Failure \mid Hazard) \times Consequences \mid Failure$$

Risk is equated to the probability of the hazard multiplied by the probability of failure given the hazard multiplied by the consequences given the failure. Relationships describing the annual chance exceedance (ACE) versus peak flow, volume (i.e. flow over a specified duration), and/or reservoir stage is used to describe the hydrologic hazard related to a specific dam.

An inflow volume-based approach to estimating stage-frequency curves for dams has been accepted by USACE for use within Semi-Quantitative Risk Assessments (SQRA) (U.S. Army Corps of Engineers, 2017). To be used within the SQRA process, the stage-frequency curve must encompass a wide range of possible hydrologic loadings from frequently occurring to extremely rare events. It is common practice to extend the stage-frequency curve to at least the Inflow Design Flood (IDF) peak stage, if not further. In most cases, the IDF is determined from the Probable Maximum Precipitation (PMP) that can occur over the watershed upstream of the dam (U.S. Army Corps of Engineers, 1991). The PMP is iteratively centered and aligned within the contributing watershed to maximize the runoff response at the dam in question in order to determine the Probable Maximum Flood (PMF).

STUDY PURPOSE

Due to the age of most USACE dams and reservoirs, there is usually not enough observed data (generally less than 50 years) to directly estimate a stage-frequency relationship for rare events. Therefore, extrapolation of the stage-frequency curve to extremely rare probabilities is needed. Also, uncertainty in the stage-frequency curve must be incorporated to assist in making risk-informed decisions. These needs are further compounded by time and funding constraints. Hence, simple, yet accurate methods are desirable to help shape the stage-frequency curve beyond observed data.

The analyses used to help shape the stage-frequency curve generally fall within two categories: deterministic and stochastic. Deterministic analyses assume that input variables can be represented by fixed values. Conversely, stochastic analyses treat selected inputs as random variables. While stochastic analyses incorporating parameter uncertainty can provide extremely detailed stage-frequency curves with uncertainty (U.S. Army Corps of Engineers, 2015), they tend to be computationally intensive. Therefore, simplified (but still accurate) deterministic approaches for rapidly developing stage-frequency curves are necessary.

Recent advances in flood frequency, hydrologic, and hydraulic modeling capabilities have expanded the ways in which users can rapidly and accurately develop stage-frequency curves and incorporate parameter uncertainty for use in dam and levee safety studies. The Hydrologic Engineering Center's Statistical Software Package (HEC-SSP) now allows users to fit the Log Pearson Type III distribution to an annual maximum series (AMS) using Bulletin 17C procedures. Using observed hydrograph shapes and derived flow frequency information, users can then create hypothetical hydrographs that “balance” flow rates, volumes, and frequencies (U.S. Army Corps of Engineers, 2016). The Hydrologic Modeling System (HEC-HMS) (U.S. Army Corps of Engineers, 2016) and River Analysis System (HEC-RAS) (U.S. Army Corps of Engineers, 2016) can then be used to route these hypothetical events through a reservoir and/or river system to determine the corresponding stage-frequency curve at locations of interest.

Using these new modeling capabilities within HEC-SSP and HEC-HMS, stage-frequency curves were rapidly developed for Foster Joseph Sayers Dam (hereafter referred to as Sayers Dam), which is a high hazard multi-purpose dam and reservoir project located within the state of Pennsylvania. Construction of Sayers Dam was operationally completed by USACE in August 1969. Sayers Dam is a multi-purpose project with authorized purposes of flood control, water quality control, and recreation (U.S. Army Corps of Engineers, 1996). Sayers Dam is located on Bald Eagle Creek, approximately 10 miles upstream of Lock Haven, PA, as shown in Figure 1. The total drainage area for the watershed above Foster Joseph Sayers Dam is approximately 339 square miles (sq. mi.). The Bald Eagle Creek watershed is prone to major flooding at any time of the year.

Sayers Dam is operated as part of a system of projects to reduce flooding risks within the West Branch Susquehanna River watershed, which is a tributary to the Susquehanna River. Three other major flood control dams are located within the West Branch Susquehanna River. Curwensville Dam, Alvin R. Bush Dam, and Sayers Dam are owned by USACE while George B. Stevenson Dam is owned by the PA Department of Conservation and Natural Resources (DCNR). However, flood control operations at all four projects are coordinated by the Baltimore District (NAB) Water Control Team. Over the past 50 years, the combined operations at these four projects have generated over $860 million in flood damage reduction benefits (U.S. Army Corps of Engineers, 2014). In addition to these flood control dams, multiple local flood protection projects (which mainly consist of levee systems) have been constructed by USACE at major population centers. The locations of these projects in relation to Sayers Dam is shown in Figure 1.

Sayers Dam consists of a rolled earth fill embankment approximately 600 feet in length with a 100 foot maximum section height above the streambed. The dam crest has an elevation of 682.3 feet relative to the North American Vertical Datum of 1988 (NAVD88). The embankment was designed to provide 20 feet of spillway surcharge plus five feet of freeboard. The top width of the embankment is 25 feet. The storage capacity of 100,505 acre-feet (when filled to the spillway crest) equates to approximately 5.5 inches of total runoff from the 339 sq. mi. drainage area. The resulting pool covers a surface area of approximately 3450 acres. Additional information related to Sayers Dam is shown in Table 1.

