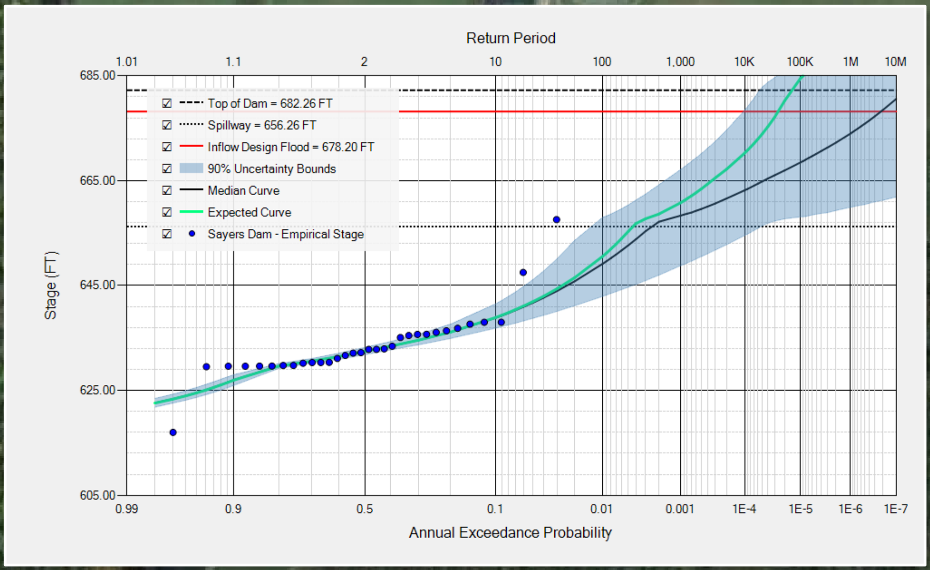
Hydrologic Hazard Methodology for Semi-Quantitative Risk Assessments

RMC-TR-2018-03

An Inflow Volume-Based Approach to Estimating Stage-Frequency for Dams



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14. ABSTRACT

The purpose of this document is to establish methods and procedures for assessing the hydrologic hazard of dams in the USACE Dam Safety Program for use in semi-quantitative risk assessments (SQRA). This document is primarily focused on an inflow volume-based approach to estimating stage-frequency curves for dams. This document provides guidance on fitting inflow volume-frequency curves and simulating reservoir stage-frequency curves. Techniques for quantifying the uncertainty in inflow volume- and stage-frequency curves caused by small sample sizes are demonstrated. The information contained in this document reflects the methodologies currently used by USACE in performing hydrologic hazard assessments. These methodologies provide satisfactory results for use in an SQRA. Periodically, there may be minor improvements and revisions to this report to clarify data inputs, software updates, and other details based on annual reviews and feedback from the Dam Safety Program.

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An Inflow Volume-Based Approach to Estimating Stage-Frequency for Dams

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Purpose and Scope

The purpose of this document is to establish methods and procedures for assessing the hydrologic hazard of dams in the USACE Dam Safety Program for use in semi-quantitative risk assessments (SQRA). In the risk assessment of dams, the annual peak reservoir stage is typically the primary loading parameter for evaluating a potential failure mode. Other parameters such as discharge, duration, and velocity can also be important. The probability of failure is often conditional on the magnitude of the hydrologic loading. The consequences of failure are also a function of the reservoir stage, outflow, and corresponding reservoir volume. Therefore, the annual probability of exceeding a given reservoir stage, commonly referred to as stage-frequency, is a critical consideration in performing a risk analysis. In some cases, such as for spillway erosion potential failure modes, probability as a function of dam release flows is also required. The general risk equation for dam safety is defined as follows:

$$Risk\ = P(Hazard) \times P(Failure|Hazard) \times Consequences|Failure \qquad \text{Equation 1}$$

Risk is equal to the probability of the hazard, $P(Hazard)$, multiplied by the probability of failure given the hazard, $P(Failure|Hazard)$, multiplied by the consequences given the failure, $Consequences|Failure$. The hydrologic hazard for dams is described with a hydrologic hazard curve (HHC). An HHC is defined as a graph of estimated annual exceedance probability (AEP) versus peak flow, flood volume (for a specified duration), and/or reservoir stage. These HHCs are also commonly referred to as annual peak flow-, volume-, and stage-frequency curves. An example stage-frequency curve with uncertainty bounds is provided in Figure 1 below.

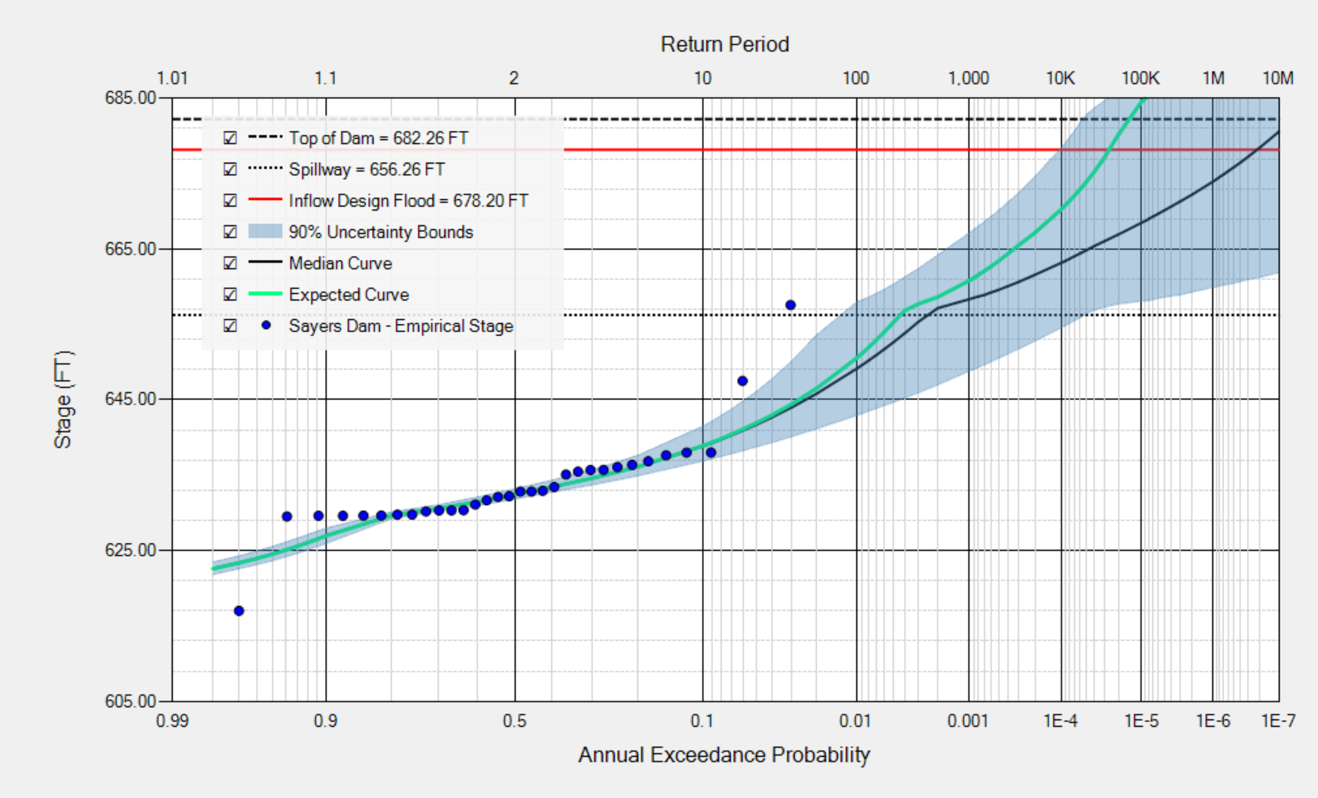


Figure 1: Example of Stage-Frequency Curve with Uncertainty Bounds

This document is primarily focused on an inflow volume-based approach to estimating stage-frequency curves for dams. The objective of frequency analysis in the context of hydrologic hazards is to infer the probability that various size events will be exceeded from a sample of recorded events (U.S. Army Corps of Engineers, 1993).

There are two primary components of randomness in inflow volume and reservoir stage exceedance probabilities: natural variability and knowledge uncertainty. Natural variability is best described as the effect of randomness and is a function of the system (Vose, 2008). It is not reducible through either study or further measurement. For example, a peak flow-frequency curve describes the natural variability in peak flow.

Knowledge uncertainty is the lack of knowledge about parameters that characterize the system being modeled. Knowledge uncertainty can be reduced through further measurement or study. For example, the confidence intervals, or uncertainty bounds, around a peak flow-frequency curve describe the knowledge uncertainty in the statistical parameters of the peak flow-frequency curve.

There are two primary sources of knowledge uncertainty in hydrologic hazard assessments: sampling uncertainty and model uncertainty. First, the sample of historical flood events is usually small, resulting in knowledge uncertainty pertaining to the true probability distribution and corresponding exceedance probabilities. This sampling uncertainty is a property of the effective record length (sample size) of the hydrologic variable; the sampling uncertainty decreases as the record length increases. Secondly, an analytical probability distribution or model does not always fit a particular data-type (flow, volume, stage, etc.) well in all applications. This model uncertainty is due to the inherent assumption in the formulation of the mathematical model itself or our inability to identify the best fitting model.

This document provides guidance on fitting inflow volume-frequency curves and simulating reservoir stage-frequency curves. Techniques for quantifying the uncertainty in inflow volume- and stage-frequency curves caused by small sample sizes are also demonstrated.

Applicability

The methods described herein are appropriate for use in screening level risk assessments, such as the SQRA process for Period Assessments (PA) and Phase 1 Issue Evaluation Studies (IES Phase I). The information contained in this document reflects the methodologies currently used by USACE in performing hydrologic hazard assessments. These methodologies provide satisfactory results for use in an SQRA. Periodically, there may be minor improvements and revisions to this report to clarify data inputs, software updates, and other details based on annual reviews and feedback from the Dam Safety Program.

This document is not intended to be a textbook. It is by no means comprehensive, as each project is unique and will potentially require additional analysis. Nor is this document a substitute for critical thinking and good engineering judgment. Rather, this document only provides procedures for a minimum level of effort required for a SQRA. If more information, better quality data, or better hydrologic models exists, they should be incorporated into the assessment when applicable.

It is assumed that the readers of this document are familiar with flood frequency analysis concepts, Bulletin 17C methods (U.S. Geological Survey, 2018), and have experience using the data storage system, HEC-DSSVue, and statistical software package, HEC-SSP.

Scope

This methodology document is based on the current state of the practice and recent improvements in hydrologic frequency analysis and uncertainty estimation. Information from the following USACE engineering regulations and manuals are used as a foundation and background:

1. ER 1110-2-1450, Hydrologic Frequency Estimates
2. ER 1110-2-1464, Hydrologic Analysis of Watershed Runoff
3. EM 1110-2-1413, Hydrologic Analysis of Interior Areas.
4. EM 1110-2-1415, Hydrologic Frequency Analysis.
5. EM 1110-2-1417, Flood-Runoff Analysis.
6. EM 1110-2-1420, Hydrologic Engineering Requirements for Reservoirs.
7. EM 1110-2-1619, Risk-Based Analysis for Flood Damage Reduction Studies.
8. EM 1110-2-3600, Management of Water Control Systems.

Procedures for derivation of a reservoir stage-frequency curve using inflow volume-based methods are discussed and illustrated. This methodology document is sub-divided into seven chapters and two appendices, as outlined below.

Each Chapter provides a definition of the topic, the role it plays in the hydrologic hazard assessment, and provides a step-by-step tutorial on how to evaluate it. The tutorials use the Bald Eagle Creek dataset for Foster Joseph Sayers

Dam located in Pennsylvania. The procedures described in this document are outlined below; detailed description of the following procedures are provided in the respective chapters of this document.

Software Requirements and Data Sources

This chapter outlines all software requirements and lists some representative data sources. These sources are intended to be used as a references for data collection, and are not all-inclusive.

Initial Data Analysis

This chapter provides an overview of general frequency analysis concepts and discusses the initial data analyses that are required for a hydrologic hazard assessment. In addition, this chapter provides procedures for creating an empirical stage-frequency curve using the RMC-RFA software, and for determining the critical inflow duration for use the inflow volume-frequency analysis.

Inflow Volume-Frequency Analysis

This chapter discusses advanced flood frequency analysis concepts, and provides detailed procedures for developing inflow volume-frequency curves using HEC-SSP.

Flood Seasonality Analysis

This chapter discusses the relative frequency of flood events by season, the role it plays in the hydrologic hazard assessment and provides procedures for determining flood seasonality using RMC-RFA.

Reservoir Starting Pool Duration Analysis

This chapter discusses the antecedent reservoir pool conditions, how duration curves are used in the hydrologic hazard assessment and greater risk assessment, and provides procedures for determining reservoir starting pool duration curves using the RMC-RFA and HEC-SSP*.*

Reservoir Model Development

This chapter provides an overview of reservoir routing concepts and discusses the inputs required to develop a reservoir model for a hydrologic hazard assessment. In addition, this chapter provides procedures for developing stage-storage-discharge relationships and creating a reservoir model using RMC-RFA and HEC-HMS.

Reservoir Stage-Frequency Analysis

This chapter provides an overview of stochastic and uncertainty analysis concepts, and describes how to estimate a reservoir stage-frequency curve with uncertainty bounds using the reservoir frequency analysis software, RMC-RFA.

Appendix A: Balanced Hydrograph Analysis

In some extreme cases, the reservoir operations included in RMC-RFA are not adequate to accurately assess the hydrologic hazard for an SQRA. In these situations, routing discrete, “balanced hydrographs” through a reservoir model can be used as a means to inform reservoir stage-frequency curves. This chapter provides procedures for developing balanced hydrographs manually and using HEC-SSP.

Appendix B: Coincident Frequency Analysis

In some extreme cases, the reservoir operations included in RMC-RFA are not adequate to accurately assess the hydrologic hazard for an SQRA. This chapter provides procedures for routing balanced hydrographs of a known AEP through a reservoir model and deriving a reservoir stage-frequency curve using a coincident frequency analysis method.

Estimated Cost and Schedule

The following table lists the estimated work duration (in hours) and cost for each task (assuming $100/hour) required to perform an inflow-volume based stage-frequency analysis for a SQRA. The cost estimates reflect the effort required for both production and documentation. These estimates are appropriate for performing the hydrologic work needed for the majority of SQRAs, where the focus is on a single reservoir and where system effects can be ignored. It is assumed that the hydrologic and hydraulic engineers performing the tasks have a background and training in flood hydrology, hydrologic statistics, and hydrologic modeling.

Table 1: Estimated Schedule and Cost to Perform the Procedures

Task	Duration (Hours)	Cost ($)
Software and Data Acquisition	16	$1,600
Data Quality Control	8	$800
Empirical Stage-Frequency Analysis	2	$200
Critical Inflow Duration Analysis	4	$400
Inflow Volume-Frequency Analysis	30	$3,000
Flood Seasonality Analysis	4	$400
Reservoir Starting Pool Duration Analysis	4	$400
Reservoir Model Development	20	$2,000
Reservoir Stage-Frequency Analysis	30	$3,000
DQC / Peer Review	16	$1,600
Consistency Review	16	$1,600
Total:	**150**	**$15,000**
Optional Task If Applicable		
Balanced Hydrograph Analysis	16	$1,600
Coincident Frequency Analysis	16	$1,600

Software Requirements and Data Sources

The first step of a stage-frequency curve analysis is to obtain all required software necessary to perform the analysis, and locate all available hydrologic data for the project. This chapter outlines all software requirements and lists some representative data sources. These sources are intended to be used as a references for data collection, and are not all-inclusive.

Software Requirements

Use the App Portal (https://app-portal.usace.army.mil/ESD) to request installation of the most recent versions of the following HEC software:

- Required
    - HEC-DSSVue
    - HEC-SSP
    - RMC-RFA
- Optional
    - HEC-HMS
    - HEC-ResSim
    - STATS_LPIII_ExpectedProbability_v2.0.xlsb

RMC-RFA can be downloaded from https://sites.google.com/a/alumni.colostate.edu/jengland/resources, or from ProjectWise at pw:\\140.194.161.13:RMC01\Documents\Technical Library\Software\.

The above Microsoft Excel Spreadsheet Tool can be downloaded from ProjectWise at pw:\\140.194.161.13:RMC01\Documents\Technical Library\USACE Guidance-Policy-Procedures\Guidance\.

Contact Carl Broyles at Kansas City District for user permission on ProjectWise (Carl.A.Broyels@usace.army.mil).

Contact Ed Stowasser at the Dam Safety Modification Mandatory Center of Expertise for assistance with software and tool acquisition (Edward.L.Stowasser@usace.army.mil).

Example Models and Data

The examples and tutorials provided in this document use the Bald Eagle Creek dataset for Foster Joseph Sayers Dam located in Pennsylvania. The example models and data can be downloaded from ProjectWise at pw:\\140.194.161.13:RMC01\Documents\Technical Library\Training\Periodic Assessments\.

Data Sources

Because dam safety risk assessments typically include risks associated with infrequent to extreme floods, it is important to gather as much historic information data as possible. Likewise, it is important to perform quality control to minimize uncertainties due to missing data or measurement error. The data-types, such as hydrologic models, reports, and gage records, which are required to perform a reservoir stage-frequency analysis, are described below along with a brief description of potential data sources.

Types of Models, Data and Potential Data Sources

1. **Hydrologic and Hydraulic Models**: Existing hydrologic and hydraulic models should be made use of when available. Locate all previous models, such as HEC-HMS models, HEC-ResSim models, HEC-RAS models, analysis and design calculations, and any modeling or design reports available for the dam of interest. Contact the local USACE District Hydrology and Hydraulics office for existing models. Often, the District and Division Water Management offices will also have models, such as CWMS models, available for forecasting purposes that can be utilized.

2. **Water Control Manual and Design Hydrology Memorandum**: Locate the water control manual for the dam of interest. Gather information from the water control manual pertaining to historical and design flood events for the dam. Also, collect all reservoir operational information, such as stage-storage-discharge relationships. Contact the local District Water Management office for a copy of the manual. Locate and obtain the design hydrology and hydraulics memorandum for the dam from District Engineering and Construction offices. The design hydrology and hydraulics memorandum provides critical background information on the standard project flood and spillway design flood with relevant design data, estimates of large floods, assumptions, and models used.

3. **Systematic Gage Records**: Acquire all available instantaneous peak and daily average inflow, stage, and discharge data for the systematic record, including periods prior to dam, reservoir, or levee construction. The data collection interval (e.g. hourly, daily average by calendar date or by event, once per day at a particular time) should be considered because daily average values can sometimes dampen flood peaks and data collected at a particular time of day can miss flood peaks altogether. Consideration should also be given to how the data is derived (e.g. computed data or observed gage data) to understand the potential errors associated with the data. This can be a source of measurement error, especially when the duration of interest is about the same as the data collection interval. An example is shown in Figure 2.

   Typically, daily values are readily available in HEC-DSS files from the local water management office. From the mid-1980s to the present, hourly values are typically available in HEC-DSS files. If digital files are not available, paper files are typically available from the local water management office or at the project site. Daily values and instantaneous peak values are typically available from U.S. Geological Survey (USGS) gage records at site or at a nearby gage location. Additional information may be available from the National Weather Service (http://water.weather.gov/ahps/). More detailed information may also be available from USACE and the USGS for specific flood events.

   Hourly values can be directly used for peak flow-frequency analysis, in most cases. Peak values can be estimated from daily values by developing a relationship between the peak and the 1-day volume. The relationship could be a simple ratio between the instantaneous peaks and the daily values. The ratio could be estimated by using data from observed events, data from similar nearby streams, or a regional analysis. Typically, the benefits of having more data outweighs the drawbacks of the measurement error introduced by estimating peaks from 1-day volumes.

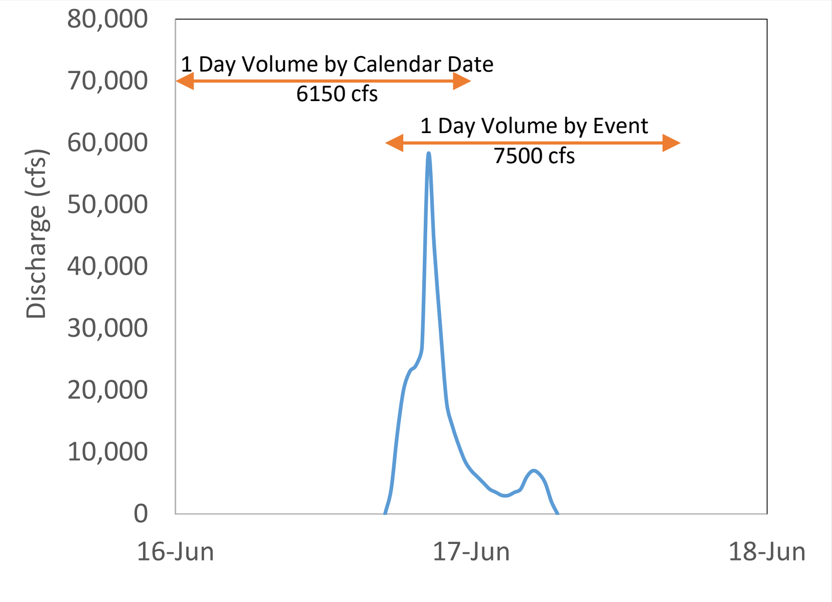


Figure 2: Data Collection Interval Example

In most reservoir stage-frequency analyses, the peak-flow frequency is not of critical importance since most flood control facilities are driven by inflow volume. However, in some cases, such as low head navigation dams, peak-flow frequency will be the driver.

USACE water management offices at the District and Division maintain streamflow and reservoir information. For example, the Northwestern Division provides data for the Missouri River basin through the reservoir control center at http://www.nwd-mr.usace.army.mil/rcc/current.html.

In the absence of readily available reservoir inflow data provided by the District, daily streamflow data can be obtained from various sources. The main data source is the USGS National Water Information System (NWIS) at https://maps.waterdata.usgs.gov/. Data such as annual maximum instantaneous peak streamflow and gage height, daily average streamflow, rating curves, and streamflow measurements can be obtained from the NWIS.