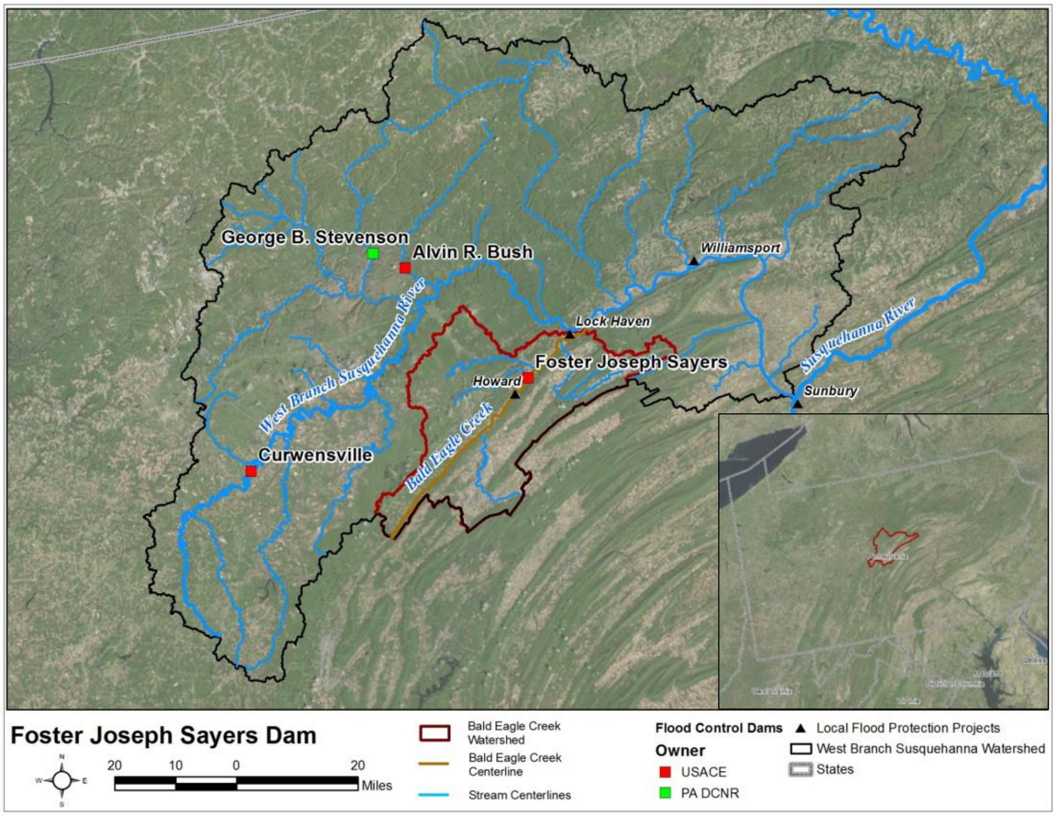


Figure 1. Location of the Study Area

Table 1. Pertinent Features of Sayers Dam

Reservoir	
Spillway Crest	656.3 feet NAVD88
Summer Recreation	629.3 feet NAVD88
Early Winter	624.3 feet NAVD88
Late Winter Conservation	609.3 feet NAVD88
Conduit Invert	589.3 feet NAVD88
Embankment	
Type	Rolled earthfill
Length	600 feet
Top Width	25 feet
Top Elevation	682.3 feet NAVD88
Maximum Height	100 feet

Spillway	
Location	Left (North) Abutment
Type	Uncontrolled Ogee Weir
Length	600 feet
Crest Elevation	656.3 feet NAVD88
Capacity	200,000 cfs at 677.1 feet NAVD88
Outlet Works	
Type	Circular concrete-lined tunnel
Tunnel Inside Diam.	15 feet
Tunnel Length	634.3 feet
Gate Number	8
Gate Size	7’ X 10’ (7) and 7' x 4.9' (1)

DATA COLLECTION

Multiple stream gages are operated by NAB and the United States Geologic Survey (USGS) in and around Sayers Dam. The locations of the stream gages in relation to the Bald Eagle Creek watershed and Sayers Dam are shown in Figure 2. Due to the relatively large increase in drainage area between upstream gages and Sayers Dam, an inflow record that better reflects the total drainage area to the project was computed using change in storage relationships and outflow. Pool stage and computed inflow records for Sayers Dam were available for a total historical record of 32 years. Due to the lack of significant upstream diversions or flood control operations, no regulation effects needed to be removed from the previously mentioned datasets.

Commonly, continuous and systematic inflow records to dams only contain 30 – 40 years of data. However, during risk assessments (including SQRA), the pool stage-frequency curve must extend to extremely remote loadings, such as the 1/100,000 ACE. To lend credence to estimates of pool stage-frequency at these remote loadings using an inflow volume approach, it is essential to extend the period of record of the dataset(s) in question to the maximum extent possible. This is done in an effort to reduce knowledge uncertainty, which can be reduced through data collection efforts. Oftentimes, this requires the combination of records that reflect pre- and post-construction conditions as well as historic events that aren't a part of the systematic record.

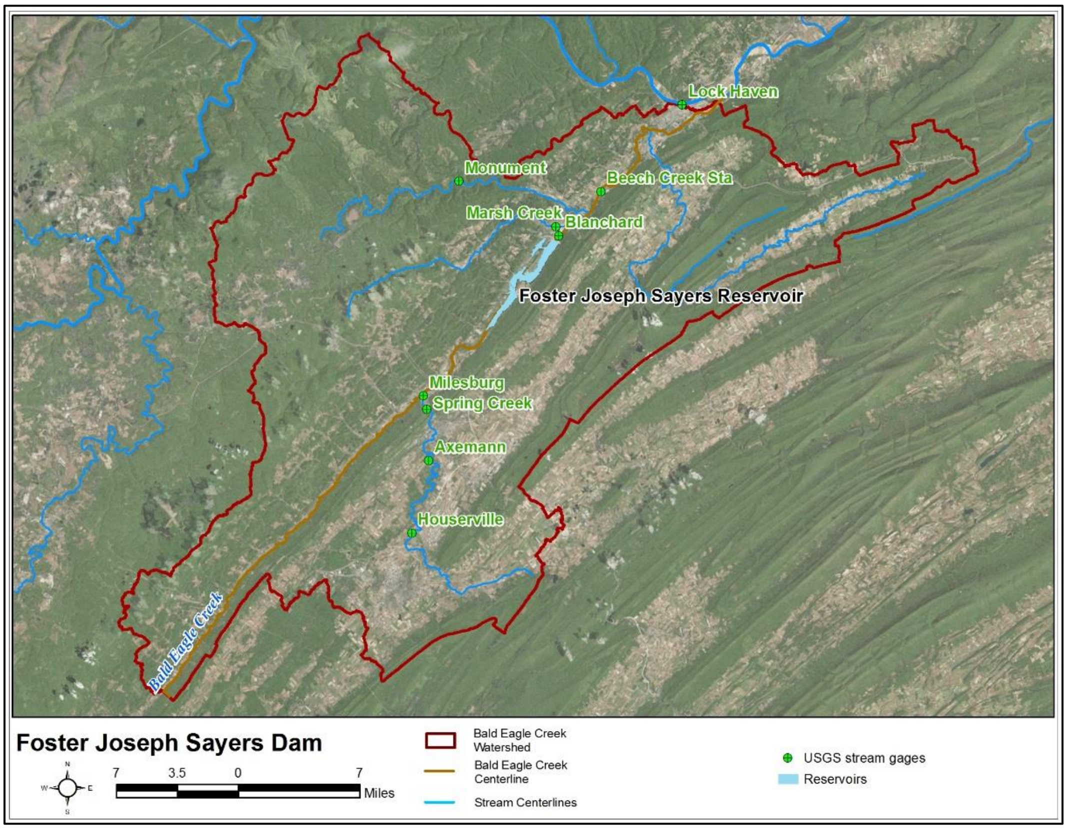


Figure 2. Location of Pertinent Stream Gages

The systematic inflow record to Sayers Dam was extended through the inclusion of pre-construction flow records and historical event reconstructions. Firstly, prior to June 1968 (initial diversion of Bald Eagle Creek through the partially-completed Sayers Dam outlet works), the records at the Blanchard gage were essentially unregulated. Therefore, this data was incorporated to add an additional 14 years of systematic data and 30 years to the historic period of inflow to Sayers Dam.

Secondly, two historical events were added. These two events are the largest streamflow events that have occurred within the Bald Eagle Creek watershed within at least 100 years (Bogardus & Ryder, 1936). The first historical event occurred in March 1936. A flow hydrograph estimated at the future site of Sayers Dam during this event was digitized from a Post Flood Report (Baltimore District, 1996) and incorporated with the inflow records to Sayers Dam. The second historical event occurred in June 1972. An inflow hydrograph was computed from a Post Flood Report and assimilated with the other inflow records (Baltimore District, 1974).

Data from these two large events, pre-construction records, and post-construction inflow records were collated to create an instantaneous peak inflow AMS, hourly inflow, and daily inflow time series that significantly expanded the period of record at Sayers Dam. AMS for the 1-, 2-, 3-, and 4-day durations were extracted from the daily inflow time series. This was done in anticipation of performing duration-specific volume-frequency analyses. The complete instantaneous peak inflow AMS and daily inflow time series are shown in Figure 3.

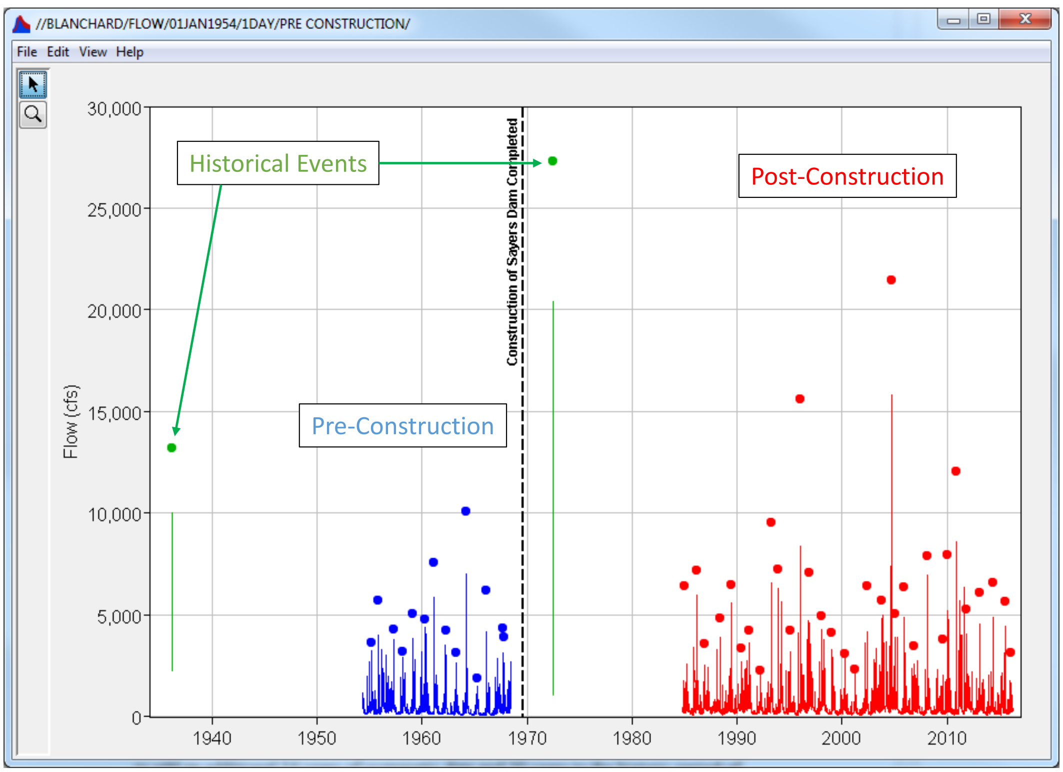


Figure 3. Instantaneous Peak Flow Annual Maximum Series and Daily Inflow Records for Sayers Dam