4. **Historical Flood Information**: Typically, systematic gage records are limited relative to the frequency events that need to be estimated for a dam safety risk assessment. Therefore, it is important to incorporate as much additional information as possible. Acquire all available information on historical storms and floods within the watershed of interest, especially noting the largest floods in the watershed or region of interest. Historical flood data sources can be obtained from a variety of locations including the water control manual, design documents, post flood reports, water supply papers, and others.

   USACE retains flood files such as post flood reports for major historical events at District offices. Historical floods can also be found in design documents and the water control manual for the dam of interest. Information on observed floods are described in various USGS publications, such as Water-Supply Papers (https://pubs.er.usgs.gov/), Professional Papers, and Scientific Investigations Reports. The information generally consists of basin rainfall estimates, types of discharge or indirect measurements made, stage and discharge hydrograph estimates, damage estimates, pictures of damaged structures, and erosion and deposition in channels and floodplains. In some cases, past historical flood dates, stages, and peak discharge estimates in the region are described in each report.

   The USGS Water-Supply Papers (1900-1971) and Water Resources Data Reports (https://wdr.water.usgs.gov/), which have been published for each state (1971-2005), contain some historical flood descriptions and information that can be valuable for a frequency analysis. The information is provided on the site information sheet for individual gaging stations. Since 2006, this same information can be obtained for each individual gage, if the gaging station is currently in operation. Three types of data are typically presented in the reports and site information summaries: (1) dates, stages, and sometimes discharges of observed floods prior to the gaging station period of record; (2) a large flood during the period of record that is known to be the maximum stage and discharge since at least some historic date; and (3) a large flood during the period of record that is known to be the maximum stage and discharge since some historic date.

   State reports and publications are another major source of historical flood information. These publications can contain information on record floods, stages, historical periods, and impacts to infrastructure. Journals and other Federal Agency reports are invaluable sources for historical flood information. Community flood information and experiences are usually included in Federal Emergency Management Agency (FEMA) Flood Insurance Studies.

5. **Paleoflood Data**: Paleoflood hydrology is the study of past or ancient flood events which occurred before the time of human observation or direct measurement by modern hydrological procedures (Baker, 1987). Unlike historical data, paleoflood data do not involve direct human observation of the flood events. Instead, the paleoflood investigator studies geomorphic and stratigraphic records (various indicators) of past floods, as well as the evidence of past floods and streamflow derived from historical, archeological, dendrochronologic, or other sources. The advantage of paleoflood data is that it is often possible to develop records that are 10 to 100 times longer than conventional or historical records from other data sources in the western United States. Paleoflood data generally include records of the largest floods, or commonly, the limits on the stages of the largest floods over long time periods. Obtain any available paleoflood studies that have been performed within the watershed of interest. Journals and other Federal Agency reports, such as the USGS and the U.S. Bureau of Reclamation (USBR) are invaluable sources for paleoflood data. On some occasions, the USACE Risk Management Center or District will have performed a paleoflood study in the past. Contact the local USACE District Hydrology and Hydraulics Branch to see if any studies are available.

6. **Regional Inflow Data**: Regional studies on reservoir inflow or volume-duration frequency should be used when available to inform estimation of skew. Regional information that can be considered for flood frequency typically consists of regional estimates of flow statistics. Regional skew coefficient estimates and mean-

square error (MSE) of those estimates can be obtained, for some locations, in current USGS flood-frequency reports for regions or individual states. These flood frequency reports and additional information on regional skew and regional quantile estimates for many locations are available from the USGS at http://water.usgs.gov/osw/programs/nss/pubs.html and the Hydrology Frequency Analysis Work Group (HFAWG) at https://acwi.gov/hydrology/Frequency/b17c/supplementary-materials/reports.html. On some occasions, the District will have performed a regional study in the past. Contact the local USACE District Hydrology and Hydraulics Branch to see if any studies are available.

In the absence of any regional data, flow statistics should rely on at-site systematic, historical, and paleoflood records. It is the duty of the analyst to check if regional skew information is available. If regional skew analysis is available, it is important to understand the quality of the data. Quality of a regional skew coefficient is measured by the mean square error (MSE) of the coefficient. Smaller values of MSE correspond to smaller variance of the skewness coefficient, hence, a larger amount of information is contributed to the analysis with the use of a weighted skew. Therefore, regional skew coefficients with a smaller MSE are more favorable.

It is preferable that the regional skew and MSE of the skew have been developed for the duration of flow corresponding to the duration being analyzed in the volume-duration-frequency analysis. The use of instantaneous skew information is only considered acceptable for short durations (e.g. 1 to 3 day durations). This practice is not appropriate for longer durations because there is a high likelihood that the calculated volume over long durations contain more than one flood event and potentially more than one flood driving mechanism.

The regional skew estimates published in Bulletin 17B (1982, Plate 1) are not recommended for use in flood-frequency studies. Additional information and guidance on regional skew studies performed by the USGS is available at https://acwi.gov/hydrology/Frequency/b17c/.

7. **Historical and Design Inflow Hydrograph Data**: Locate hydrograph data for major historical flood events, large flood events found in the systematic record, and the synthetic floods, such as a probable maximum flood (PMF) or standard project flood (SPF). The hydrograph time step should be appropriate to the design event and the characteristics of the reservoir. Three to five hydrograph shapes in total will be required. The hydrographs will be scaled and routed in order to derive the reservoir stage-frequency curve. The hydrograph shapes can be found in the water control manual and through investigation of period of record and historical data described above. Reports prepared by Districts on large floods (example – Floods of December 1955, Portland District) should be investigated to find inflow hydrograph data and estimates at dams. Instantaneous data (15-minute data, unit values, complete hydrographs), from 2007 to present for active stream gages, can be obtained from the USGS NWIS at https://nwis.waterdata.usgs.gov/nwis/uv/?referredmodule=sw. Hydrograph data from about the mid-1980s to 2007 can be obtained from the instantaneous data archive at https://ida.water.usgs.gov/ida/. For flood events that occurred prior to the late 1970s, sub-daily hydrographs can sometimes be obtained from data tabulated within USGS flood reports, particularly Professional Papers or Water-Supply Papers.

Initial Data Analysis

This chapter provides an overview of general frequency analysis concepts and discusses the initial data analyses that are required for a hydrologic hazard assessment. In addition, this chapter provides a step-by-step tutorial for creating an empirical stage-frequency curve using the reservoir frequency analysis software, RMC-RFA, and for determining the critical inflow duration for use in the inflow volume-frequency analysis.

Data Quality Control

Performing quality control on the data is a critical step in any frequency analysis. Incorrect or poor quality data will produce inaccurate inflow volume- and stage-frequency results. At most USACE dams, reservoir inflow is indirectly calculated using measurements of reservoir storage (via stage) and outflow (via rating curves or gage measurements). The District water management office normally performs quality control on the calculated reservoir inflows, so the data may be used as provided after a cursory review is made to check for any obvious errors.

In cases where reservoir inflow systematic data is obtained from an upstream streamflow gage, information on manual measurements of streamflow and gage height, including indirect measurement, can be obtained from the USGS at http://waterdata.usgs.gov/nwis/measurements. These measurements are used to develop streamflow rating curves, supplement and (or) verify the accuracy of the automatically recorded estimates at gages, as well as to compute streamflow based on gage height. These are valuable for flood frequency studies to aid hydrologists in understanding how the largest flood estimates are made (such as indirect measurements), and in estimating uncertainty. See details on streamflow measurement and computation and discharge ratings from the USGS at https://water.usgs.gov/osw/furnished_records/technical_procedures.html.

In addition to potential measurement errors, many datasets have missing data, duplicate values, erroneous data, or other issues that can impact the inflow volume- and stage-frequency assessments. Plotting the flow and stage time series data can assist with identifying any potential errors.

The Chapter II-1 *Reservoir and River Stage Exceedance Probabilities* from Best Practices (U.S. Bureau of Reclamation & U.S. Army Corps of Engineers, 2015) provides a useful example data set showing daily average reservoir stages for a dam as presented in Figure 3. The plot reveals several potential data quality issues. The time periods associated with the initial reservoir filling, the dam safety emergency, and the pool restriction for interim risk reduction may not be representative of normal operation. Some of the data also appears to be missing and incorrect based on a visual inspection of the plot. Missing data should be filled and flawed data should be corrected or removed, as deemed appropriate.

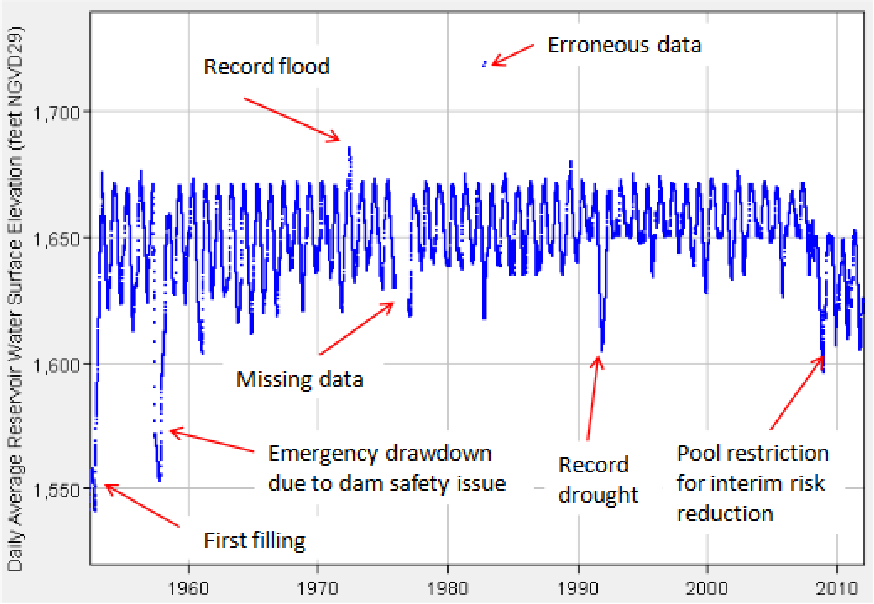


Figure 3: Daily Average Reservoir Stage Data

Data Transformation

Frequency analysis of hydrologic data requires that the data be homogeneous and independent (see the General Frequency Analysis Concepts section below for more detail). Therefore, in addition to performing quality control on the accuracy of the data, the homogeneity of the data deserves consideration.

Known changes in the watershed response, such as the effects of an upstream reservoir, should be removed from the inflow data series to make it homogeneous; i.e., if there is an upstream reservoir that significantly influences inflow to the dam of interest, the reservoir inflow needs to be *unregulated*. This can be evaluated by looking at the period of record files and visually inspecting the record with the knowledge of when flood control projects were built upstream of the project being studied.

Unregulated flows are defined as those flows that would have occurred without the dams/reservoirs regulating the river. Unregulated conditions reflect the present basin development, but without the effect of reservoir regulation. Unlike natural conditions, which are difficult to determine, only the effect of reservoir operation and major diversions are removed from the historic data. Unregulated flow data can be derived using HEC-ResSim, by simulating reservoir inflows as the observed outflow and bypassing any regulation of the upstream reservoir.

Along with reservoir inflow data, the stage data should be reviewed to verify that the period of record is representative of the current operating conditions. If there has been a change in operation somewhere during the record, this must be identified, and only data consistent with the expected future operation should be used in the evaluation. Period of record stage data can be re-regulated to reflect current operations using HEC-ResSim. Some District water management offices may have unregulated data sets and may have unregulated to regulated relationships that might be useful for the analysis.

General Frequency Analysis Concepts

Frequency analysis is a statistical method of prediction that consists of studying past events that are characteristic of a particular hydrological process in order to determine the probabilities of occurrence of these events in the future (Meylan, 2012).

Frequency analysis of hydrologic data requires that the data be independent and identically distributed (i.e., homogeneous). The restriction of homogeneity ensures that all the observations are from the same population (i.e., the stream gaging station has not been moved, a watershed has not become urbanized, or no regulating structures have been placed upstream of the reservoir or its major tributaries). The restriction of independence ensures that a hydrologic event, such as a single large storm, does not enter that data set more than once. In addition, for the prediction of the frequency of future events, the restriction of homogeneity ensures that the observed data from the past be representative of the future (Haan, 1977).

Statistical prediction is performed by defining and implementing a *frequency model*, which is a mathematical description of the statistical behavior of a random variable. Frequency analysis can be performed empirically or analytically.

This chapter provides procedures for performing an empirical frequency analysis. The Inflow Volume-Frequency Analysis chapter provides a detailed explanation of performing an analytical hydrologic frequency analysis.

The empirical frequency analysis provides useful information for a hydrologic hazard assessment, particularly for understanding exceedance probabilities for reservoir elevations in the range of flood control and spillway operation. However, as will be shown in later chapters, an analytical frequency model can be used to extrapolate beyond the observations data, providing important information for extreme flood events, such as the probable maximum flood (PMF) or a hypothetical overtopping event.

Probability Plotting and Empirical Frequency

A *probability plot* is a plot of magnitude versus a probability. The probability assigned to each data point is commonly determined using a *plotting position* formula. Plotting positions are a method for creating an *empirical frequency*. The formula computes the exceedance probability of a data point based on the rank of the data point in a sample of a given size. The plotting positions typically have significant uncertainty due to sampling error resulting from small sample sizes.

A rank-order method is used to plot the annual maxima data. This involves ordering the data from the largest event to the smallest event, assigning a rank of 1 to the largest event and a rank of n to the smallest event, and using rank (i)

of the event to obtain a probability plotting position. Many plotting position formulae are special cases of the general formula:

$$P_i = \frac{i - \alpha}{n + 1 - 2\alpha}$$

Equation 2

Where *i* is the rank of the event, *n* is the sample size, α is a constant greater than or equal to 0 and less than 1, and P_i is the exceedance probability for an event with rank *i*. The value of α determines how well the calculated plotting positions will fit a given theoretical probability distribution.

Each plotting position formula has a different motivation. Some formulas attempt to achieve unbiasedness in quantile estimates across multiple distributions, while other formulas are optimized for use with a particular theoretical probability distribution. Choosing a plotting position formula is similar to choosing a probability distribution to represent a particular set of data. It is often better to select a plotting position formula that is flexible and makes the fewest assumptions.

The Weibull plotting position formula (α = 0), which provides an unbiased estimator of exceedance probability for all distributions, should be used for constructing an empirical frequency curves for an SQRA. For more information on plotting position formulas, please see Predictive Hydrology: A Frequency Analysis Approach (Meylan, 2012), Statistical Methods in Hydrology (Haan, 1977), Handbook of Hydrology (Maidment, 1992), or Bulletin 17C (U.S. Geological Survey, 2018).

After the plotting positions have been calculated, the data is plotted on a *probability plot*. The probability data should be transformed to make it easier to visualize. In hydrology, a *normal* probability transform is typically applied to the annual exceedance probability and a log transform is applied to peak discharge and volume magnitudes. The data are transformed because the logarithm of peak discharge and volume are assumed to be normally distributed when the skewness coefficient is zero. In this case, the normally distributed data will plot in a straight line on a normal probability plot. The mean will equal the value at an AEP of 0.5 and the standard deviation will equal the slope of the line. However, when the skewness coefficient of the data is non-zero, the distribution will look curved, with a concave upward shape indicating a positive skew and a concave downward shape indicating a negative skew. The amount of curvature indicates the magnitude of the skew, with higher skew values having more curvature. For skewed distributions, the value at AEP of 0.5 still provides an approximation of the mean and the steepness provide an approximation of the standard deviation.

An example normal probability plot is provided in Figure 4. Empirical flow data from a sample of 30 observations is plotted using the Weibull plotting position formula. The flow data have a mean (of log) equal to 2.575 and a standard deviation (of log) equal to 0.587. For reference, an analytical frequency model, a log normal distribution with the same mean and standard deviation, is plotted against the empirical frequency data showing strong agreement.

For the evaluation of hydrologic hazards for an SQRA, all frequency curves, both empirical and analytical, should be plotted using a normal probability transform. Discharge and volume should be plotted using a log-normal probability transform and stage should be plotted using a linear-normal probability transform.

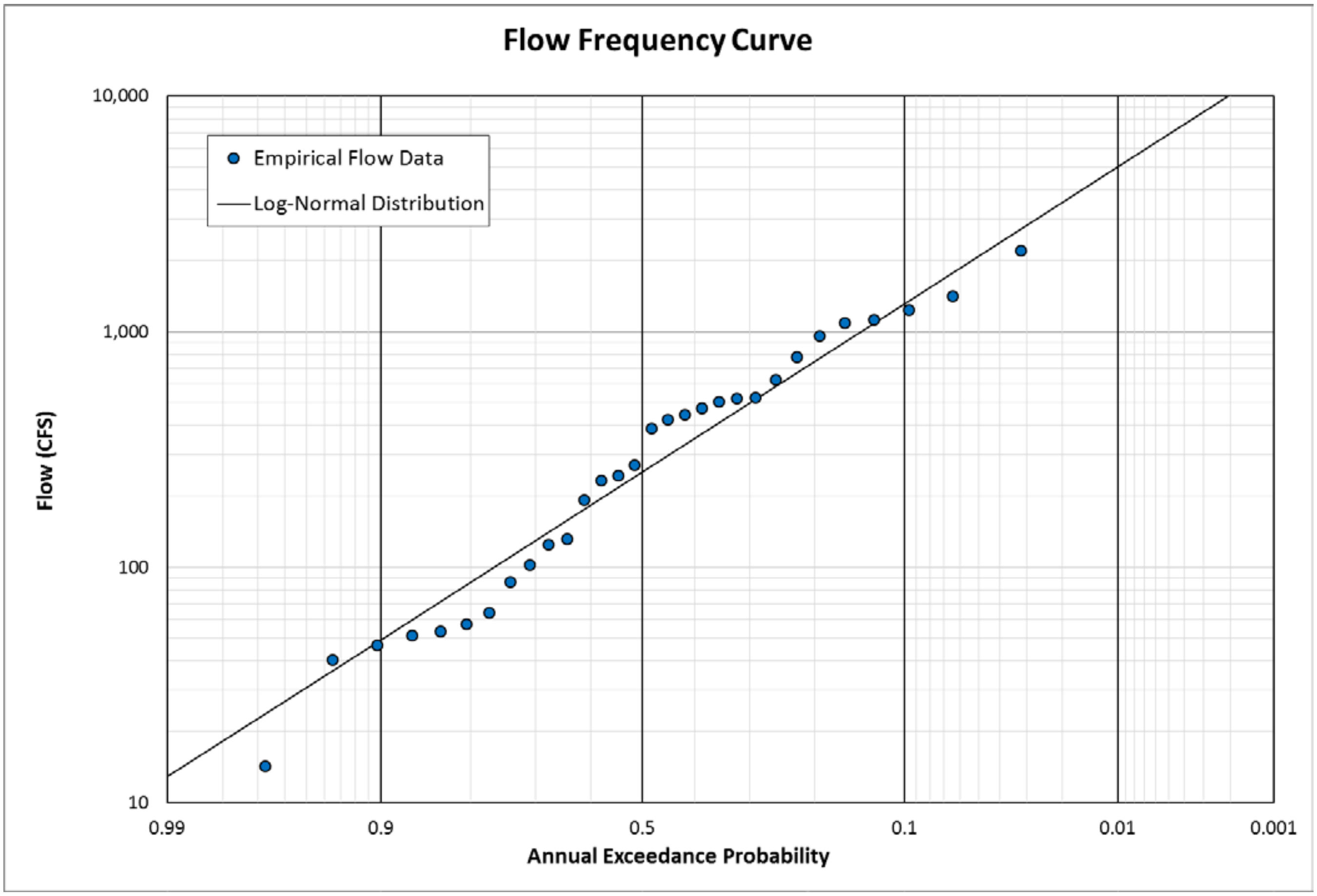


Figure 4: Example of a Log-Normal Probability Plot

Empirical Stage-Frequency Analysis

Empirical stage-frequency analysis is performed in order to understand the reservoir stage exceedance probabilities within the range of the period of record, which typically plot in the range up to the flood control pool or top of active storage.

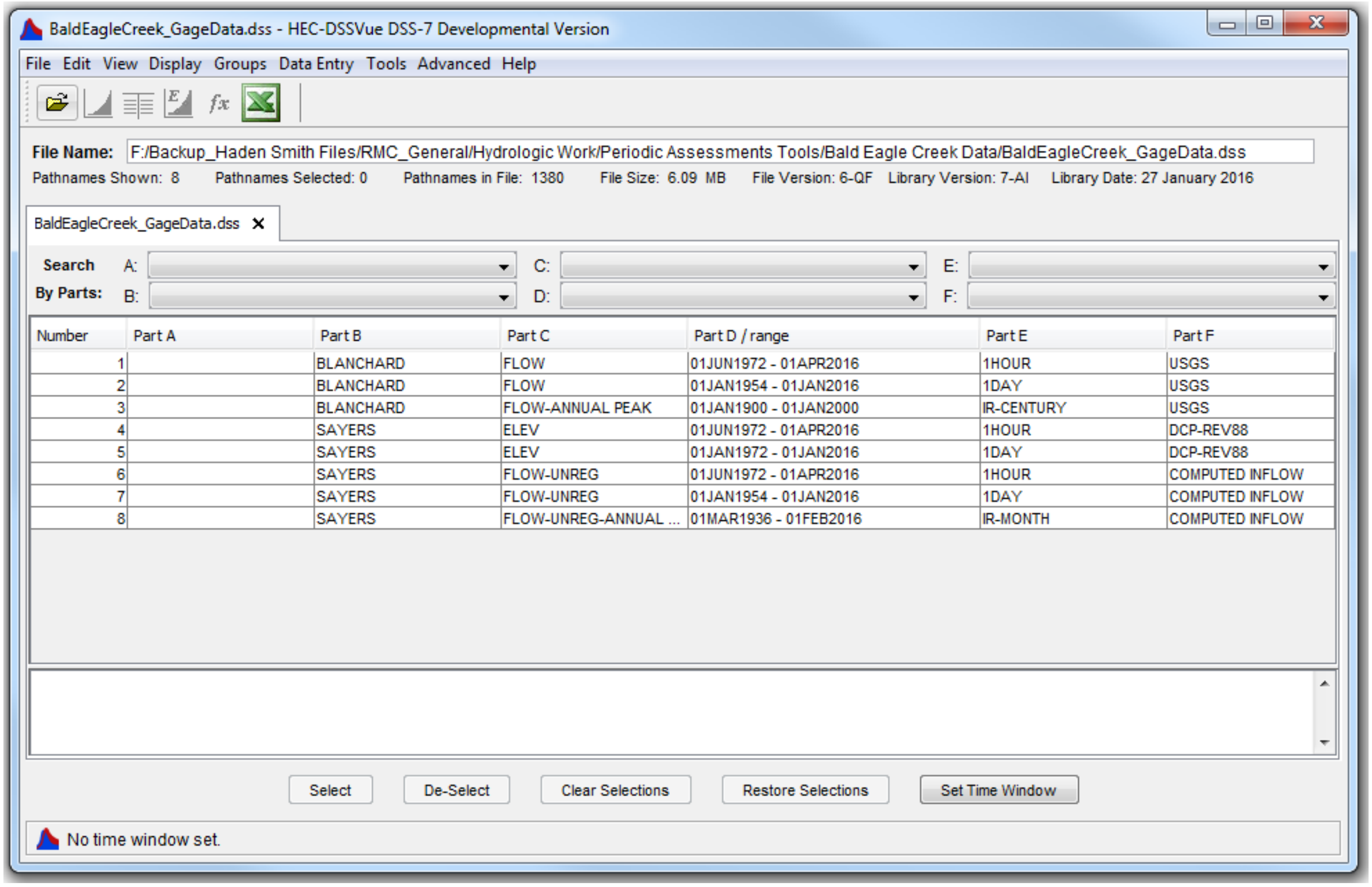
Computing Empirical Stage-Frequency using RMC-RFA

An empirical stage-frequency curve is constructed by the ranking annual maximum data in descending order, assigning the data a plotting position, and then plotting the data using a probability plot. This section provides step-by-step procedures for computing an empirical stage-frequency curve using the reservoir frequency analysis software, RMC-RFA.