CREATION OF FLOW- AND VOLUME-FREQUENCY CURVES

Bulletin 17B guidance has guided the development of peak flow-frequency analyses within the United States since the early 1980's. This guidance recommended the use of the Log Pearson Type III probability distribution for annual peak flows on unregulated streams fit by the Method of Moments (Interagency Advisory Committee on Water Data, 1982). The Bulletin 17C guidance brings about several major changes to the computation of peak flow-frequency within the United States. This guidance incorporates changes motivated by four of the items listed as future work within Bulletin 17B and more than 30 years of post-Bulletin 17B research on flood processes and statistical methods (England, et al., 2015). As part of the Bulletin 17C methodology, the moments/parameters of the Log Pearson Type III distribution are estimated using the Expected Moments Algorithm (EMA). Like Bulletin 17B, the Bulletin 17C methodology also estimates distribution parameters based on sample moments, but does so in a more integrated manner that incorporates non-standard, censored, or historical data at once, rather than as a series of adjustment procedures (Cohn, Lane, & Baier, 1997). The use of Bulletin 17C procedures can also provide improved confidence intervals for the resulting frequency curve that incorporate diverse information appropriately, as historical data and censored values impact the uncertainty in the estimated frequency curve (Cohn, Lane, & Stedinger, 2001). Within the Bulletin 17C methodology, every annual peak flow in the analysis period, whether observed or not, is represented by a flow range. That range might simply be limited to the gaged value when one exists. However it could also reflect an uncertain flow estimate.

Evidence presented in a March 1936 event Post Flood Report (Bogardus & Ryder, 1936) suggests that the March 1936 event resulted in the largest instantaneous peak flow rate at the Sayers Dam location since at least 1911. This implies that had an instantaneous peak flow rate larger than the March 1936 event occurred in the timeframe between 1911 and 1936, it would have been documented. Therefore, the analysis period for the instantaneous peak inflow could be extended to 1911. Also, similar evidence suggests that the March 1936 event could be used as a reasonable low perception threshold for missing years within the instantaneous peak inflow analysis.

Finally, due to the indirect measurement routines used to estimate the instantaneous peak flow rate for the March 1936 event, a range of +/- 10% was placed around the best guess peak flow rate estimate. The instantaneous peak inflow events and flow ranges for Sayers Dam are shown in Figure 4. The Log Pearson Type III distribution was then fit to this data using Bulletin 17C procedures within HEC-SSP.

A similar analysis was conducted for the 1-, 2-, 3-, and 4-day durations. While the analysis period for these durations could not be reasonably extended to 1911 due to a lack of stream gage data, information from the March 1936 event could be used to estimate flow ranges for the missing years for each duration. In this way, the 1-, 2-, 3-, and 4-day duration flow volumes were used as low perception thresholds for the missing periods within the respective analysis for each duration.