1. Open the **BaldEagleCreek_GageData** HEC-DSS file. You will notice there are hourly and daily records for reservoir inflow, stage, and discharge as shown in Table 2 and Figure 5

Table 2: Listing of Bald Eagle Creek Gage Data

Description	HEC-DSS Pathname
Computed reservoir inflow (hourly)	//SAYERS/FLOW-UNREG/*/1HOUR/COMPUTED INFLOW/
Computed reservoir inflow (daily)	//SAYERS/FLOW-UNREG/*/1DAY/COMPUTED INFLOW/
Reservoir stage (hourly)	//SAYERS/ELEV/*/1HOUR/DCP-REV88/
Reservoir stage (daily)	//SAYERS/ELEV/*/1DAY/DCP-REV88/
Reservoir discharge (hourly)	//BLANCHARD/FLOW/*/1HOUR/USGS/
Reservoir discharge (daily)	//BLANCHARD/FLOW/*/1DAY/USGS/



File Name: F:/Backup_Haden Smith Files/RMC_General/Hydrologic Work/Periodic Assessments Tools/Bald Eagle Creek Data/BaldEagleCreek_GageData.dss

Pathnames Shown: 8 Pathnames Selected: 0 Pathnames in File: 1380 File Size: 6.09 MB File Version: 6-QF Library Version: 7-AI Library Date: 27 January 2016

Number	Part A	Part B	Part C	Part D / range	Part E	Part F
1		BLANCHARD	FLOW	01JUN1972 - 01APR2016	1HOUR	USGS
2		BLANCHARD	FLOW	01JAN1954 - 01JAN2016	1DAY	USGS
3		BLANCHARD	FLOW-ANNUAL PEAK	01JAN1900 - 01JAN2000	IR-CENTURY	USGS
4		SAYERS	ELEV	01JUN1972 - 01APR2016	1HOUR	DCP-REV88
5		SAYERS	ELEV	01JAN1972 - 01JAN2016	1DAY	DCP-REV88
6		SAYERS	FLOW-UNREG	01JUN1972 - 01APR2016	1HOUR	COMPUTED INFLOW
7		SAYERS	FLOW-UNREG	01JAN1954 - 01JAN2016	1DAY	COMPUTED INFLOW
8		SAYERS	FLOW-UNREG-ANNUAL ...	01MAR1936 - 01FEB2016	IR-MONTH	COMPUTED INFLOW

No time window set.

Figure 5: BaldEagleCreek_GageData HEC-DSS file

2. Next, plot the hourly stage data as shown in Figure 6. You will notice that there is a significant amount of missing data. There is no data from June of 1972 until November of 1984. Also, there is intermittingly missing data for the period from 1990 to 1995. **Make note of this as the missing data will be important later in the analysis.**

    - *Note*: The empirical stage-frequency curve should be developed using instantaneous peak stage data, if available. Since hourly stage data is available, it will be used. However, many USACE dams will not have readily available hourly period of record stage data. In those cases, use daily stage data for this analysis.

    - *Note*: For the purpose of this analysis, the observed peak stage data needs to be representative of the current reservoir operations. If there have been changes in operations, the period of record stage data should be transformed to reflect the current operations.

3. Next, create a new **Stage Gage** in RMC-RFA. Within the HEC-DSS file determine the start and end dates for the data representing the period of record. For this data set, the start date is 6/21/1972 and the end date is 4/18/2016. Select those dates in RMC-RFA and click the **Resize Table** button. Then, copy and paste the stage data from HEC-DSS into the column entitled **Stage (FT)** as shown in Figure 7.

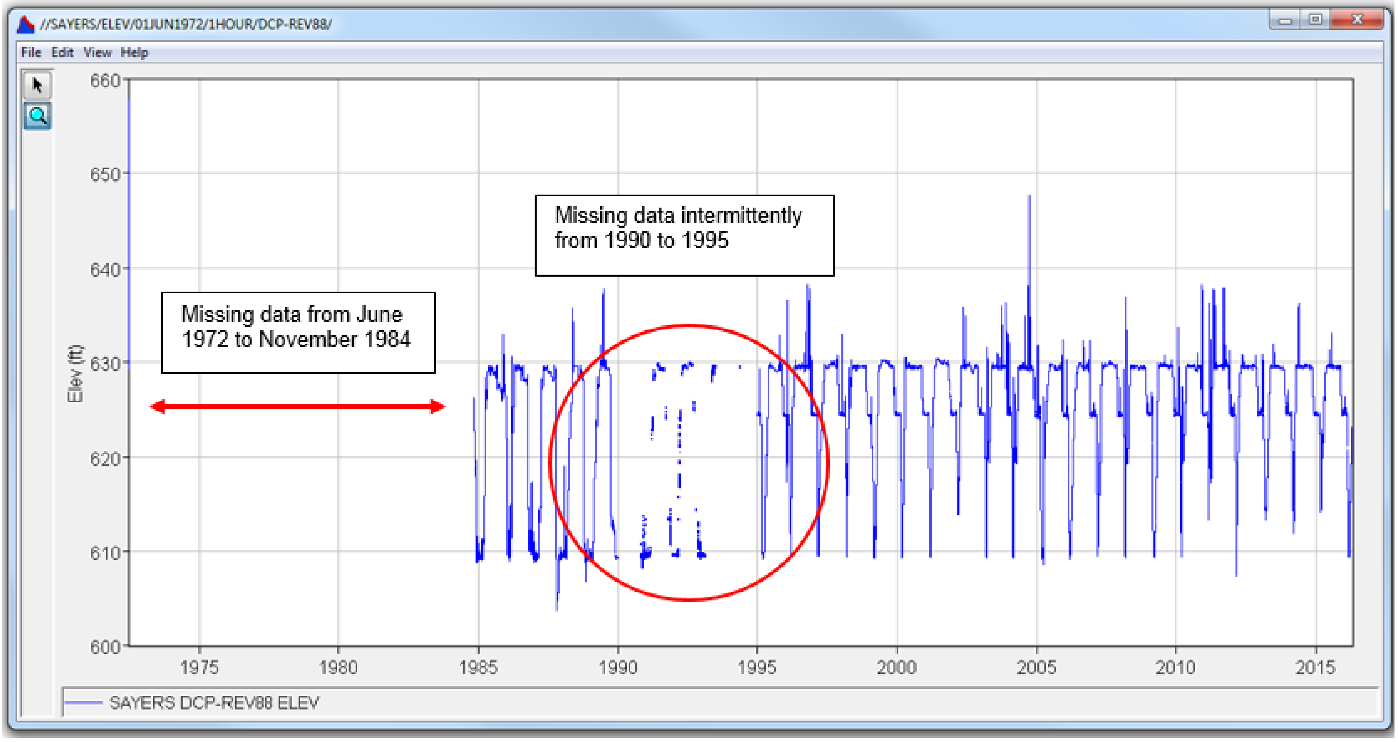
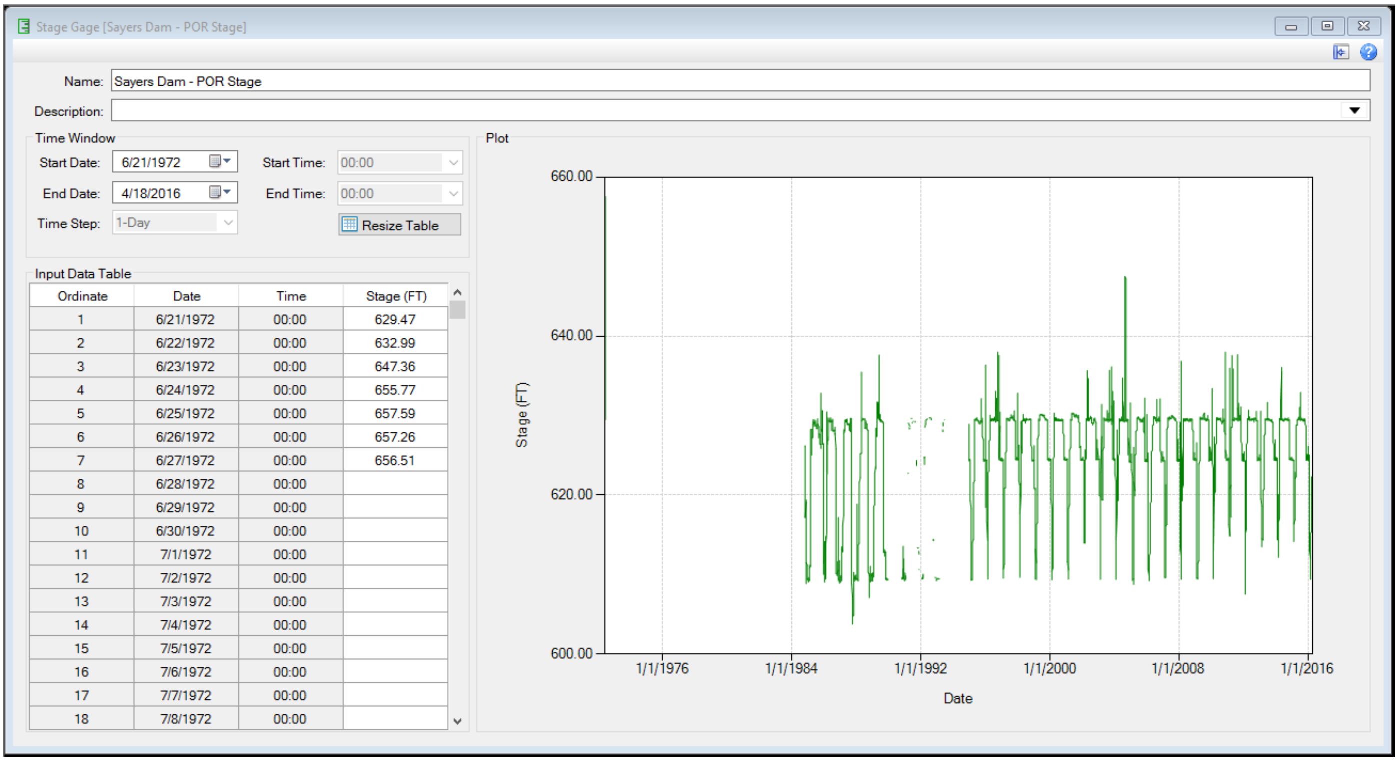


Figure 6: Plot of Hourly Period of Record Stage Data for Joseph Foster Sayers Dam



Name: Sayers Dam - POR Stage
Description:

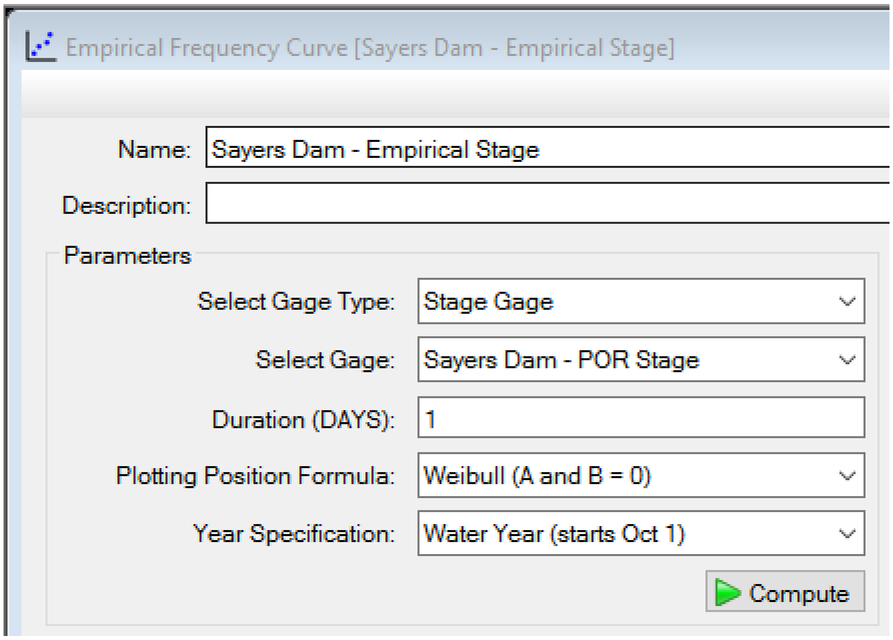
Time Window
Start Date: 6/21/1972
Start Time: 00:00
End Date: 4/18/2016
End Time: 00:00
Time Step: 1-Day
Resize Table

Input Data Table

Ordinate	Date	Time	Stage (FT)
1	6/21/1972	00:00	629.47
2	6/22/1972	00:00	632.99
3	6/23/1972	00:00	647.36
4	6/24/1972	00:00	655.77
5	6/25/1972	00:00	657.59
6	6/26/1972	00:00	657.26
7	6/27/1972	00:00	656.51
8	6/28/1972	00:00	
9	6/29/1972	00:00	
10	6/30/1972	00:00	
11	7/1/1972	00:00	
12	7/2/1972	00:00	
13	7/3/1972	00:00	
14	7/4/1972	00:00	
15	7/5/1972	00:00	
16	7/6/1972	00:00	
17	7/7/1972	00:00	
18	7/8/1972	00:00	

Figure 7: RMC-RFA Stage Gage for Foster Joseph Sayers Dam

4. Now, create a new **Empirical Frequency Curve** in RMC-RFA. Select the **Stage Gage** type and select the correct gage. For this example, the duration should be set as 1 day. Select the **Weibull** plotting position formula and the **Water Year** specification as shown in Figure 8.



Name: Sayers Dam - Empirical Stage

Description:

Select Gage Type: Stage Gage

Select Gage: Sayers Dam - POR Stage

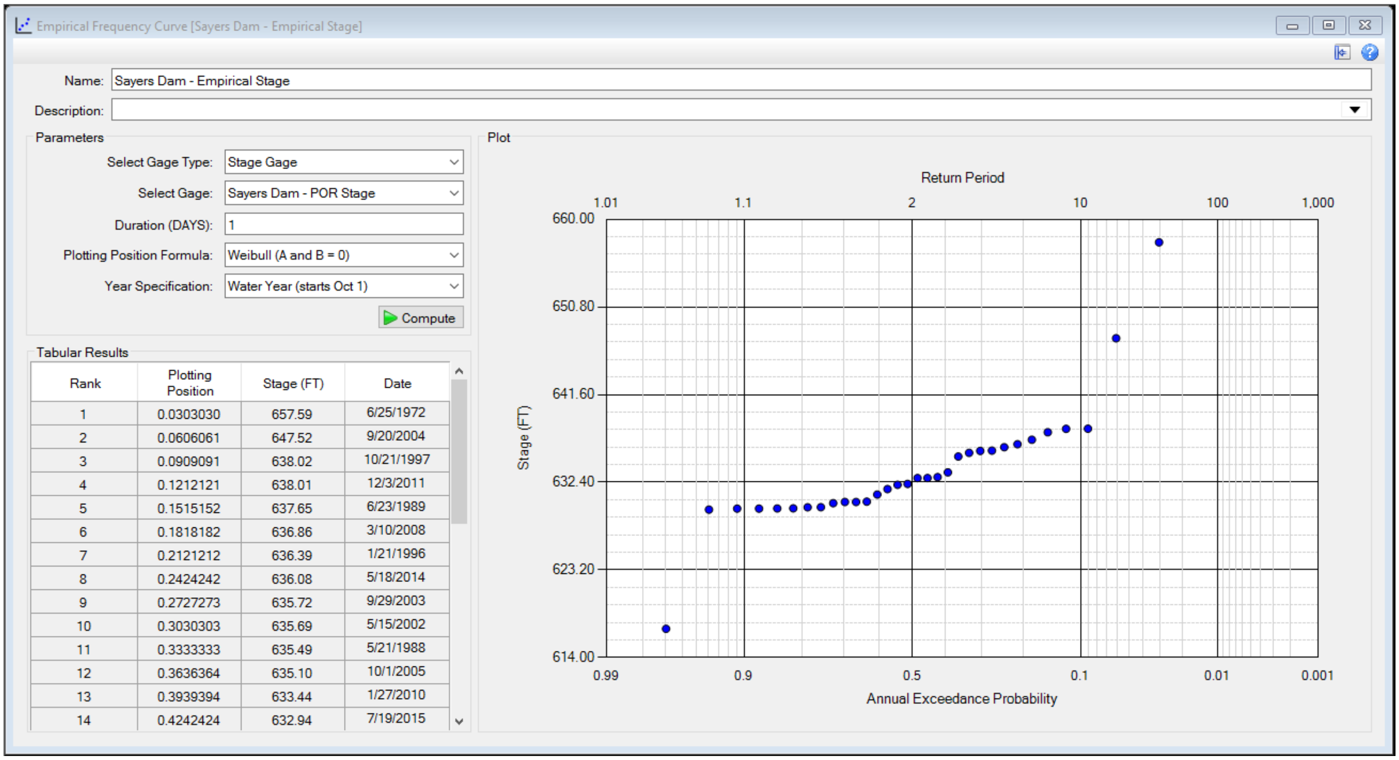
Duration (DAYS): 1

Plotting Position Formula: Weibull (A and B = 0)

Year Specification: Water Year (starts Oct 1)

Figure 8: Empirical Frequency Curve Analysis Window

5. Next, click the **Compute** button to perform the empirical frequency analysis. After the program runs, the computed results are displayed in a table and plot within the **Empirical Frequency Analysis** window as shown in Figure 9.



Name: Sayers Dam - Empirical Stage

Description:

Select Gage Type: Stage Gage

Select Gage: Sayers Dam - POR Stage

Duration (DAYS): 1

Plotting Position Formula: Weibull (A and B = 0)

Year Specification: Water Year (starts Oct 1)

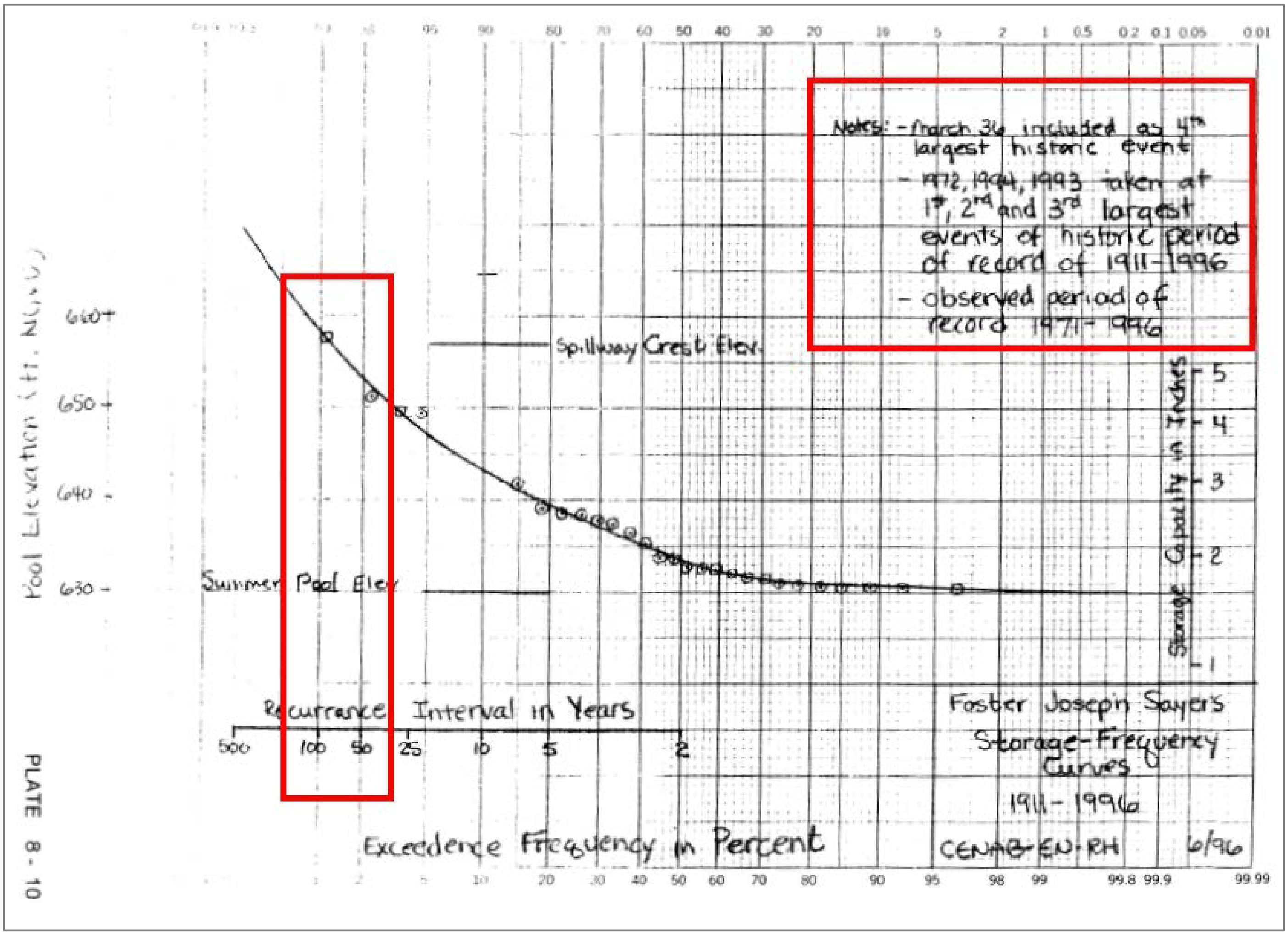
Rank	Plotting Position	Stage (FT)	Date
1	0.0303030	657.59	6/25/1972
2	0.0606061	647.52	9/20/2004
3	0.0909091	638.02	10/21/1997
4	0.1212121	638.01	12/3/2011
5	0.1515152	637.65	6/23/1989
6	0.1818182	636.86	3/10/2008
7	0.2121212	636.39	1/21/1996
8	0.2424242	636.08	5/18/2014
9	0.2727273	635.72	9/29/2003
10	0.3030303	635.69	5/15/2002
11	0.3333333	635.49	5/21/1988
12	0.3636364	635.10	10/1/2005
13	0.3939394	633.44	1/27/2010
14	0.4242424	632.94	7/19/2015

Figure 9: Empirical Frequency Curve Results

6. Notice that there are only 32 annual maximum stage values. However, there are at least 44 years of record (2016 – 1972 = 44). Recall that in **step 2** there was a significant amount of missing data identified from 1973 to 1984, and intermittingly missing data for the period from 1990 to 1995. The short record length (32 years) results in an inaccurate empirical stage-frequency curve and inaccurate plotting positions for the largest stage events.