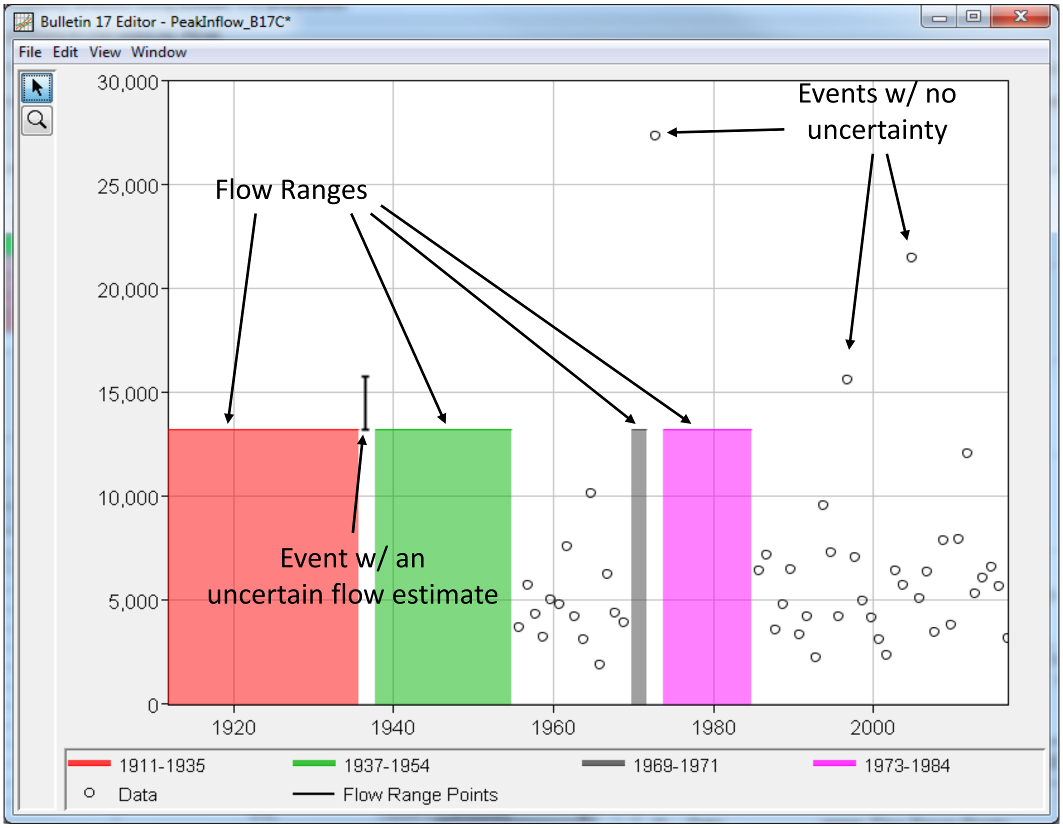


Figure 4. Instantaneous Peak Inflow Events and Flow Ranges

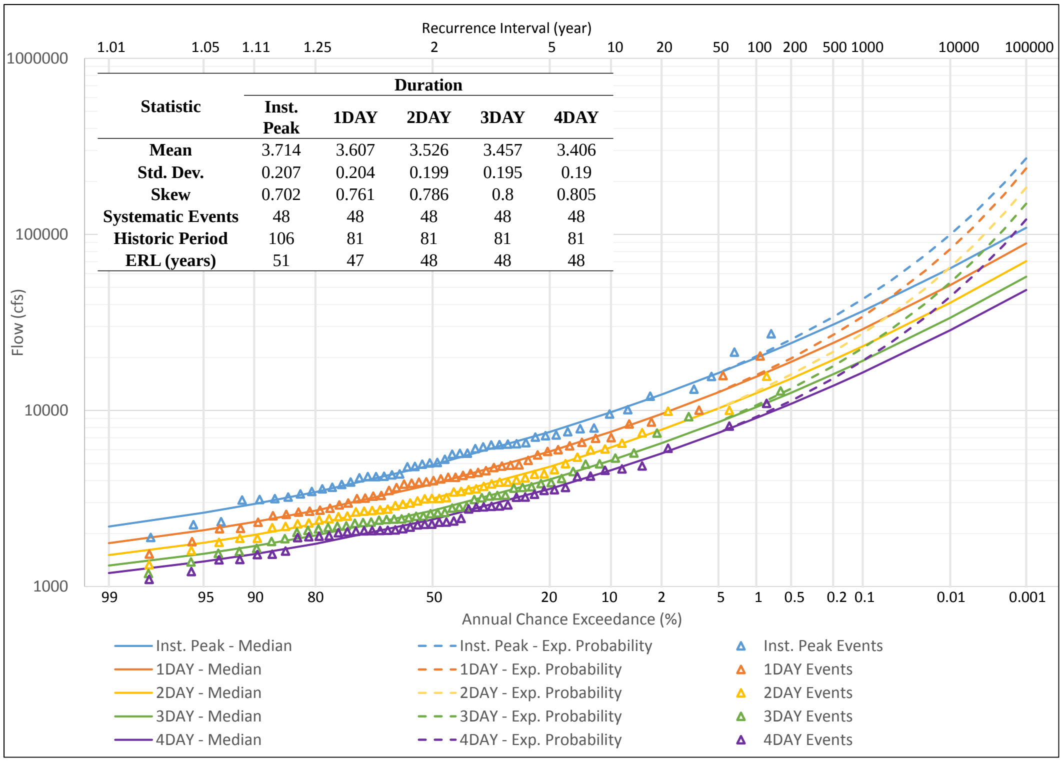
Following the initial flow- and volume-frequency computations, the at-site statistics for multiple durations were compared and smoothed to produce a family of best-fit parameters (i.e. mean, standard deviation, and skew). However, estimates of the mean, standard deviation and coefficient of skewness (i.e. the parameters of the Log Pearson Type III distribution) for each duration were made from a limited sample of annual maximum flows. Therefore, they can potentially contain a significant amount uncertainty due to sampling error. To account for this uncertainty, an unbiased (i.e. mean) adjustment was required for each duration.

The "expected probability of exceedance" reflects the fact that the probability of exceeding a threshold flow rate is itself a random variable. A flow- or volume-frequency curve that has been adjusted to reflect the expected long-run proportion of exceedances of a threshold flow rate better accounts for both natural variability and sample error caused by short record length than the biased, median estimates. Expected probability is expressed as:

$$E[P(X > x_0)] = \lim_{n \to \infty} \frac{\sum 1_{X>x_0}(X)}{n}$$

where E[ ] is the expectation operator, *X* is the random variable (e.g. flow, stage, etc.), x_0 is the threshold, and *1* is the indicator function. Expected probability is the expected value (or mean) of the probability of exceeding x_0 (U.S. Army Corps of Engineers, 2017).

The expected probability curve for each duration was computed using a Monte Carlo approach featuring parametric bootstrap sampling of the (median) flow- and volume-frequency curves. The number of samples used within the bootstrap sampling approach was equivalent to the Effective Record Length (ERL). The final "family" of flow- and volume-frequency curves are detailed and presented within Figure 5.



Statistic	Duration				
	Inst. Peak	1DAY	2DAY	3DAY	4DAY
Mean	3.714	3.607	3.526	3.457	3.406
Std. Dev.	0.207	0.204	0.199	0.195	0.19
Skew	0.702	0.761	0.786	0.8	0.805
Systematic Events	48	48	48	48	48
Historic Period	106	81	81	81	81
ERL (years)	51	47	48	48	48

Figure 5. Family of Flow- and Volume-Frequency Curves

BALANCED HYDROGRAPH CREATION

Balanced hydrographs are hydrograph shapes that are based on "naturally" occurring flood hydrographs and have been modified to contain specific exceedance flow rates/volumes across one or more durations. This implies that the maximum flow/volume for duration *X* has the same ACE as the maximum flow/volume for duration *Y*, etc. Naturally occurring hydrographs generally do not "balance" across multiple durations; the flow rate/volume for a given duration commonly does not have the same ACE as other durations. This is due to the complex meteorological conditions that caused the event making each event "unique". However, balancing natural hydrograph shapes using flow- and/or volume-frequency information provides hypothetical events that contain a reasonable distribution of flow rates over time.

Due to the eventual use of these balanced hydrographs to indirectly estimate the pool stage-frequency out to remote loadings, the four largest flood events recorded at the location of Sayers Dam where used as template shapes. These events occurred in March 1936, June 1972, September 2004, and December 2010 and are compared against one another within Figure 6.

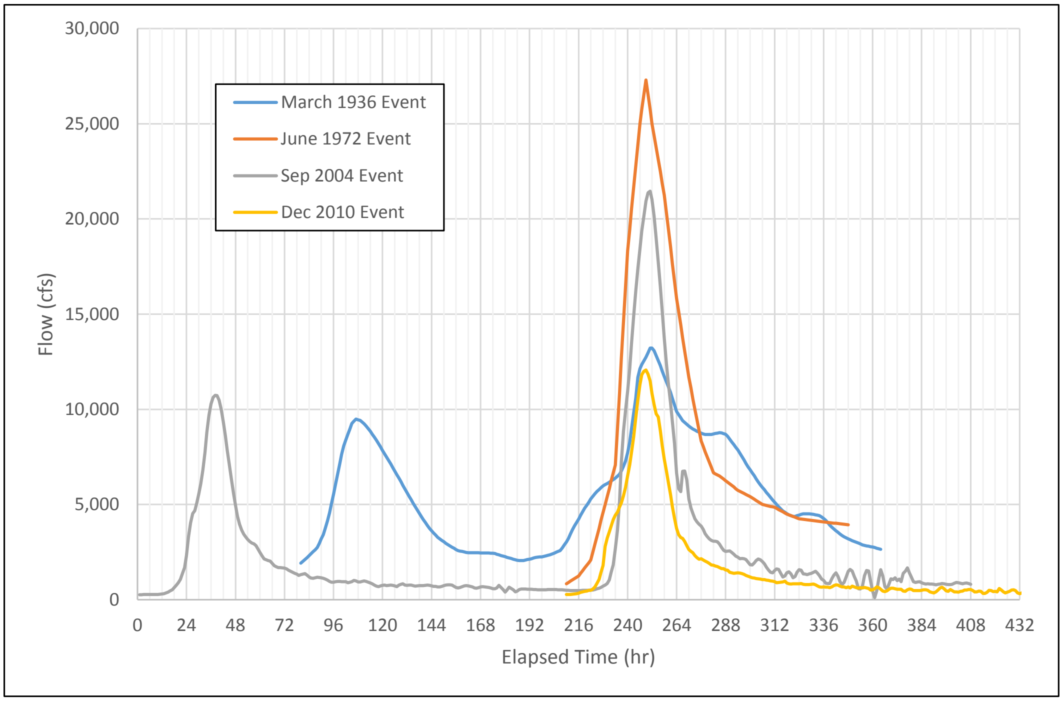


Figure 6. Four Largest Flood Events at Sayers Dam

(Note: starting time for each event modified to allow for direct comparison)

The observed hydrograph shapes and expected probability flow- and volume-frequency information were linked within HEC-SSP and used to compute balanced hydrographs for ACE of 2-, 1-, 0.5-, 0.2-, 0.1-, 0.01-, and 0.001-percent. The expected probability curve was used due to the eventual use of these balanced hydrographs to infer a stage-frequency curve using deterministic methods (as opposed to a stochastic analysis).

Balanced hydrographs were created for each event and ACE of interest using the 3-day duration. The 3-day duration was chosen as the critical inflow duration through comparison of historic high pool events. On average, inflow generally exceeds outflow (i.e. caused the pool to rise) for approximately 3 days during extreme events at Sayers Dam.

An additional set of balanced hydrographs were created using the June 1972 event hydrograph shape and balanced across the inst. peak, 1-, 2-, and 3-day durations. This was done in an effort to compare the effects of balancing across a single duration against balancing across multiple durations. An example of the 1/10,000 ACE balanced hydrograph using the June 1972 event as a template shape and balanced across the instantaneous peak, 1-, 2-, and 3-day durations is shown in Figure 7.

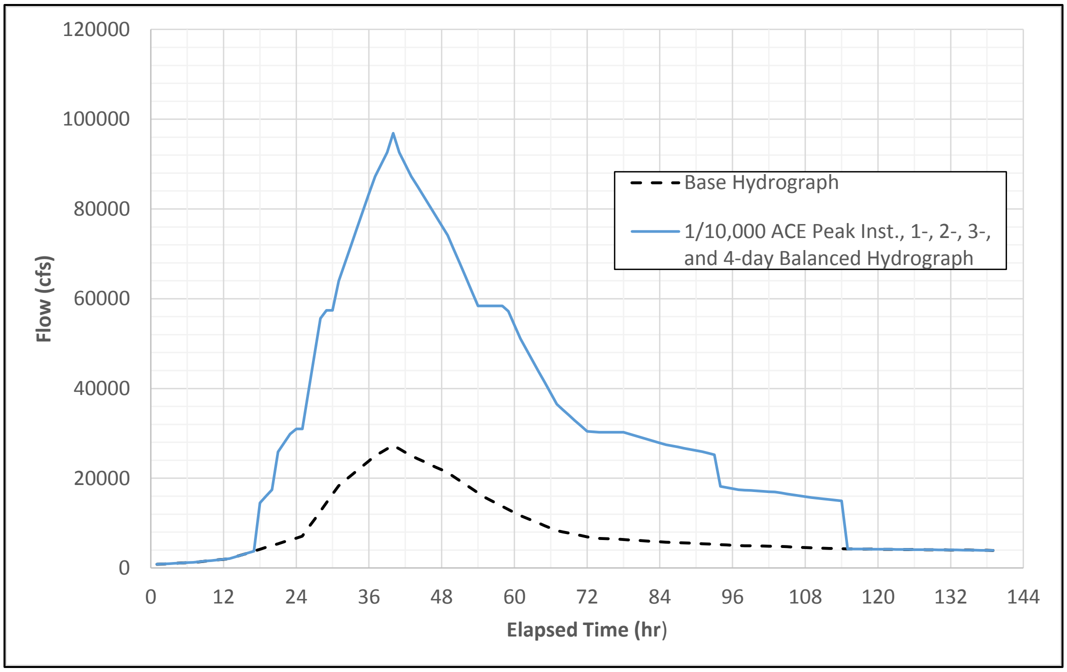


Figure 7. June 1972 Event Balanced Hydrograph Using the 1/10,000 ACE Inst. Peak, 1-, 2-, and 3-day Duration