   For example, we know that the 1972 event was at least the largest event in the last 44 years, yet the tool only plots it as the largest in 32 years because there are only 32 observations. According to the regulation manual, there is evidence to suggest that had the dam been in place, the 1972 event might have been the largest peak stage event in at least the last 100 years. Likewise, the 2004 event might have been within the top five largest peak stage events in the last 100 or more years. Figure 10 below shows Plate 8-10 from the regulation manual, which is an empirical stage-frequency curve with the probability axis plotted in reverse. At the time that the manual was published in 1996, the four largest events on record dating back to 1911 were 1972, 1994, 1993, and 1936, in that order. Therefore, as Figure 10 illustrates, the 1972 event should plot near the 100-yr return period (0.01 AEP). Similarly, the plotting positions of the last two points on the empirical stage-frequency curve performed in RMC-RFA should plot to the right near 0.01 AEP as conceptually shown in Figure 11.

   - *Note*: You will need to make note of these potential issues in the hydrologic hazard section of the risk assessment report. The Figure 11 presents a hypothetical example and should not be used as a means for estimating precise plotting positions. In cases like this where there is significant missing data, it is more appropriate to use the Hirsch-Stedinger plotting position formula (U.S. Geological Survey, 2018) rather than subjectively shifting the plotting positions.



Notes: - March 36 included as 4th largest historic event
- 1972, 1994, 1993 taken at 1st, 2nd and 3rd largest events of historic period of record of 1911-1996
- observed period of record 1971-1996

Foster Joseph Sayers
Storage-Frequency Curves
1911-1996
CENAB-EN-RH 6/96

Figure 10: Plate 8-10 from Foster Joseph Sayers Regulation Manual

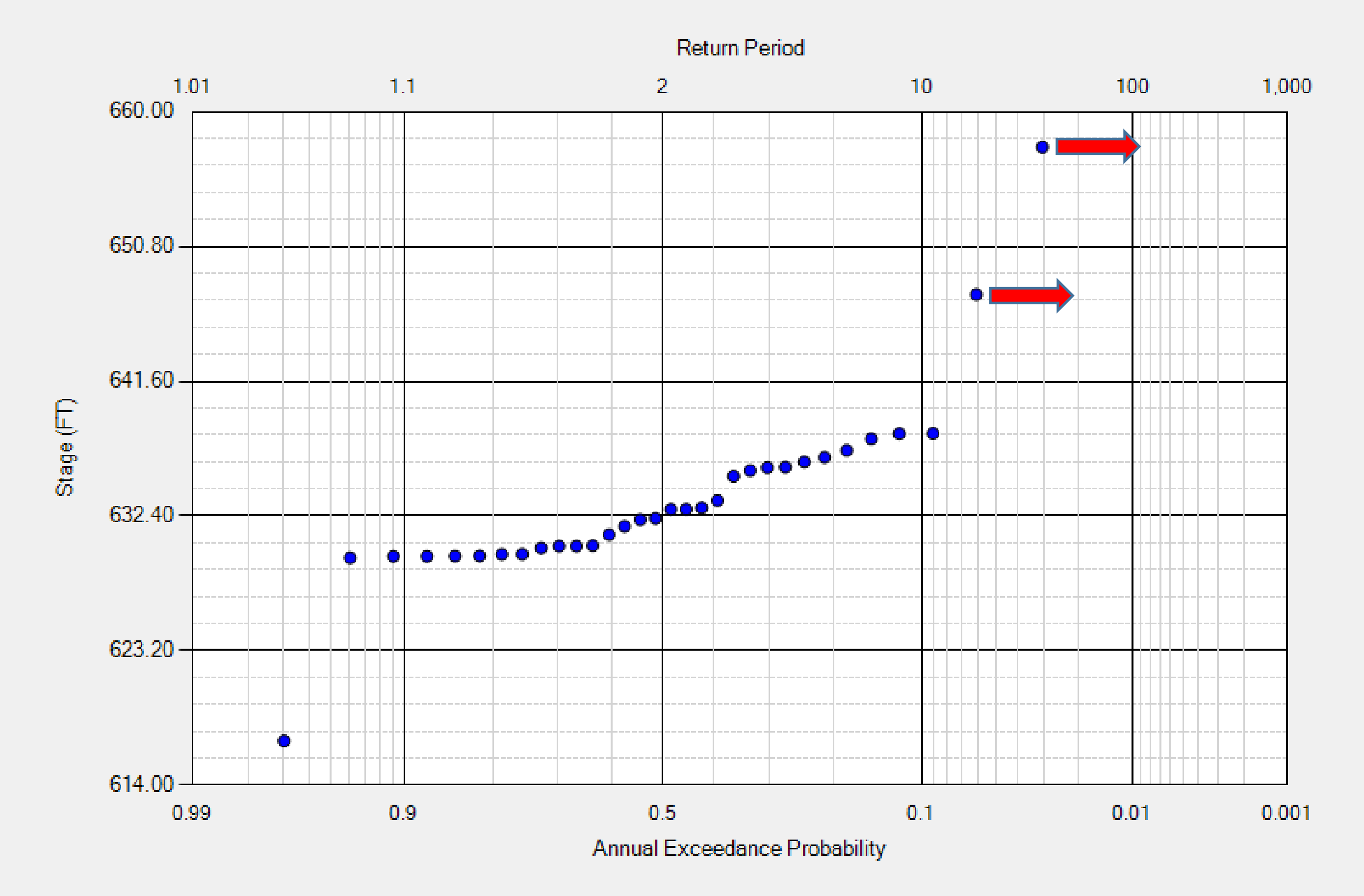


Figure 11: Hypothetical shift in Peak Stage Plotting Positions

Critical Inflow Duration Analysis

The *critical inflow duration* is defined as the inflow duration that results in the highest water surface elevations for the reservoir of interest. Here the critical inflow duration is different from the *critical storm duration*, which, in most hydrology guidance and textbooks, is defined as the critical rainfall duration that gives the maximum peak discharge for design purposes (Pilgram & Cordery, 1992). For many reservoirs in the USACE portfolio, there will be more than one critical inflow duration depending on the flood season and flood mechanism. For example, dams in the west will have a snowmelt season that typically has a longer critical inflow duration than the rainy season.

However, even though a dam might be affected by a multiple flood seasons or flood mechanisms, typically one of the flood mechanisms will generate the highest peak stages. Therefore, you will need to determine the critical inflow duration for the most critical flood season/mechanism. Flood seasonality is discussed in the Flood Seasonality Analysis chapter.

Accurate assessment of reservoir stage-frequency relies on estimates of annual maximum stages. Therefore, the critical inflow duration of flood events must be considered in order to properly identify the highest peak stages for the reservoir of interest. This is important to the analysis because the critical duration is used to scale inflow hydrograph shapes to represent events that have not been observed in the watershed yet. These scaled hydrographs will be used to determine the reservoir stage-frequency curve.

Determining the Critical Inflow Duration

1. Identify the three to five historical peak reservoir events as seen in Table 3. Then, locate the reservoir inflow, stage, and discharge hydrographs corresponding to each peak stage event. Select events that are consistent with the types of events likely to be the driver of extreme peak stages; i.e. don't pick snow events if rain events are the driver.

- *Note*: For this type of analysis, the inflow hydrograph should be unregulated, if possible. If unregulated flow data is not available, the analyst should consider what impact this might have on the critical duration estimate and decide whether additional effort is required to deregulate and re-regulate the inflow data to ensure the data is homogeneous.

Table 3: Top Five Peak Stage Events at Foster Joseph Sayers Dam

Historical Peak Stage Events	
Date	**Stage (FT)**
06/25/1972	657.66
09/20/2004	647.60
10/21/1996	638.17
12/03/2010	638.16
09/09/2011	637.80

2. Reservoir peak stage occurs when the reservoir outflow equals the inflow on the receding limb of the inflow hydrograph. Visually assess the duration it takes from the beginning of the inflow event to the point where inflow equals outflow on the receding limb of the inflow hydrograph. Figure 12 through Figure 16 illustrate this visual procedure.

    - *Note*: The inflow hydrograph for the 1972 event was reconstructed and not precise. As such, the peak stage event doesn't occur exactly when the inflow equals the outflow. Therefore, engineering judgment is used to estimate a critical duration of 4 days.

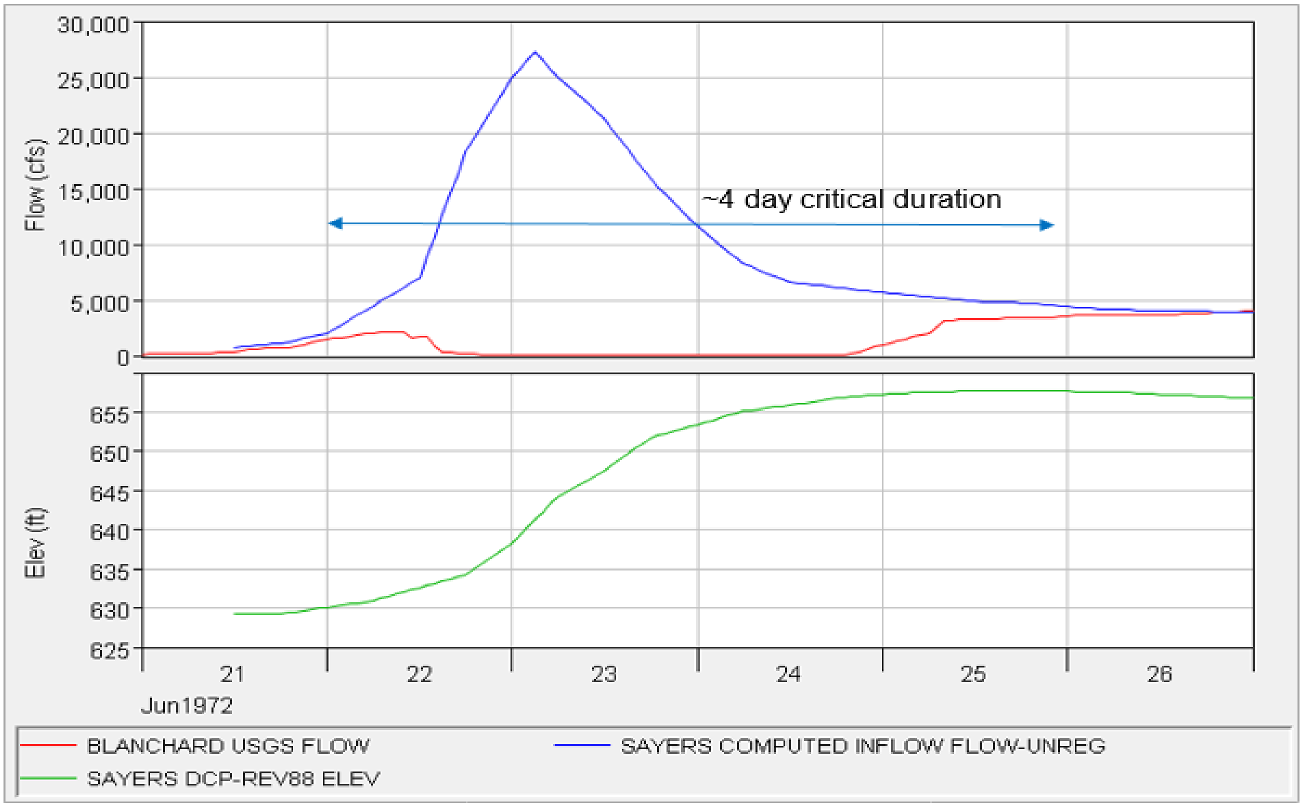


Figure 12: June 1972 Flood Event

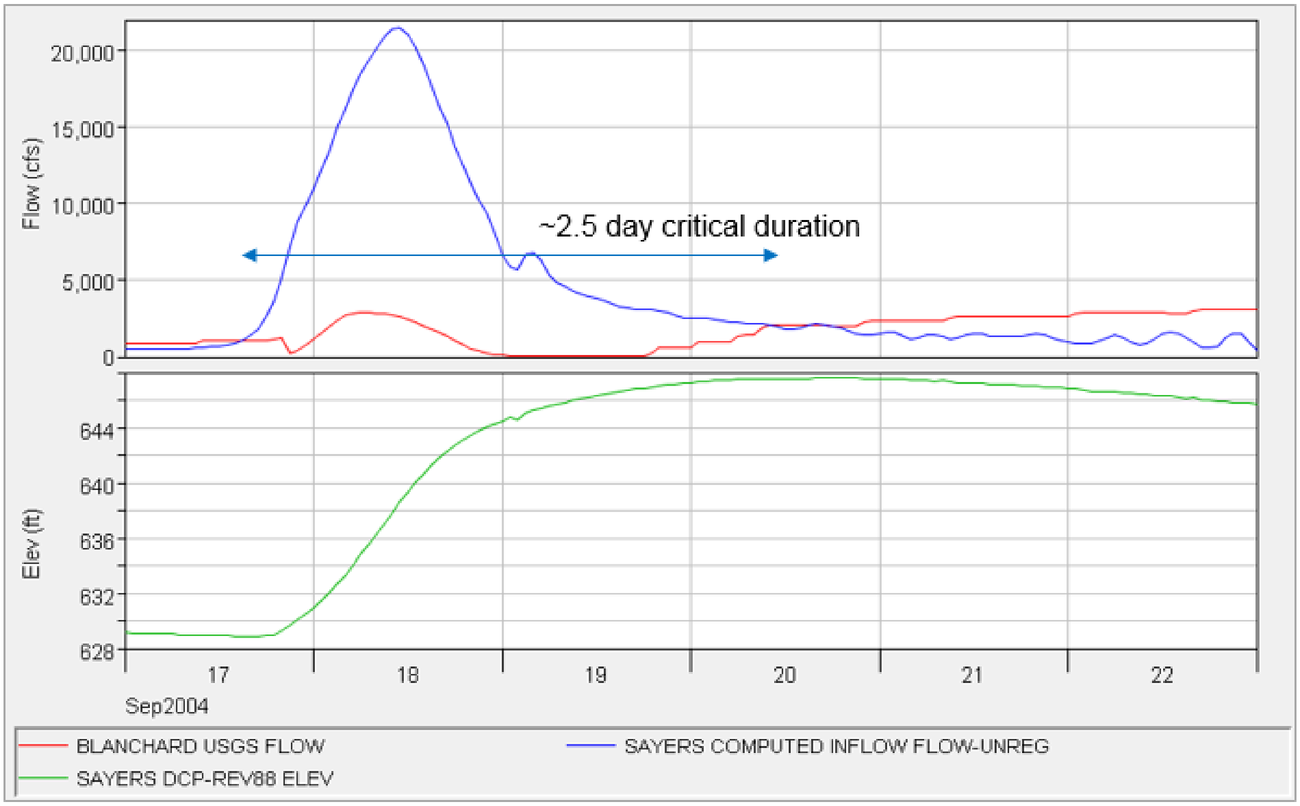


Figure 13: September 2004 Flood Event

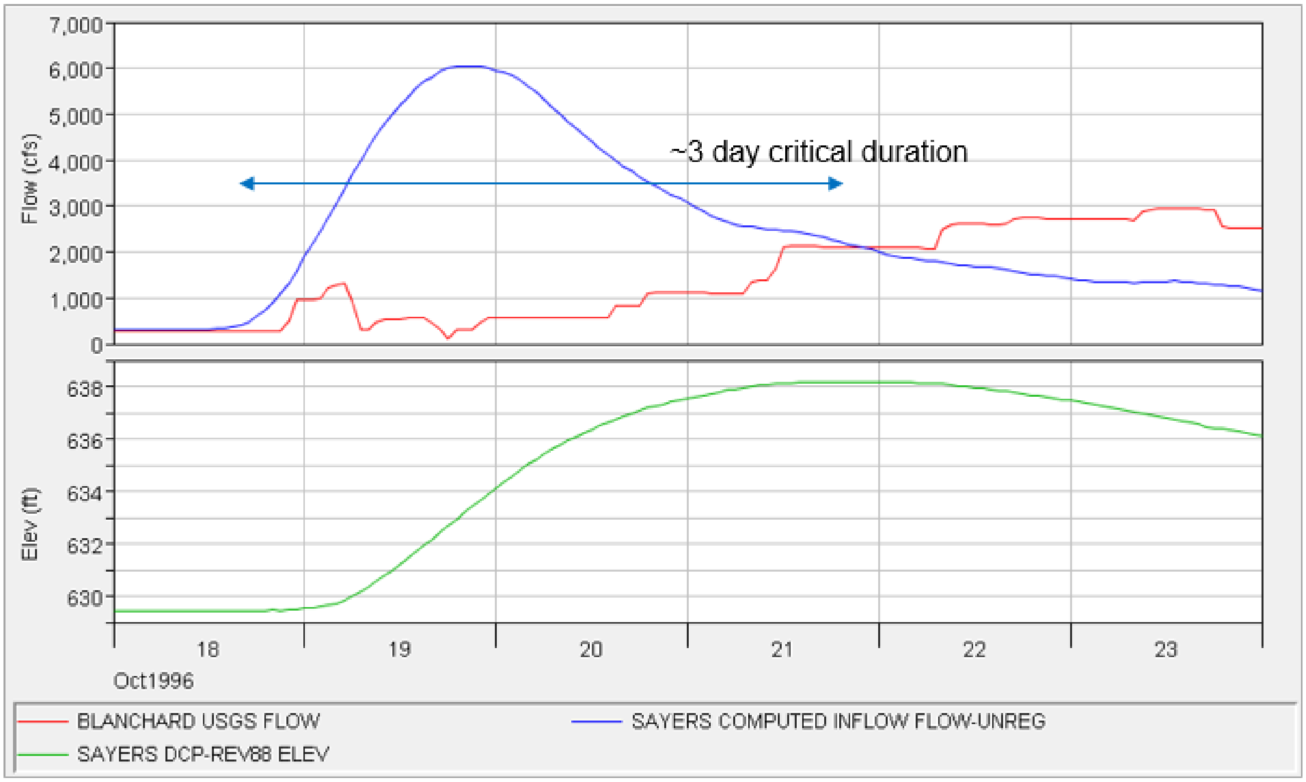


Figure 14: October 1996 Flood Event

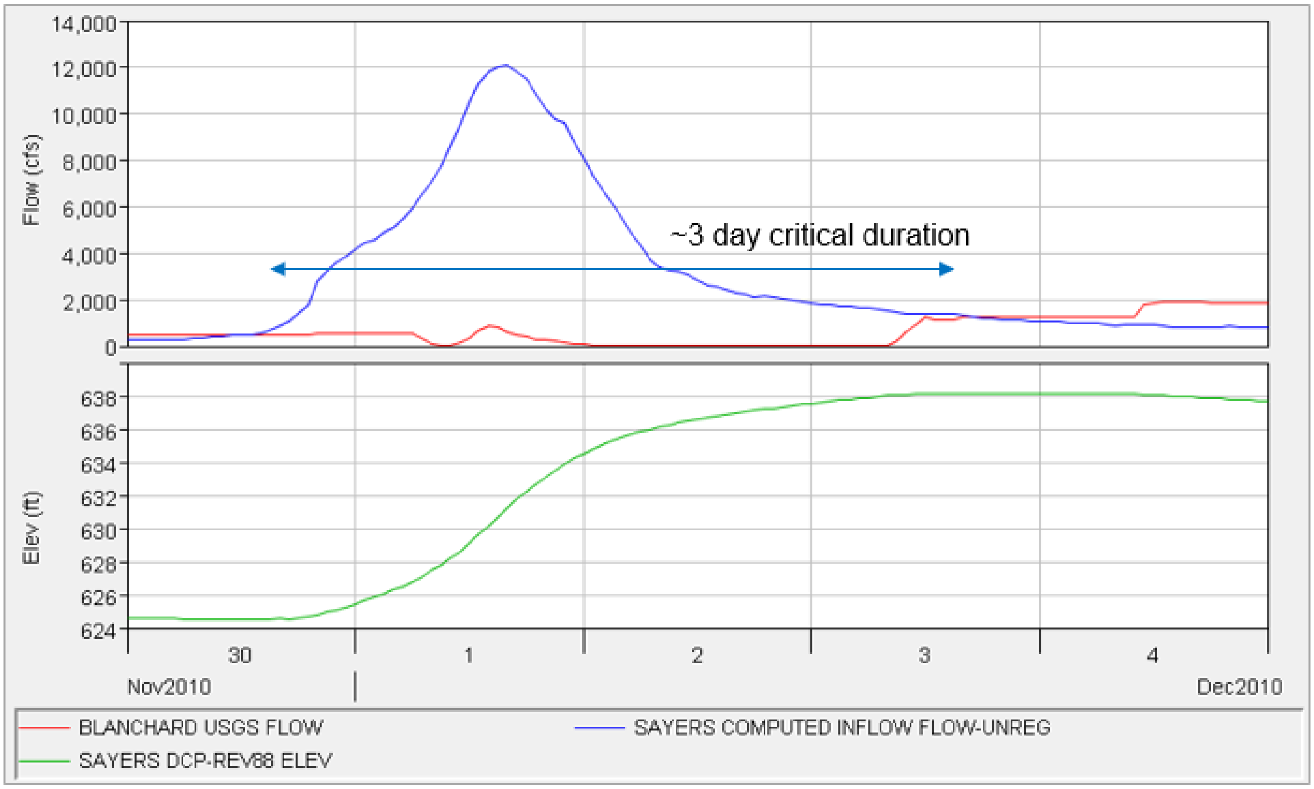


Figure 15: December 2010 Flood Event

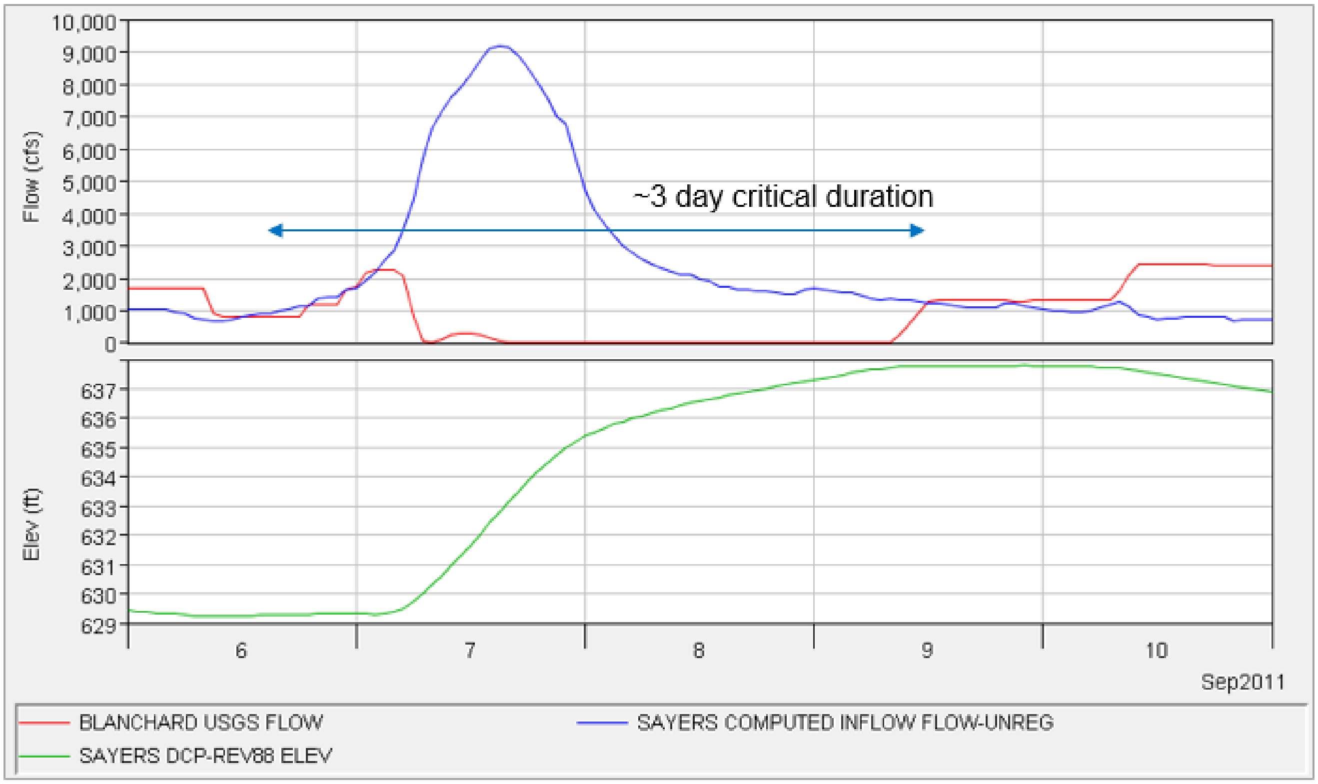


Figure 16: September 2011 Flood Event

3. Next, select a best-estimate critical inflow duration for the reservoir. Table 4 shows the estimated critical inflow durations for the top five peak stage events. As can be seen, the best estimate for the critical inflow duration is 3 days.
   - *Note*: For scenarios where the critical duration is less than 24 hours, it is appropriate to assume the critical duration is 1 day for the purposes of stage-frequency analysis.

Table 4: Estimated critical inflow durations for major historical peak stage events

Historical Peak Stage Events		Critical Inflow Duration
Date	**Stage (FT)**	**Days**
06/25/1972	657.66	4
09/20/2004	647.60	2.5
10/21/1996	638.17	3
12/03/2010	638.16	3
09/09/2011	637.80	3
	Best Estimate:	3

- *Note:* There are several other ways to estimate critical inflow duration. The following documents describe procedures for alternative methods:
  i. *Central Valley Hydrology Study (CVHS): Technical procedures document* (US Army Corps of Engineers, Sacremento District, 2011)
  ii. *How "Critical" is Critical Duration in Determining Flood Risk, Flood Damages and Stormwater Management Solutions?* (Lau & Gali, 2011)
  iii. *Herbert Hoover Dike Standard Project Flood Update* (U.S. Army Corps of Engineers, 2015)
  iv. *Review and Application of GRADEX and Australian Methods for Developing Extreme Floods* (U.S. Bureau of Reclamation, 2005)

Inflow Volume-Frequency Analysis

This chapter provides an overview of flood frequency analysis concepts, the role it plays in the hydrologic hazard assessment, and provides a step-by-step tutorial on inflow volume-frequency curves using HEC-SSP.

Flood frequency analysis refers to statistical techniques that can be used to estimate exceedance probabilities associated with specific flow rates. Relationships between flow magnitude and frequency can be established using flows that have been measured.

The frequency of flows (or floods) is commonly described in terms of annual exceedance probability (AEP) or annual chance exceedance (ACE). For instance, a flow or flood with a 1 percent ACE has a 1 in 100 chance of being exceeded at least once in any given year. However, this does not imply that the 1 percent ACE flow cannot be exceeded twice (or more) in one year or a shorter time frame, or in consecutive years.

Typically, the term “flow-frequency” refers to the frequency with which an instantaneous maximum flow rate is expected to be exceeded. However, the term “volume-frequency” is used to refer to the frequency with which a flow over a given duration (such as 1-day or 2-day) is expected to be exceeded.

Normally, stream gage records are relatively short (i.e. less than 100 years). However, within dam and levee safety studies, estimates of extremely rare flow rates are required to adequately assess the risk associated with the structure(s) in question. The peak flow and volume-frequency curves form a family of frequency curves for the various durations of interest (i.e. the critical inflow duration). This family of curves can then be used for multiple purposes, which includes:

1. To construct hypothetical inflow frequency events. These events can then be routed through the dam in question to estimate reservoir stage-frequency curves.
2. A means to estimate the frequencies of other hypothetical events such as the PMF.

Short Note on Bulletin 17C

In most cases, analytical distributions (i.e. Log-Pearson Type III, Log-Normal, etc.) are used as a means to improve the accuracy of flow-frequency estimation for specified quantiles (i.e. the 1% ACE flow rate) as well as the extrapolation of flow-frequency estimation to extremely rare frequencies (i.e. 1/100,000 ACE).

The new Bulletin 17C (U.S. Geological Survey, 2018) guidance brings a change to the computation of peak flow frequency within the United States. This guidance incorporates changes motivated by some 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 (U.S. Geological Survey, 2018). 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/EMA (17C EMA) 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 will 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 17C EMA 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. The Bulletin 17C methodology should be used when developing flow- and volume-frequency curves for SQRA level risk assessments. Do not use Bulletin 17B.

Unregulated versus Regulated Flows

In some cases, the use of an analytical distribution may not be appropriate to estimate flow- and/or volume-frequency curves. In these situations, graphical or empirical means may be more appropriate. This is a common occurrence when the effects of regulation cannot be easily removed from the annual maximum series due to a lack of time and/or funding. In these cases, fitting an analytical distribution to regulated discharges or volumes is not recommended. Significant errors can arise due to the regulation of upstream projects, especially when extrapolating beyond the limits of observed data. An example of these errors is shown in Figure 17. Refer to (Engineer Manual 1110-2-1415, Hydrologic Frequency Analysis, 1993) for guidance about developing a graphical/empirical frequency curves, including methods for using synthetic floods and reservoir simulation to extend the frequency curve to exceedance probabilities not covered by historic observations. If graphical/empirical frequency curves must be used, follow the procedures for estimating reservoir stage-frequency curves using balanced hydrographs and coincident frequency analysis described in Appendix A: Balanced Hydrograph Analysis and Appendix B: Coincident Frequency Analysis, respectively.

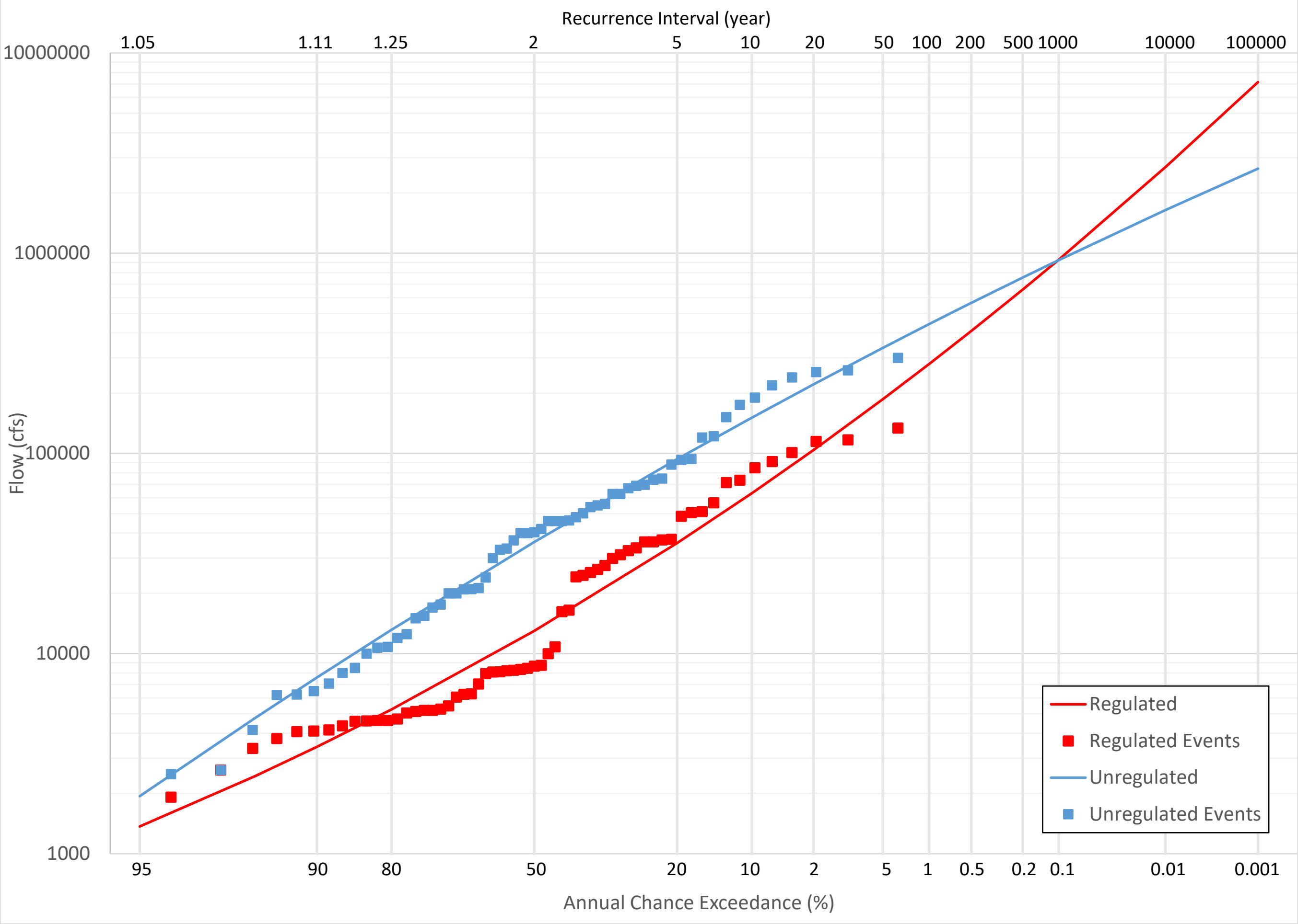


Figure 17: LPIII Fit to a Regulated AMS Resulting in Errors

Annual Maximum Series versus Partial Duration Series

Annual maximum series (AMS) refers to a listing of events that are the largest to have occurred within a given year (i.e. water year or calendar year). For instance, if two relatively large events occur within the same year, only the larger of the two events would become part of the AMS. Partial Duration Series (PDS) refers to a listing of the largest (or smallest) independent events regardless of whether two or more occurred within the same year. The partial duration series is also known as “peaks over threshold” because all flows above or below a threshold are used.

If the estimation of a relatively frequent flow (i.e. 10% ACE) is required, an AMS may not adequately capture the frequency of flows that occurred because it neglects many flow occurrences in the range of interest. In these instances, a PDS may be necessary. Analytical distributions typically do not provide a good fit for PDS. Therefore, graphical techniques are recommended to estimate flow-frequency relationships when using PDS.

An AMS is ordinarily used when the primary events of interest have an ACE less than about 10%. Conversely, a PDS may be required to capture the frequency of flows for ACE greater than 10%, particularly in cases where multiple events can occur in the same year. A flow-frequency curve based upon an annual maximum and a partial duration series will normally converge to form a single flow-frequency curve as exceedance probability decreases, as shown in Figure 18. Note that the AMS significantly under predicts the magnitude of floods for ACE greater than about 10% which can result in under estimating the risk for PFMs that might be initiated by annual loading events (e.g. internal erosion). This occurs because there is a relatively high probability of two or more events occurring in the same year when the ACE is greater than 10%. The probability of two or more events occurring in the same year decreases as ACE decreases. The probability of two or more events becomes negligible between the 0.1 and 0.01 exceedance probabilities (Langbein, 1949). The probability of two or more events exceeding the 1/2 ACE flood in the same year is about 0.1 (20% of the ACE). The probability of two or more events exceeding the 1/100 ACE flood in the same year is about $5X10^{-5}$ (0.5% of the ACE).

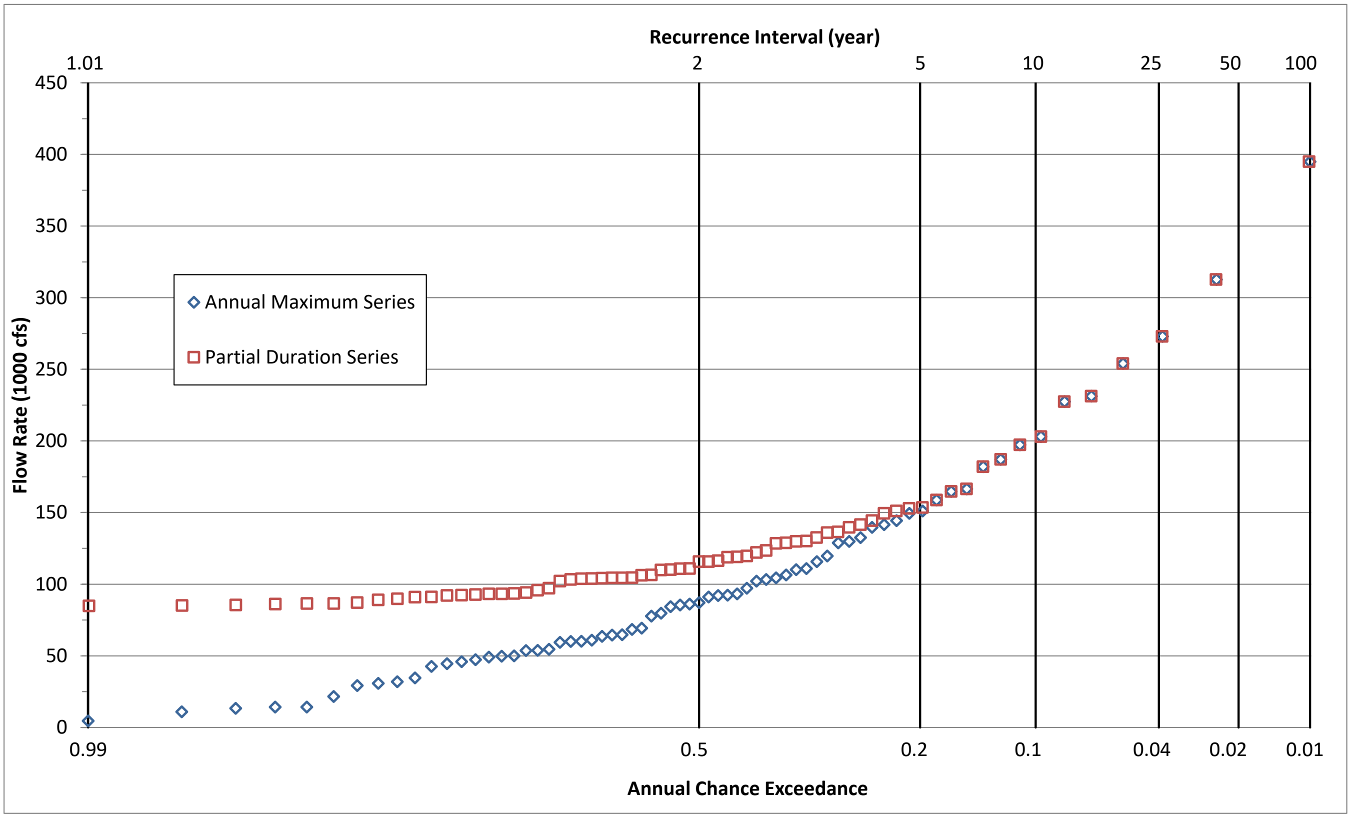


Figure 18: Annual Maximum Series vs. Partial Duration Series

Computing Flow- and Volume-Frequency Curves

The following steps illustrate the procedure for estimating flow and volume frequency curves using the Bald Eagle Creek watershed.

1. The **critical inflow duration** to the project in question needs to be determined before computing flow- and volume-frequency curves. In the previous section, the critical duration was estimated to be approximately 72 hours.

2. Collect all necessary inflow information to the dam in question. This includes both instantaneous peak flows and daily average flow rates.

    - *Note*: Multiple stream gages are operated by the Baltimore District (NAB) and United States Geologic Survey (USGS) in and around Foster Joseph Sayers Dam. The locations of the gages in relation to Bald Eagle Creek and Sayers Dam are shown in Figure 19. Annual peak flows at the Spring Creek at Milesburg, PA (Spring Creek), Bald Eagle Creek below Spring Creek at Milesburg, PA (Milesburg), and Bald Eagle Creek at Blanchard, PA (Blanchard) gages are shown in Figure 20.

    - Due to the relatively large increase in drainage area between the Bald Eagle Creek at Milesburg, PA gage 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. These computed inflow records are commonly housed within an Oracle database managed by the USACE District/Division office that owns and/or operates the dam in question.

    - If flows at a particular location of interest include significant regulation affects through the actions of upstream projects, these regulation effects will need to be removed prior to fitting an analytical distribution. However, in this case, no upstream regulation effects need to be removed from the datasets in question.