ROUTING AND CREATION OF STAGE-FREQUENCY CURVE

An HEC-HMS project was created to route the balanced hydrographs through Sayers Dam. A source element was created to provide the inflow hydrograph to Sayers Dam and linked to the output from the HEC-SSP analyses. Flow attenuation and translation affects due to operations at Sayers Dam were replicated using a reservoir element. The elevation-storage relationship was extracted from the most recent water control manual along with detailed outlet works and spillway operations information (U.S. Army Corps of Engineers, 1996). Controlled releases during flood control operations are made in an attempt limit downstream stages at numerous control points. Generally speaking, as inflow begins to greatly exceed outflow and pool stages rise, releases are reduced until the pool rises to the spillway crest. At that point, releases are increased in an attempt to limit any further rise in the pool elevation. Using past events as a guide, these operations were simplified and input as a non-looped elevation-discharge relationship (i.e. only one flow rate was allowed for each elevation). The performance of these simplified routing relationships were compared against past events and shown to be appropriate.

A coincident frequency analysis was performed within HEC-SSP to ascertain the sensitivity of the peak pool elevation to the starting pool elevation for the extreme events in question. It was found that the multiple simulated stage hydrographs (each using a different starting pool elevation) quickly aligned with one another. This demonstrated the relative insensitivity to the starting pool elevation. Therefore, the initial conditions of Sayers Dam was set to the median pool elevation based upon historical observations which was approximately equal to the summer recreation pool of 629.3 feet NAVD88.

Reservoir routing was accomplished using a linear routing routine with a 1-hour time step. The peak pool elevation was extracted from each simulation and the ACE of each balanced hydrograph was directly transferred to the resulting peak pool elevation. The AMS of observed peak pool elevations were assigned ACE using the Weibull plotting position:

$$P_i = \frac{i}{n+1}$$

where P_i is annual chance exceedance, *i* is the rank of the event (assigned in descending order), and *n* is the sample size (33 years in this case). Peak pool elevations from the balanced hydrograph simulations are compared against the AMS of observed peak pool elevations in Figure 8 which uses normal probability paper along with the probability axis being expressed as a percentile.

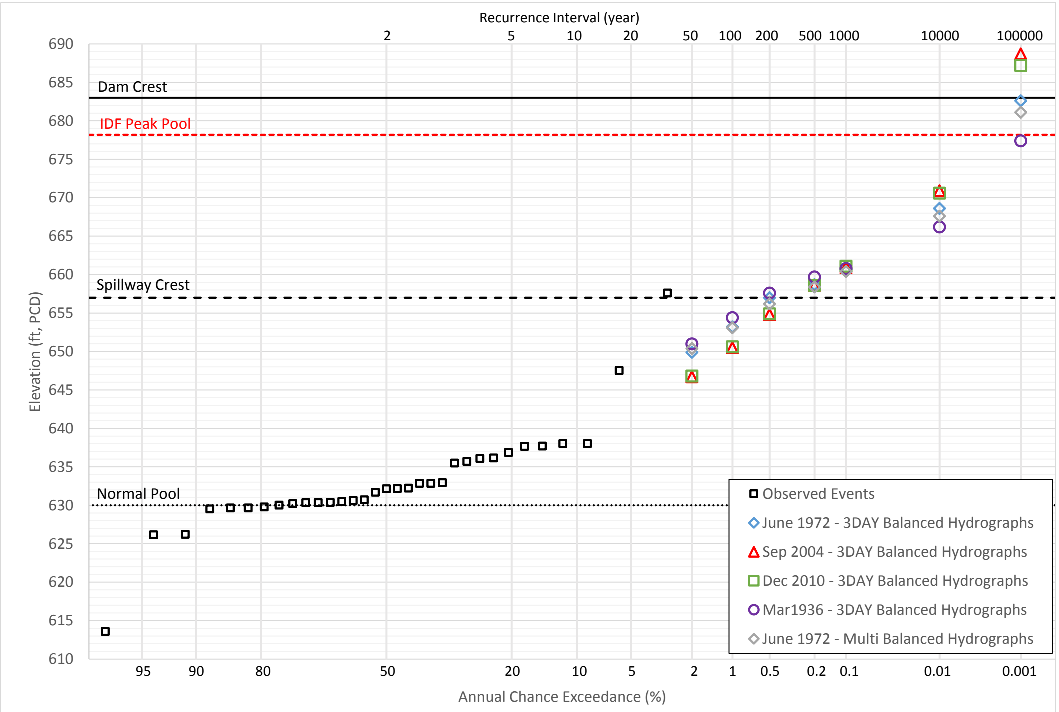


Figure 8. Balanced Hydrograph Event Routing Results

The rarity of the June 1972 event and September 2004 events are likely misrepresented by the Weibull plotting position when using a sample size of 33 years. In fact, it is probable that the June 1972 event was the largest since at least 1911 (104 years). Therefore, these two events should likely be plotted further to the right. However, it is evident that the results from the balanced hydrograph events align well with the observed events.