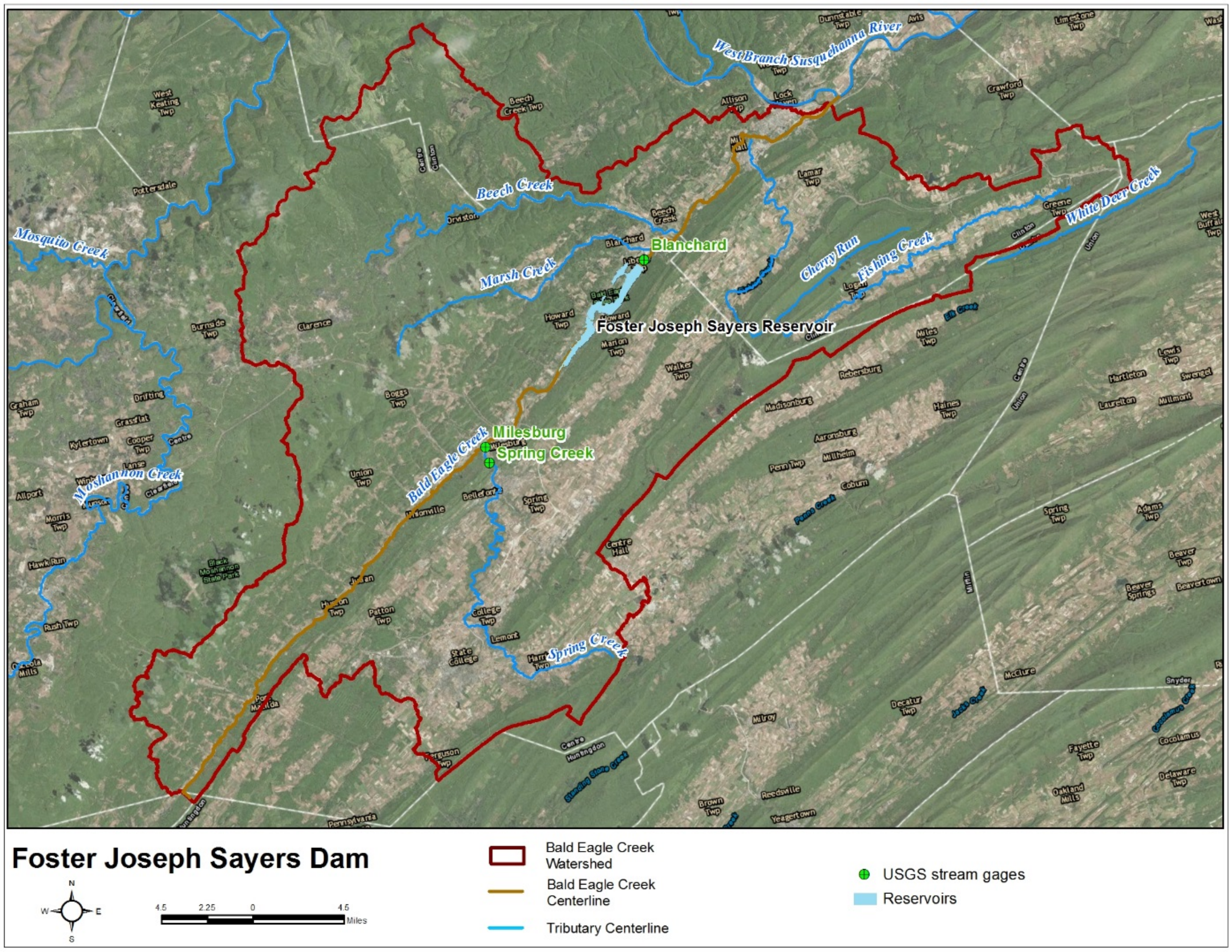


Figure 19: Stream Gage Locations

3. Merge pre- and post-construction peak inflow records as well as extreme event information using HEC-DSSVue.

    - *Note*: It is essential to extend the period of record to the maximum extent possible when estimating flow- and volume-frequency curves. Oftentimes, this requires the combination of records that reflect pre- and post-construction conditions. Prior to June 1968 (completion of Sayers Dam construction), the records at the Blanchard gage were essentially unregulated. The use of this data adds an additional 14 years of systematic data and 30 years to the historic period of inflow to Sayers Dam. The drainage area at the Blanchard gage is the same as the drainage area at Sayers Dam, no adjustment in the Blanchard gage flows was required.

    - The March 1936 flood event was caused by rapid snowmelt which was augmented with heavy rainfall. This was an extremely large scale event causing flooding that stretched from the Potomac River in West Virginia and Maryland to Maine. This flood event led to authorization and construction of numerous flood control projects throughout the mid-Atlantic and northeastern United States as contained within the Flood Control Act of 1936.

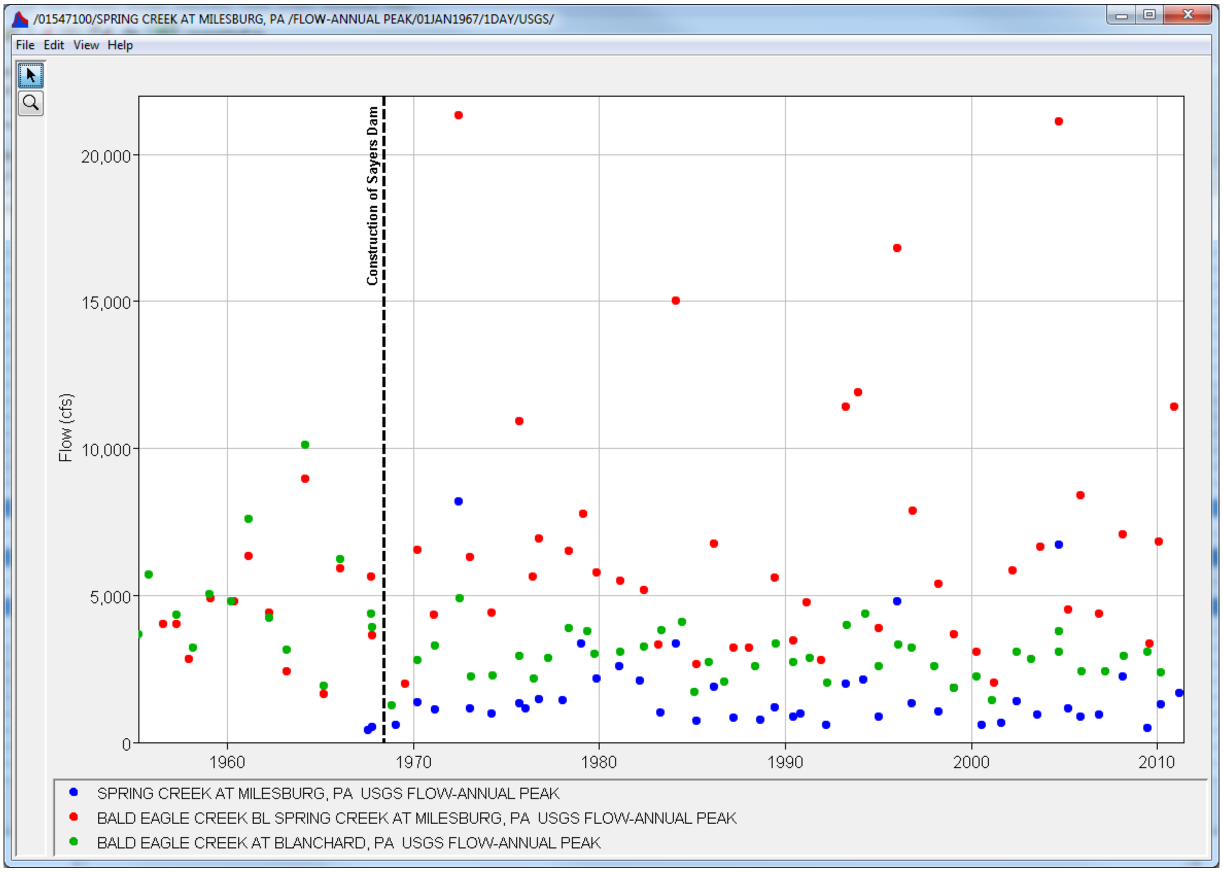


Figure 20: Instantaneous Peak Flow Annual Maximum Series at Spring Creek, Milesburg, and Blanchard

- The March 1936 event was the event of record within the Susquehanna River watershed prior to 1972. During June of that year, the remnants of Tropical Storm Agnes led to record breaking flooding along the majority of the Susquehanna River, including Bald Eagle Creek. This event exceeded flood storage at Sayers Dam and the activation of the uncontrolled spillway. As of 2016, this is the only time a flood control dam within the West Branch Susquehanna River has exceeded flood storage.

- 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). An inflow hydrograph for the June 1972 event was found within the June 1972 Event Post Flood Report (Baltimore District, 1974). A flow hydrograph for the March 1936 event was found within the Reservoir Regulation Manual (Baltimore District, 1996).

- Data from these two large events, pre-construction records, and post-construction inflow records were merged to create an instantaneous peak inflow AMS that significantly expanded the records that were extracted from the Baltimore District Oracle database. This process should be duplicated using daily inflow records (i.e. merge pre- and post-construction records in addition to the largest historical events). The complete instantaneous peak inflow AMS is shown in Figure 21 and the complete daily inflow time series is shown in Figure 22. A relationship or correlation between instantaneous peaks and daily flows can be used to create a similar time series for daily flows. An additional analysis could be performed looking at the two upstream gages, Millersburg and Spring Creek, to extend the flow record at Sayers Dam. Follow guidance in Bulletin 17C for possibly extending the observed short record with a longer nearby gage record.

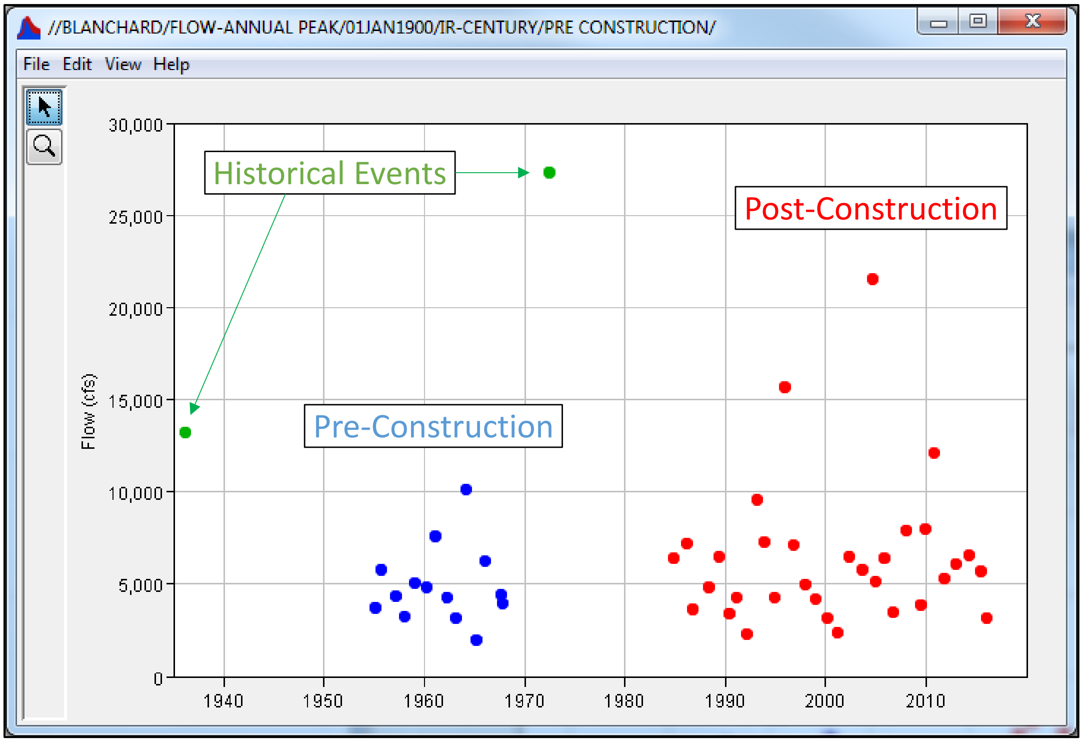


Figure 21: Complete Instantaneous Peak Inflow AMS

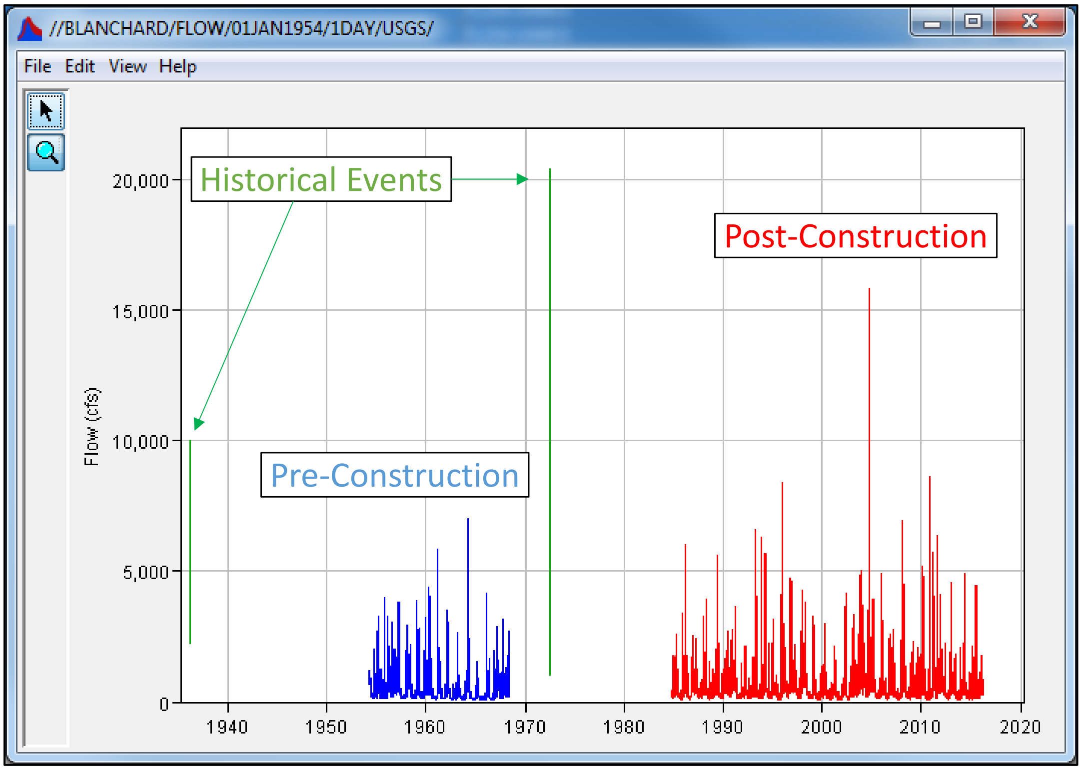
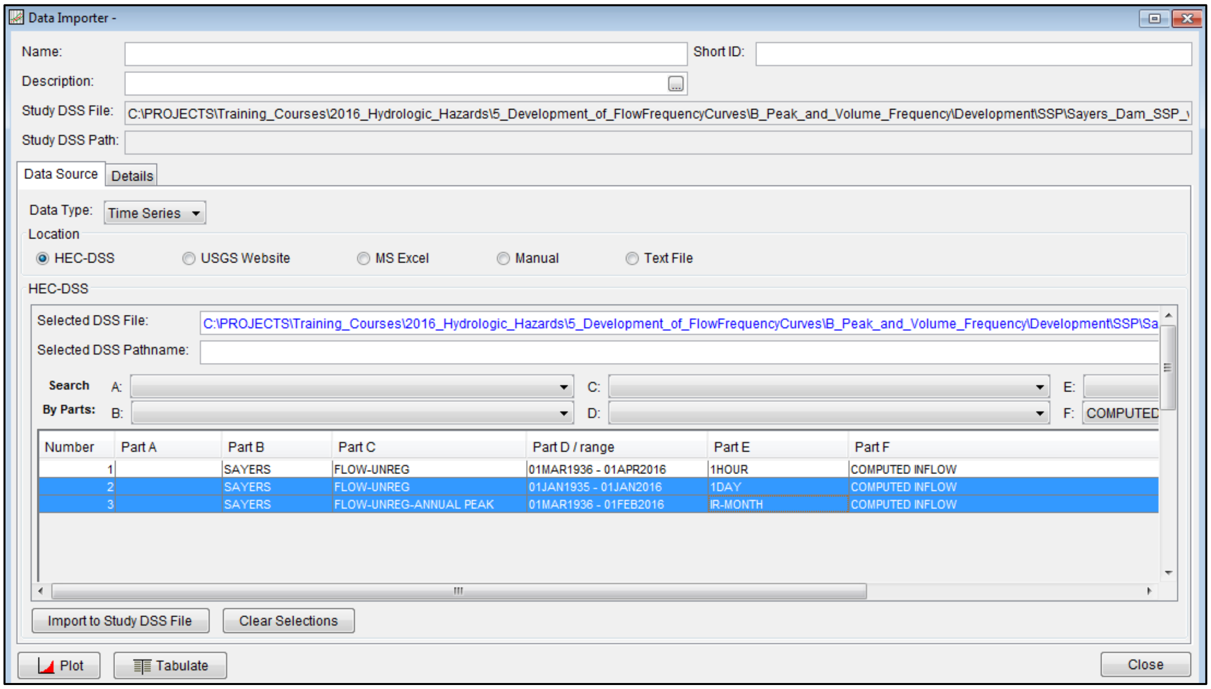


Figure 22: Complete Daily Inflow Time Series

4. Create a new HEC-SSP project and import inflow data sets. The instantaneous peak AMS and daily duration flow time series records will be needed to estimate the complete family of flow- and volume-frequency curves. Figure 23 shows these records being imported to HEC-SSP.



Name:

Description:

Study DSS File: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers_Dam_SSP_\

Study DSS Path:

Short ID:

Data Type: Time Series

Location

● HEC-DSS ○ USGS Website ○ MS Excel ○ Manual ○ Text File

HEC-DSS

Selected DSS File: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sa

Selected DSS Pathname:

A:

B:

C:

D:

E:

F: COMPUTED

Number	Part A	Part B	Part C	Part D / range	Part E	Part F
1		SAYERS	FLOW-UNREG	01MAR1936 - 01APR2016	1HOUR	COMPUTED INFLOW
2		SAYERS	FLOW-UNREG	01JAN1935 - 01JAN2016	1DAY	COMPUTED INFLOW
3		SAYERS	FLOW-UNREG-ANNUAL PEAK	01MAR1936 - 01FEB2016	IR-MONTH	COMPUTED INFLOW

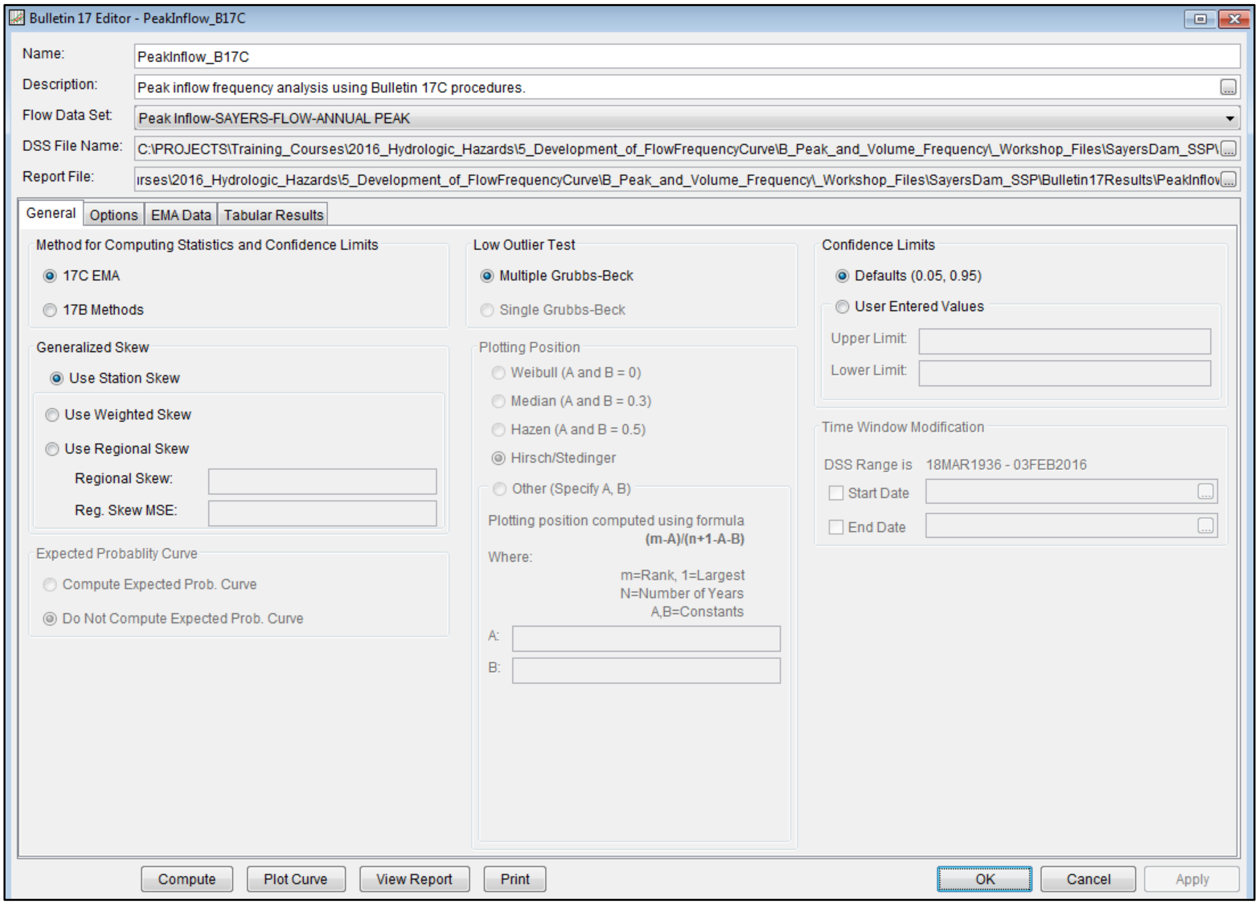
Figure 23: Importing the AMS and Daily Flow Time Series Records within HEC-SSP

5. Create a **Bulletin 17** analysis. Select the data set that corresponds to the instantaneous peak inflow AMS. Select “**17C EMA**” within the **Method for Computing Statistics and Confidence Limits** section. This will automatically select other features including the **Multiple Grubbs-Beck** low outlier test and **Hirsch/Stedinger** plotting positions. The **General** tab should look similar to Figure 24.

    - *Note*: Regional studies on instantaneous peak flow and/or duration-specific flows should be used when available. Regional information that can be considered for use within flow- and volume-frequency analyses typically consists of regional estimates of flow statistics. In the absence of regional data, flow statistics should rely on at-site systematic data, as is the case for the Bald Eagle Creek watershed.

    - The use of the water year is assumed when performing Bulletin 17C analyses within HEC-SSP. A water year is defined as the 12 month period from October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. For example, water year 1990 starts on 1 October 1989 and ends on 30 September 1990.

6. Move to the **Options** tab. Toggle the ability to define more values within the **User Specified Frequency Ordinates** section. Right-click within the table and add an additional three rows. Within the new rows, add the 0.1-, 0.01-, and 0.001-percent frequency ordinates. The **Options** tab should look similar to Figure 25.



Bulletin 17 Editor - PeakInflow_B17C

Name: PeakInflow_B17C

Description: Peak inflow frequency analysis using Bulletin 17C procedures.

Flow Data Set: Peak Inflow-SAYERS-FLOW-ANNUAL PEAK

DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\

Report File: ırses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\Bulletin17Results\PeakInflov

General | Options | EMA Data | Tabular Results

Method for Computing Statistics and Confidence Limits
- ● 17C EMA
- ○ 17B Methods

Generalized Skew
- ● Use Station Skew
- ○ Use Weighted Skew
- ○ Use Regional Skew
  - Regional Skew:
  - Reg. Skew MSE:

Expected Probablity Curve
- ○ Compute Expected Prob. Curve
- ● Do Not Compute Expected Prob. Curve

Low Outlier Test
- ● Multiple Grubbs-Beck
- ○ Single Grubbs-Beck

Plotting Position
- ○ Weibull (A and B = 0)
- ○ Median (A and B = 0.3)
- ○ Hazen (A and B = 0.5)
- ● Hirsch/Stedinger
- ○ Other (Specify A, B)

Plotting position computed using formula
(m-A)/(n+1-A-B)
Where:
m=Rank, 1=Largest
N=Number of Years
A,B=Constants
A:
B:

Confidence Limits
- ● Defaults (0.05, 0.95)
- ○ User Entered Values
  - Upper Limit:
  - Lower Limit:

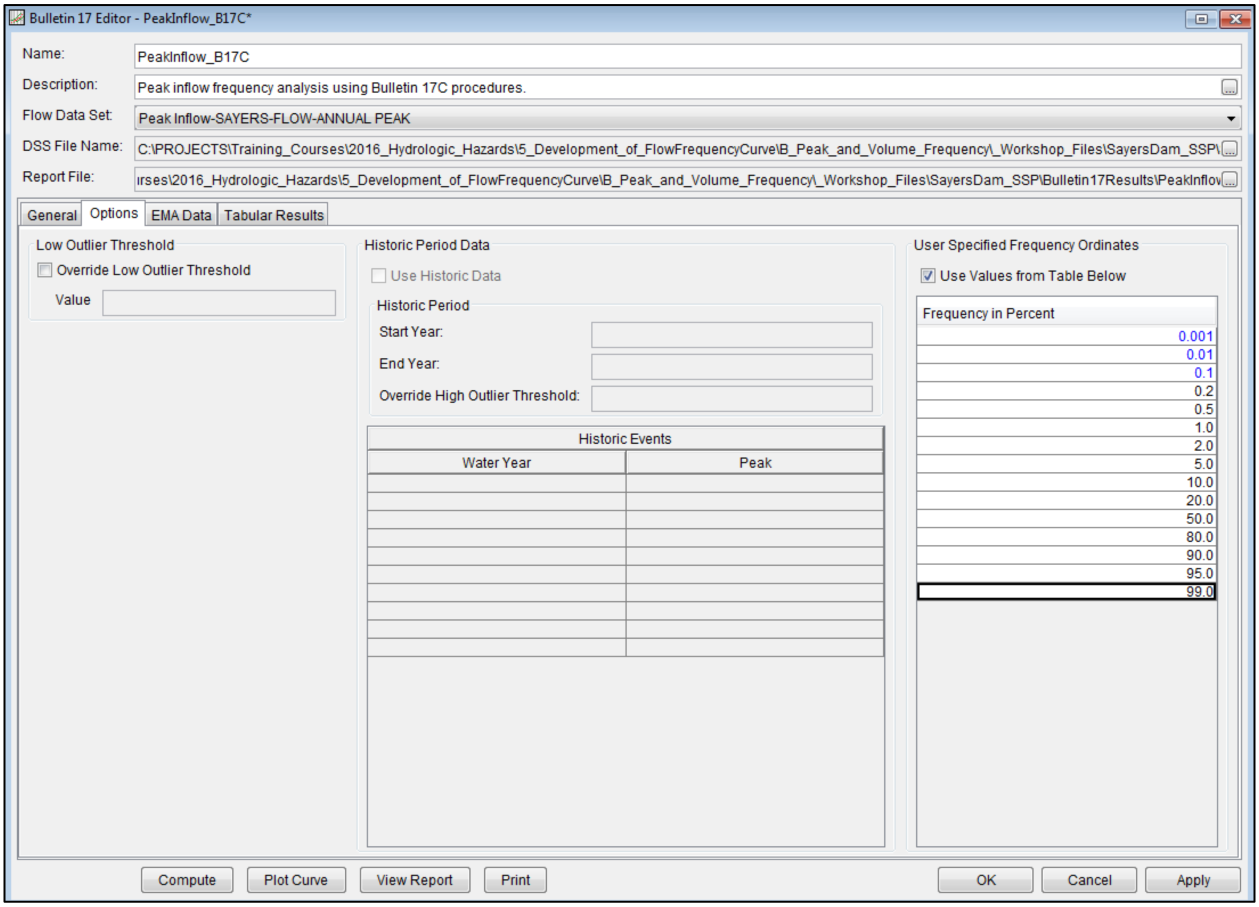
Time Window Modification
DSS Range is 18MAR1936 - 03FEB2016
- ☐ Start Date
- ☐ End Date

Figure 24: Peak Inflow B17C General Tab

7. Move to the **EMA Data** tab.

    - *Note*: The EMA procedure used within the Bulletin 17C methodology introduces the new concept of **Perception Thresholds**. Perception thresholds define the range of streamflow for which a flood event would likely have been observed had it occurred. The inherent assumption and consequence is that any year for which an event was not observed and recorded must have had a peak flow rate outside of (usually below) the perception range.

    - *Note*: HEC-SSP version 2.1 has a limitation on the dates used for a flow frequency analysis. Dates must be in the years 1000 – 4500. If paleoflood information is being used, then systematic peak flows might need to be shifted to the upper end of the time window range. If a longer time period is needed for the analysis, the PeakfqSA program should be used, which can be download at https://sites.google.com/a/alumni.colostate.edu/jengland/bulletin-17c.



Name: PeakInflow_B17C

Description: Peak inflow frequency analysis using Bulletin 17C procedures.

Flow Data Set: Peak Inflow-SAYERS-FLOW-ANNUAL PEAK

DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\

Report File: ırses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\Bulletin17Results\PeakInflov

☐ Override Low Outlier Threshold

Value:

☐ Use Historic Data

Start Year:

End Year:

Override High Outlier Threshold:

☑ Use Values from Table Below

Frequency in Percent
0.001
0.01
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
80.0
90.0
95.0
99.0

Figure 25: Peak Inflow B17C Options Tab

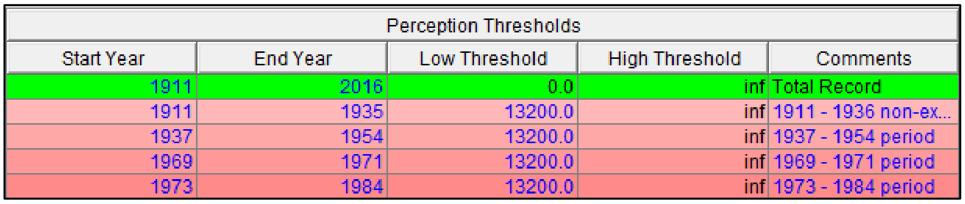
- The first row within the Perception Thresholds table will automatically be created to span the entire period of record of the selected Flow Data Set. The start and end year of this first perception threshold can be modified to alter the analysis time frame. This first perception threshold must have a low value of 0 and a high value of infinity. Additional rows within the perception threshold table supersede the rows above, for the specified time frame. Within HEC-SSP, perception threshold time frames should not overlap one another and should not overlap historic events.

- For any missing years in the analysis period, perception thresholds other than zero to infinity must be entered after the first row. The reason for this requirement is that a perception threshold of zero to infinity presumes any flow that occurred could have been observed, implying that unobserved years would not be possible. Therefore, unobserved years must have a perception threshold with either a lower bound greater than zero or an upper bound less than infinity. Most commonly, since very large flows do tend to be observed in some way (as historical events are estimated based on some evidence in the watershed), a lower bound greater than zero is chosen.

- Evidence presented in the March 1936 event post-flood report (Bogardus & Ryder, 1936) suggests that the March 1936 event was the largest peak flow rate in the Bald Eagle Creek watershed since at least 1911. This implies that had an event larger than the March 1936 event occurred in the timeframe between 1911 and 1936, it would have been documented. Therefore, the analysis period can be extended to 1911 using the 1936 flood to define a perception threshold. Change the first row in the **Perception Thresholds** table so that the analysis spans **1911** through **2016**. The low and high perception thresholds for this first row should be left at **0** and “**inf**”.

- Perception thresholds other than zero to infinity must be added for the missing years in the analysis period. These missing years are 1911 – 1935, 1937 – 1954, 1969 – 1971, and 1973 – 1984. Notice that the years for events 1936 and 1972 and the systematic record (1955-1968 and 1985-2016) are not included. Therefore, four additional rows must be added to the Perception Thresholds table. Since the March 1936 event had a peak flow rate of approximately 13,200 cfs, this flow rate can be used as a low threshold for the perception thresholds of missing years. The use of this perception threshold assumes that had a peak flow rate occurred in excess of 13,200 cfs, it would have been documented.

- In the second row of the Perception Thresholds table, type **1911**, **1935**, and **13200** in the cells corresponding to **Start Year**, **End Year**, and **Low Threshold**. In the **High Threshold** cell, double left-click to begin editing. Then, right-click and select **Set as INF**. This sets the high threshold to infinity. Use the **Comments** column to provide an adequate descriptive note. Continue creating rows in the Perception Thresholds table until all of the missing years in the analysis period are accounted. The Perception Thresholds table should resemble Figure 26.



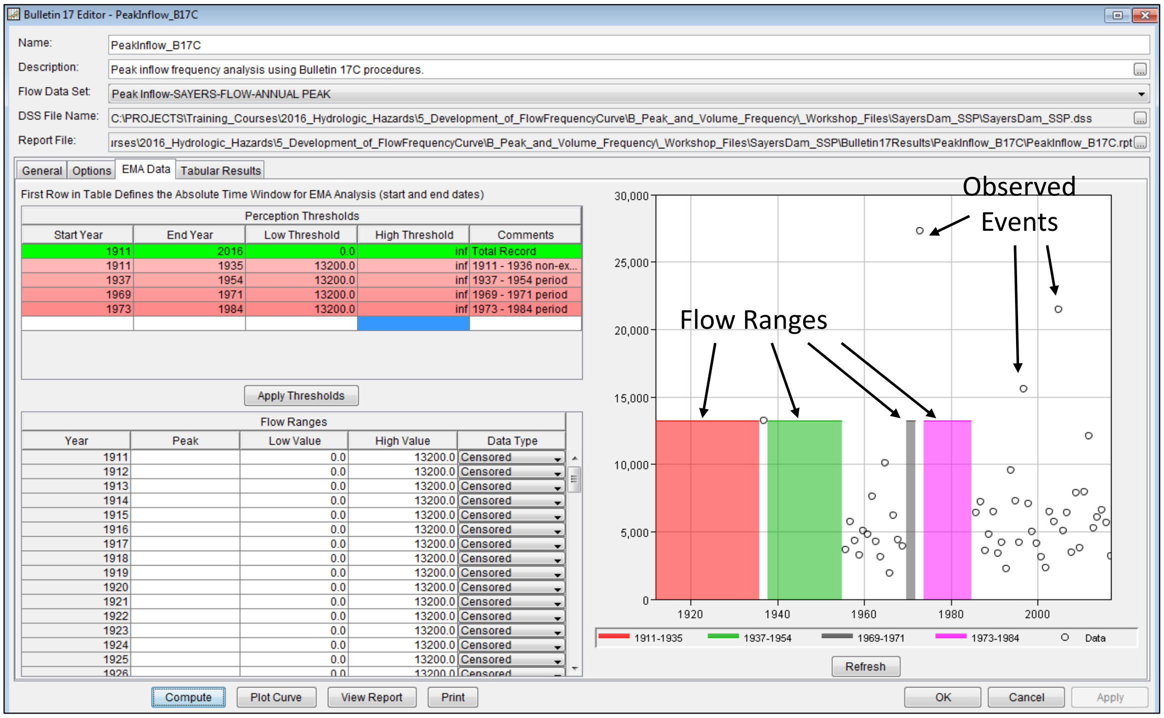
Perception Thresholds				
Start Year	End Year	Low Threshold	High Threshold	Comments
1911	2016	0.0	inf	Total Record
1911	1935	13200.0	inf	1911 - 1936 non-ex...
1937	1954	13200.0	inf	1937 - 1954 period
1969	1971	13200.0	inf	1969 - 1971 period
1973	1984	13200.0	inf	1973 - 1984 period

Figure 26: Peak Inflow B17C Perception Thresholds Table

- Once all of the information has been entered to the **Perception Thresholds** table, click **Apply Thresholds**. This will fill out the **Flow Ranges** table with the corresponding information. For instance, if the perception threshold from 1911 – 1935 is 13,200 cfs to infinity (i.e. if the peak flow for these years was above 13,200 cfs, it would have been documented), the corresponding flow range is zero to 13,200 cfs (the annual peak flows for these years must be in this range). Ensure that the **Flow Ranges** table contains a low and high value for every single year in the analysis period. The completed **EMA Data** tab should resemble Figure 27.

- Within the Flow Ranges table, make sure the Data Type is correctly set for all water years. The systematic data type should be selected for all water years with a flow measurement. The historic data type is used for those water years with no direct flow measurement but the flood was large enough that indirect methods could be used to estimate a low and high flow range. The censored data type should be used for those water years with no direct or indirect measurement of flow, the perception threshold is used to bracket the low and high values. The data type is used in computations of the Hirsh/Stedinger plotting positions and the confidence limits. The data type also impacts the identification and treatment of potentially influential low flows (PILFs) which can directly impact the computation of the computed flow frequency curve. Systematic data are checked for low outliers while the historic data are not. Systematic data that are detected as a PILF are replaced by censored data with a perception threshold equal to the PILF threshold.

- Historic flood events should be manually entered into the Flow Ranges table. Locate the water year where the historic flood occurred. The peak value can be entered, and then the low and high values entered that exactly match the peak value, if no estimation of uncertainty about the flood flow is available. If there is uncertainty about the flood flow for the historic event, then enter the low value and high value that define the flow range, the peak value does not need to be defined for this case.



Name: PeakInflow_B17C

Description: Peak inflow frequency analysis using Bulletin 17C procedures.

Flow Data Set: Peak Inflow-SAYERS-FLOW-ANNUAL PEAK

DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\SayersDam_SSP.dss

Report File: ırses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\Bulletin17Results\PeakInflow_B17C\PeakInflow_B17C.rpt

First Row in Table Defines the Absolute Time Window for EMA Analysis (start and end dates)

Perception Thresholds				
Start Year	End Year	Low Threshold	High Threshold	Comments
1911	2016	0.0	inf	Total Record
1911	1935	13200.0	inf	1911 - 1936 non-ex...
1937	1954	13200.0	inf	1937 - 1954 period
1969	1971	13200.0	inf	1969 - 1971 period
1973	1984	13200.0	inf	1973 - 1984 period

Flow Ranges				
Year	Peak	Low Value	High Value	Data Type
1911		0.0	13200.0	Censored
1912		0.0	13200.0	Censored
1913		0.0	13200.0	Censored
1914		0.0	13200.0	Censored
1915		0.0	13200.0	Censored
1916		0.0	13200.0	Censored
1917		0.0	13200.0	Censored
1918		0.0	13200.0	Censored
1919		0.0	13200.0	Censored
1920		0.0	13200.0	Censored
1921		0.0	13200.0	Censored
1922		0.0	13200.0	Censored
1923		0.0	13200.0	Censored
1924		0.0	13200.0	Censored
1925		0.0	13200.0	Censored
1926		0.0	13200.0	Censored

Figure 27: Peak Inflow B17C EMA Data Tab

8. Compute the analysis then plot and tabulate the flow-frequency curve. Clicking **Plot Curve** produces a plot that should resemble Figure 28.

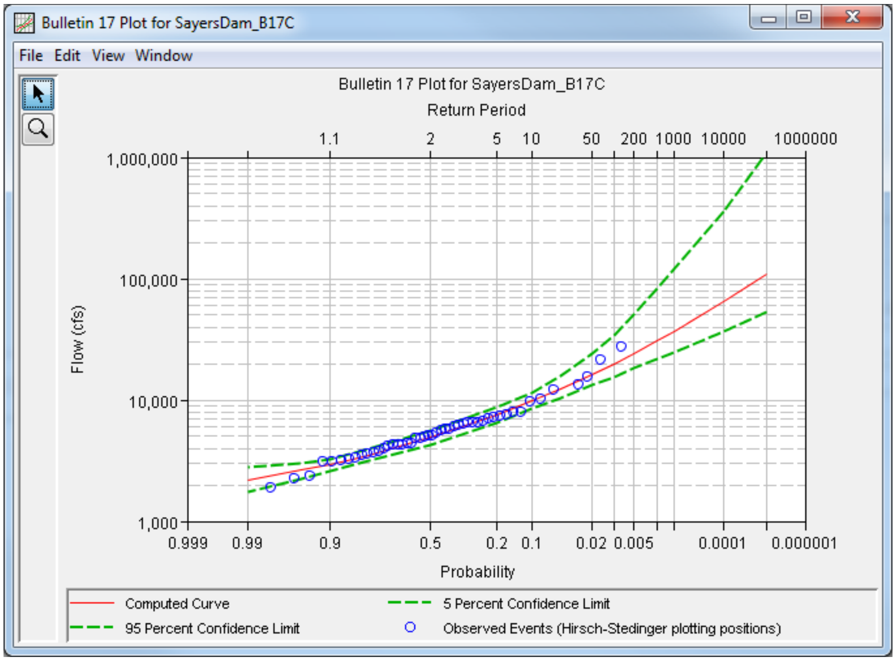
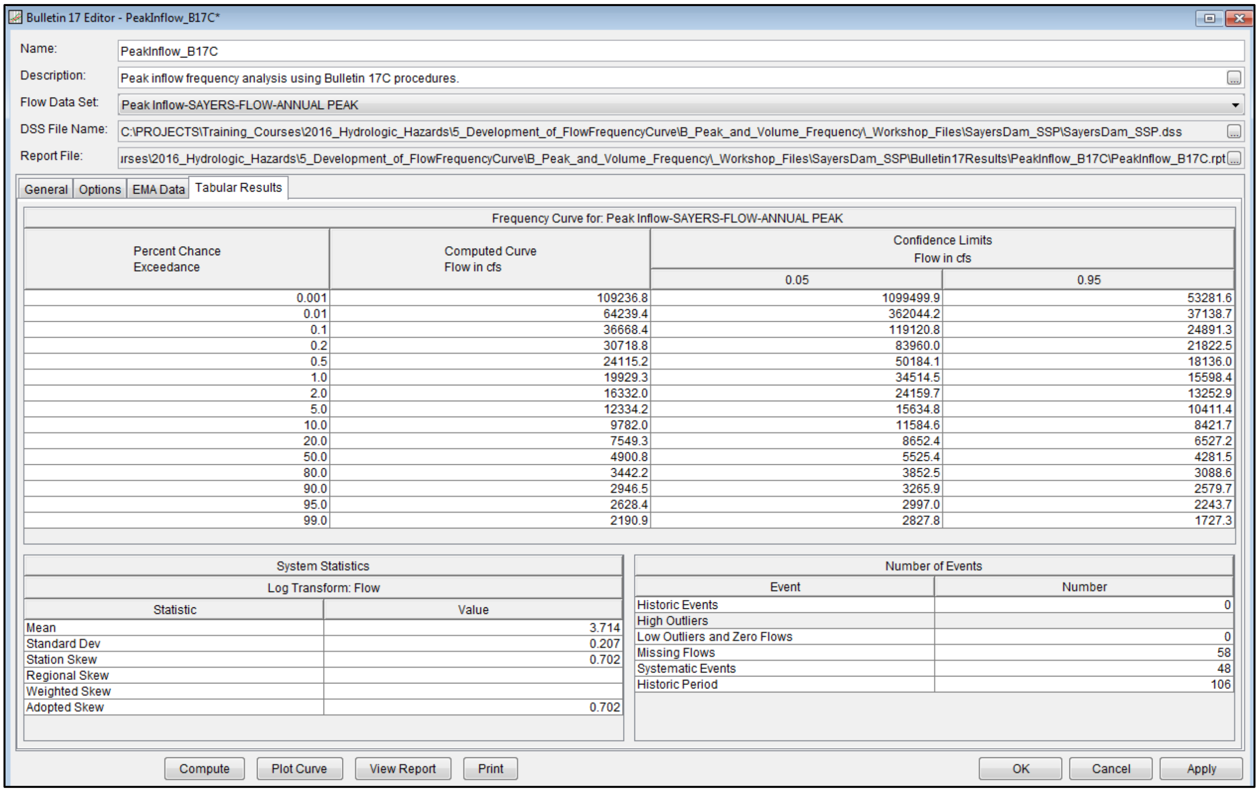


Figure 28: Peak Inflow B17C Plot

9. Move to the **Tabular Results** tab. Note the **Computed Curve**, **5-**, and **95-percent Confidence Limits** for all of the desired frequency ordinates, the moments/parameters of the LPIII fit to the data, and other information related to the analysis. The computed **Tabular Results** tab should resemble Figure 29.