The balanced hydrograph event routings for the 1/50 ACE (i.e. 2-percent) cover a range of approximately 5 feet in peak pool elevation. This range decreases as the spillway crest is equaled and slightly exceeded, which is primarily due to the large increase in discharges relative to a small increase in pool elevation as the spillway becomes activated. Then, as the ACE decreases, the range in peak pool elevation begins to increase once again. At the 1/100,000 ACE, the range in peak pool elevation is approximately 11.3 feet. These differences are solely due to the input hydrograph shape and reflect the uncertainty introduced by this parameter.

Also, at the 1/50 ACE, the March 1936 event shape produces the highest peak pool elevation while the September 2004 event shape produces the lower peak pool elevation. This trend reverses by the 1/10,000 ACE, where the March 1936 event shape produces the lowest peak pool elevation and the September 2004 event produces the highest peak pool elevation.

Finally, the differences produced by balancing across a single duration when compared against the use of multiple durations when balancing are slight. In this instance, the differences are greatest at extremely small ACE (approximately 1.5 feet). This reaffirms the use of the 3-day duration as the critical inflow duration for Sayers Dam.

The results from the balanced hydrograph simulations were then compared against the results from a more complicated stochastic simulation, as shown within Figure 9. In this case, the results from the Monte Carlo Reservoir Analysis Model (MCRAM) were used for comparison. MCRAM was developed to facilitate hydrologic hazards within the USACE Dam Safety Program. Within this model, flood season, reservoir starting stage, inflow event volume, and the inflow hydrograph shape are treated as random variables (U.S. Army Corps of Engineers, 2017). Outputs from MCRAM include a median and mean (i.e. expected probability) pool stage-frequency curve in addition to uncertainty bounds (represented as 90% confidence limits). However, these results from MCRAM were obtained after 10,000,000 individual simulations, which takes many hours of computing time and resources.

As is shown in Figure 9, the much more complicated MCRAM simulations produced results that compared favorably with the balanced hydrograph simulations. The shape and magnitude of the MCRAM expected probability pool stage-frequency follows closely with the results from the balanced hydrograph simulations while the balanced hydrograph simulations lie within the 90% confidence limits. Information from both of these sources (and others) are recommended for use in the generation of a best fit pool stage-frequency curve that encompasses the full range of probabilities needed within an SQRA.

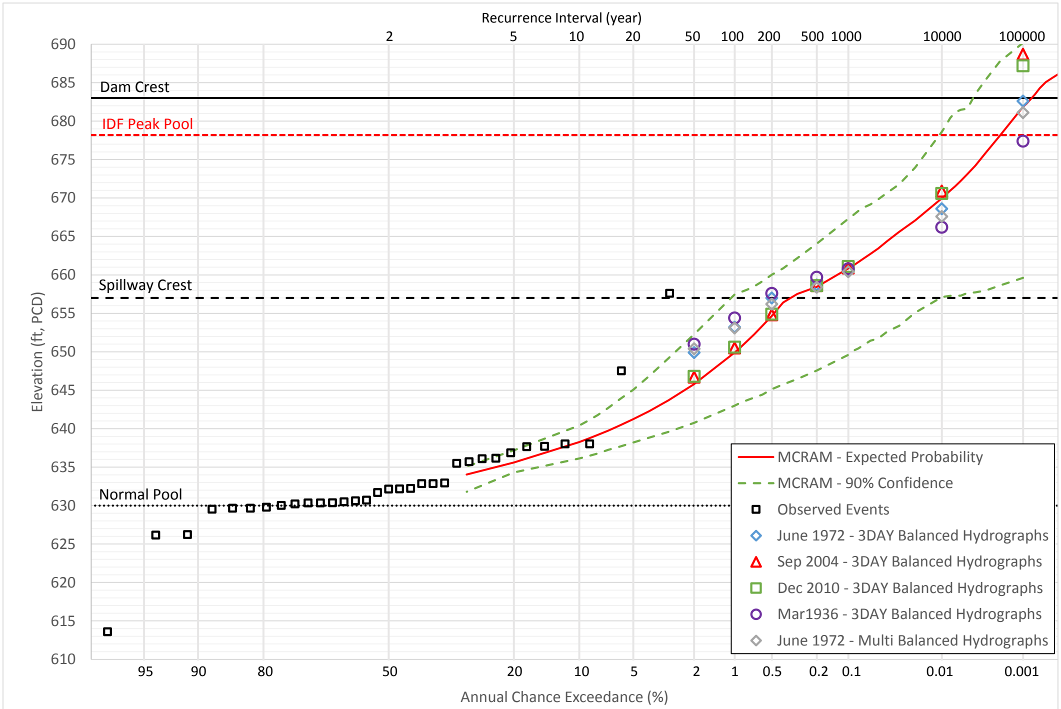


Figure 9. Comparison of Balanced Hydrograph Routing Results to Stochastic Simulations

CONCLUSION

The results from this study indicate that balanced hydrographs created using flow- and volume-frequency curves in addition to observed event hydrograph shapes can be routed through a reservoir model to provide a rapid and accurate way to develop stage-frequency curves for use within dam and levee safety studies, such as Semi-Quantitative Risk Analyses within USACE. Tools that have recently been developed by the Hydrologic Engineering Center have decreased the amount of effort required to create and use these balanced hydrographs in a deterministic fashion while also increasing the accuracy and applicability of the results. The results from these balanced hydrograph simulations compared favorably with much more complex stochastic simulations and were achieved at a fraction of the computation time.

This research will be used to inform future dam and levee safety studies within USACE through additional applications at other dams and levee systems. Ongoing enhancements within HEC-SSP, HEC-HMS, and other HEC software products will continue to add much needed capabilities for use within these types of analyses.

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