Name: PeakInflow_B17C
Description: Peak inflow frequency analysis using Bulletin 17C procedures.
Flow Data Set: Peak Inflow-SAYERS-FLOW-ANNUAL PEAK
DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\SayersDam_SSP.dss
Report File: ırses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\Bulletin17Results\PeakInflow_B17C\PeakInflow_B17C.rpt

Frequency Curve for: Peak Inflow-SAYERS-FLOW-ANNUAL PEAK

Percent Chance Exceedance	Computed Curve Flow in cfs	Confidence Limits Flow in cfs	
		0.05	0.95
0.001	109236.8	1099499.9	53281.6
0.01	64239.4	362044.2	37138.7
0.1	36668.4	119120.8	24891.3
0.2	30718.8	83960.0	21822.5
0.5	24115.2	50184.1	18136.0
1.0	19929.3	34514.5	15598.4
2.0	16332.0	24159.7	13252.9
5.0	12334.2	15634.8	10411.4
10.0	9782.0	11584.6	8421.7
20.0	7549.3	8652.4	6527.2
50.0	4900.8	5525.4	4281.5
80.0	3442.2	3852.5	3088.6
90.0	2946.5	3265.9	2579.7
95.0	2628.4	2997.0	2243.7
99.0	2190.9	2827.8	1727.3

System Statistics

Log Transform: Flow

Statistic	Value
Mean	3.714
Standard Dev	0.207
Station Skew	0.702
Regional Skew	
Weighted Skew	
Adopted Skew	0.702

Number of Events

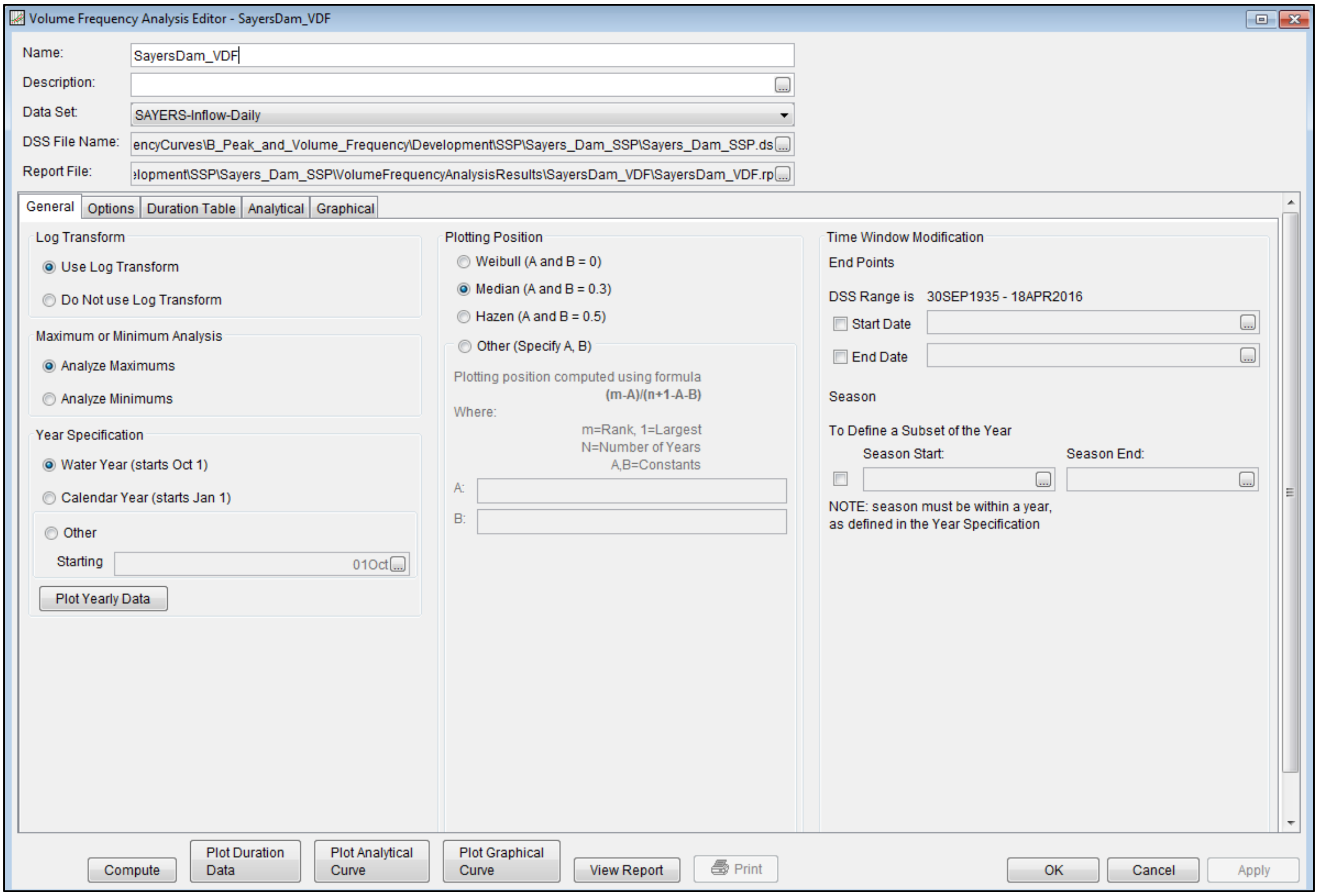
Event	Number
Historic Events	0
High Outliers	
Low Outliers and Zero Flows	0
Missing Flows	58
Systematic Events	48
Historic Period	106

Figure 29: Peak Inflow B17C Tabular Results Tab

10. Create a **Volume Frequency** analysis. Select the data set that corresponds to the daily duration flow time series records. The **General** tab should look similar to Figure 30.

    - *Note*: The **Volume Frequency** analysis within HEC-SSP v2.1 does not currently allow for the use of Bulletin 17C procedures. However, the existing **Volume Frequency** analysis is only used to extract duration-specific AMS from the daily flow time series. The extracted annual maximum data is added as a new gage record and used as input to a Bulletin 17C analysis

    - *Note*: The volume frequency analysis automatically computes annual maximum volumes for each duration selected in the analysis. Depending on the time-step of the data used for the analysis, the extracted volumes might not match the volumes estimated in post flood reports. For example, a 24-hour flood event that was spread over two days will not be captured when using daily average flow. The Duration Table tab in the HEC-SSP Volume Frequency Analysis contains an option to edit the extracted annual maximums.


Volume Frequency Analysis Editor - SayersDam_VDF

Name: SayersDam_VDF

Description:

Data Set: SAYERS-Inflow-Daily

DSS File Name: encyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers_Dam_SSP\Sayers_Dam_SSP.ds

Report File: :lopment\SSP\Sayers_Dam_SSP\VolumeFrequencyAnalysisResults\SayersDam_VDF\SayersDam_VDF.rp

Log Transform
- ● Use Log Transform
- ○ Do Not use Log Transform

Maximum or Minimum Analysis
- ● Analyze Maximums
- ○ Analyze Minimums

Year Specification
- ● Water Year (starts Oct 1)
- ○ Calendar Year (starts Jan 1)
- ○ Other
- Starting 01Oct

Plotting Position
- ○ Weibull (A and B = 0)
- ● Median (A and B = 0.3)
- ○ Hazen (A and B = 0.5)
- ○ Other (Specify A, B)

Plotting position computed using formula (m-A)/(n+1-A-B)

Where: m=Rank, 1=Largest; N=Number of Years; A,B=Constants

A:

B:

Time Window Modification

End Points

DSS Range is 30SEP1935 - 18APR2016

☐ Start Date

☐ End Date

Season

To Define a Subset of the Year

☐ Season Start: Season End:

NOTE: season must be within a year, as defined in the Year Specification

Figure 30: Volume Frequency Analysis General Tab

- *Note*: The analyst should decide whether the water year, calendar year, or other should be used when extracting the duration data and performing the analysis. The flow data for each year can be plotted in the same window by using the **Plot Yearly Data** button. Plotting the data is a quick visual cue that helps determine when major flood events occur and whether the selection of a water year will impact the assumption of independence in the annual maximum floods. The key to selecting the water year is that a flood event in the previous year should not influence a flood event in the following year. For example, a large flood starting on December 31 could be the largest flood in the current and following year, when using calendar year as opposed to the water year. In order to treat this flood as an independent event, the calendar year should not be used to define the water year. A warning message is generated in HEC-SSP that gives information about the number of events where annual maximum flows occur at the beginning of the water year, which indicates flood flows from the prior year are impacting the current year. Move the definition of the water year to reduce the number of instances where flood flows from the previous year impact the current year.

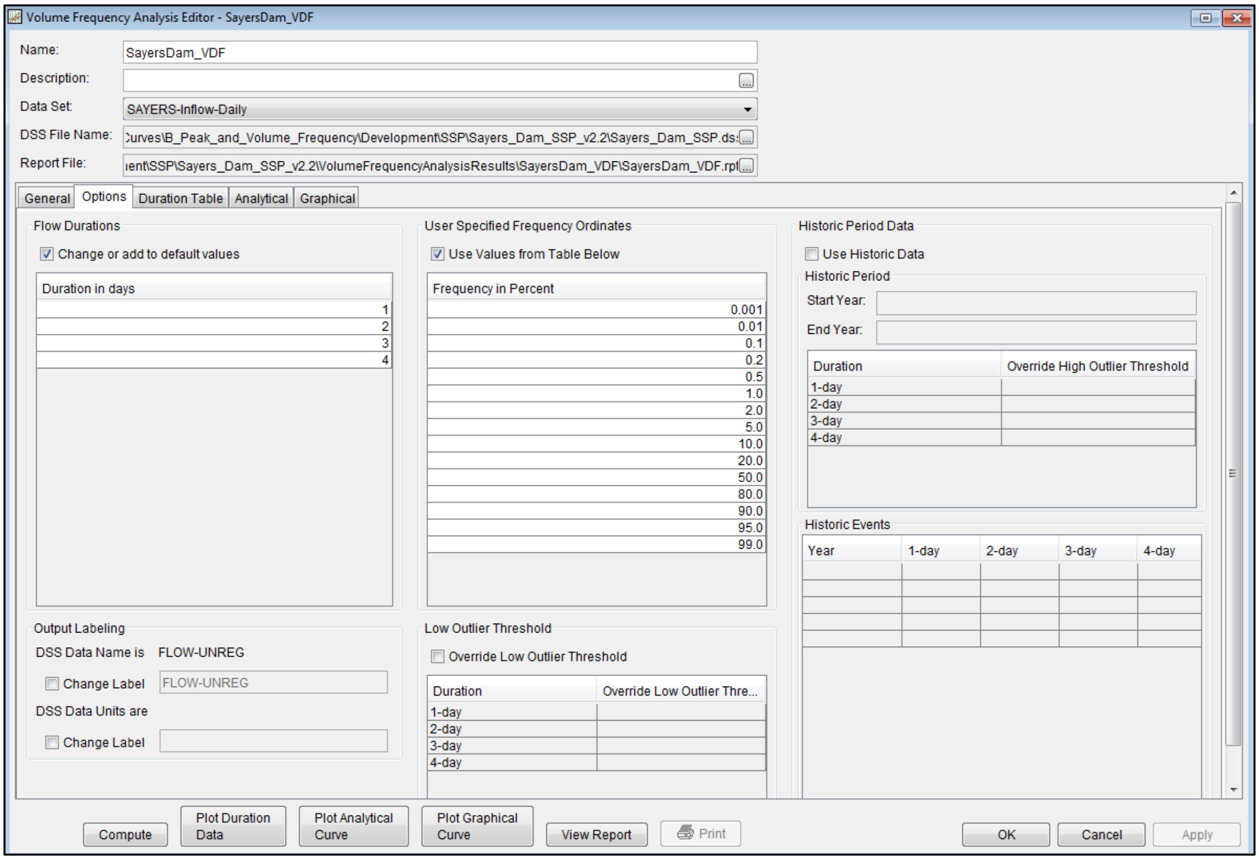
11. Move to the **Options** tab.

12. Toggle the ability to define different flow durations. Within the **Flow Durations** table, enter the 1-, 2-, 3-, and 4-day durations.

    - *Note*: The durations chosen for this analysis should correspond to the standard durations in EM 1110-2-1415 plus the critical duration. In order to achieve adequate definition around the critical duration, multiple durations less than/greater than the critical duration were chosen.

13. Toggle the ability to define more values within the **User Specified Frequency Ordinates** section. Right-click

within the table and add an additional three rows. Within the new rows, add the 0.1-, 0.01-, and 0.001-percent frequency ordinates. The **Options** tab should look similar to Figure 31.



Name: SayersDam_VDF

Description:

Data Set: SAYERS-Inflow-Daily

DSS File Name: Curves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers_Dam_SSP_v2.2\Sayers_Dam_SSP.ds

Report File: ient\SSP\Sayers_Dam_SSP_v2.2\VolumeFrequencyAnalysisResults\SayersDam_VDF\SayersDam_VDF.rpt

Flow Durations

☑ Change or add to default values

Duration in days
1
2
3
4

User Specified Frequency Ordinates

☑ Use Values from Table Below

Frequency in Percent
0.001
0.01
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
80.0
90.0
95.0
99.0

Historic Period Data

☐ Use Historic Data

Historic Period

Start Year:

End Year:

Duration	Override High Outlier Threshold
1-day	
2-day	
3-day	
4-day	

Historic Events

Year	1-day	2-day	3-day	4-day

Output Labeling

DSS Data Name is FLOW-UNREG

☐ Change Label FLOW-UNREG

DSS Data Units are

☐ Change Label

Low Outlier Threshold

☐ Override Low Outlier Threshold

Duration	Override Low Outlier Thre...
1-day	
2-day	
3-day	
4-day	

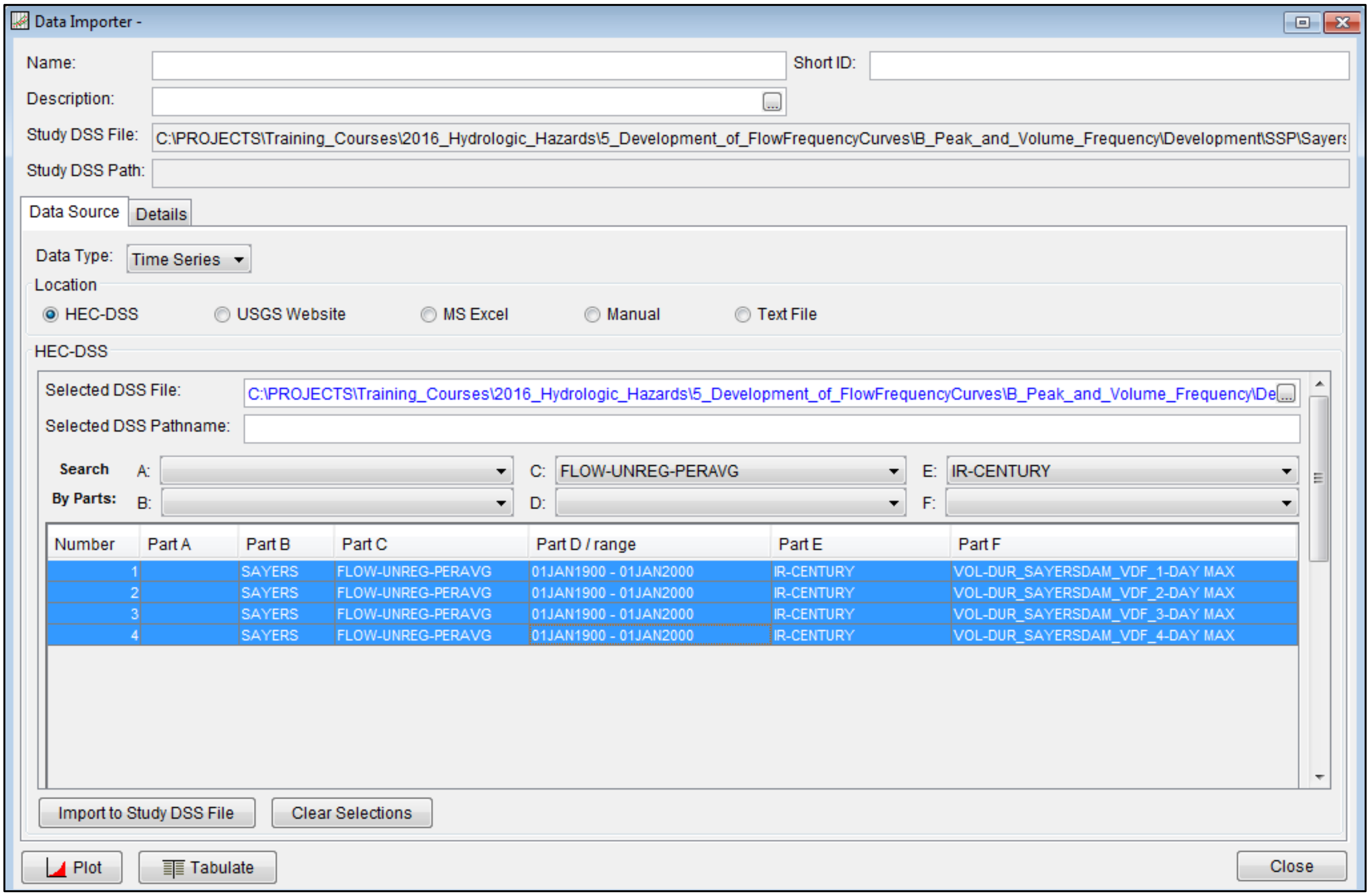
Figure 31: Volume Frequency Analysis Options Tab

14. Move to the **Duration Table** tab.

15. Click **Extract Volume-Duration Data** at the bottom of the window.

    - *Note*: When extracting volume-duration data, HEC-SSP will search within the daily flow data set to find the AMS for the specified durations. These records are written to the HEC-SSP study DSS file.

16. Import the AMS for the **1-**, **2-**, **3-**, and **4-day** durations from the HEC-SSP study DSS file. Figure 32 shows these records being imported to HEC-SSP. Results from analyses are saved to the study's HEC-DSS file. When importing the annual maximum volumes, navigate to the study HEC-DSS file and select the records with the correct F-part name.



Study DSS File: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers

Data Type: Time Series

● HEC-DSS ○ USGS Website ○ MS Excel ○ Manual ○ Text File

HEC-DSS

Selected DSS File: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\De

Search By Parts: A: B: C: FLOW-UNREG-PERAVG D: E: IR-CENTURY F:

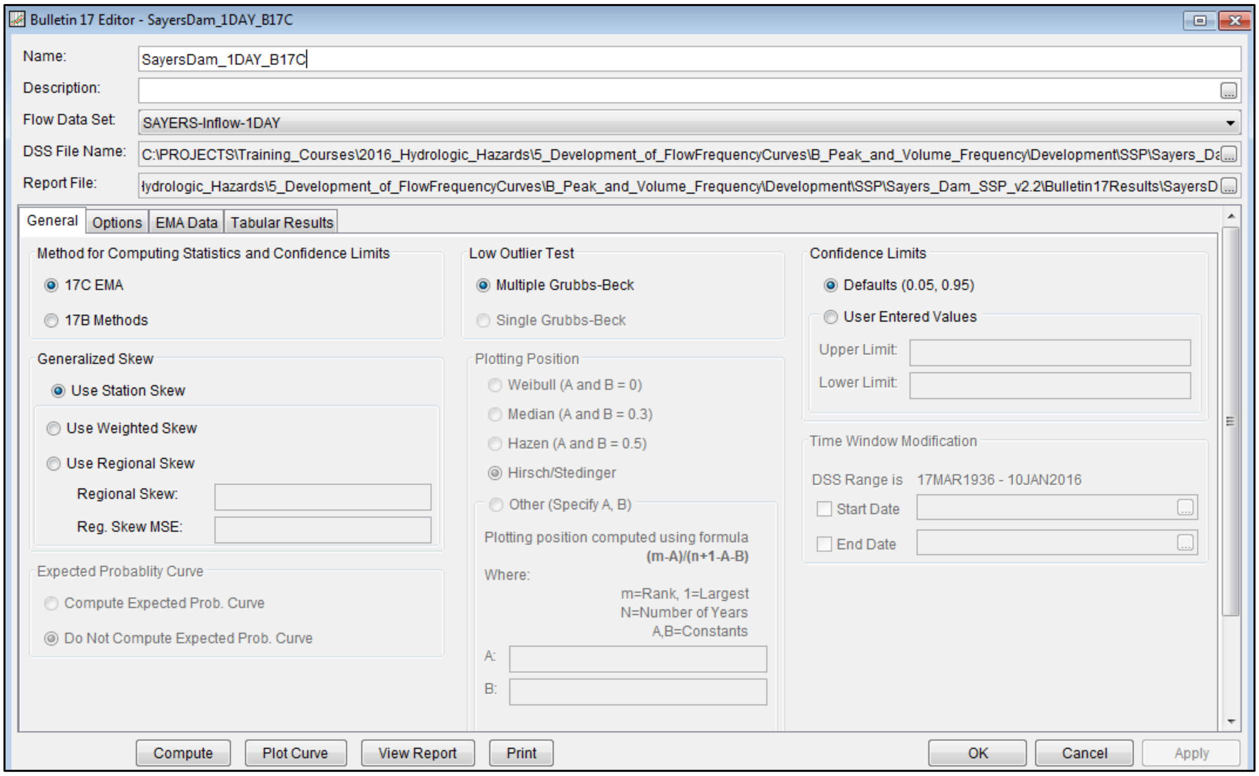
Number	Part A	Part B	Part C	Part D / range	Part E	Part F
1		SAYERS	FLOW-UNREG-PERAVG	01JAN1900 - 01JAN2000	IR-CENTURY	VOL-DUR_SAYERSDAM_VDF_1-DAY MAX
2		SAYERS	FLOW-UNREG-PERAVG	01JAN1900 - 01JAN2000	IR-CENTURY	VOL-DUR_SAYERSDAM_VDF_2-DAY MAX
3		SAYERS	FLOW-UNREG-PERAVG	01JAN1900 - 01JAN2000	IR-CENTURY	VOL-DUR_SAYERSDAM_VDF_3-DAY MAX
4		SAYERS	FLOW-UNREG-PERAVG	01JAN1900 - 01JAN2000	IR-CENTURY	VOL-DUR_SAYERSDAM_VDF_4-DAY MAX

Figure 32: Importing the AMS for the 1-, 2-, 3-, and 4-day Durations within HEC-SSP

- *Note*: The datasets of interest will contain a C-Part that has been appended with “-PERAVG” and an E-Part of “IR-CENTURY”.

17. Create a **Bulletin 17** analysis. Select the data set that corresponds to the instantaneous 1-day duration AMS. Select “**17C EMA**” within the **Method for Computing Statistics and Confidence Limits** section. This will automatically select other features including the **Multiple Grubbs-Beck** low outlier test and **Hirsch/Stedinger** plotting positions. The **General** tab should look similar to Figure 33.

18. Move to the **Options** tab. Toggle the ability to define more values within the **User Specified Frequency Ordinates** section. Right-click within the table and add an additional three rows. Within the new rows, add the 0.1-, 0.01-, and 0.001-percent frequency ordinates. The **Options** tab should look similar to Figure 34.



Bulletin 17 Editor - SayersDam_1DAY_B17C

Name: SayersDam_1DAY_B17C
Description:
Flow Data Set: SAYERS-Inflow-1DAY
DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers_Da
Report File: ydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers_Dam_SSP_v2.2\Bulletin17Results\SayersD

Method for Computing Statistics and Confidence Limits
● 17C EMA
○ 17B Methods

Generalized Skew
● Use Station Skew
○ Use Weighted Skew
○ Use Regional Skew
Regional Skew:
Reg. Skew MSE:

Expected Probablity Curve
○ Compute Expected Prob. Curve
● Do Not Compute Expected Prob. Curve

Low Outlier Test
● Multiple Grubbs-Beck
○ Single Grubbs-Beck

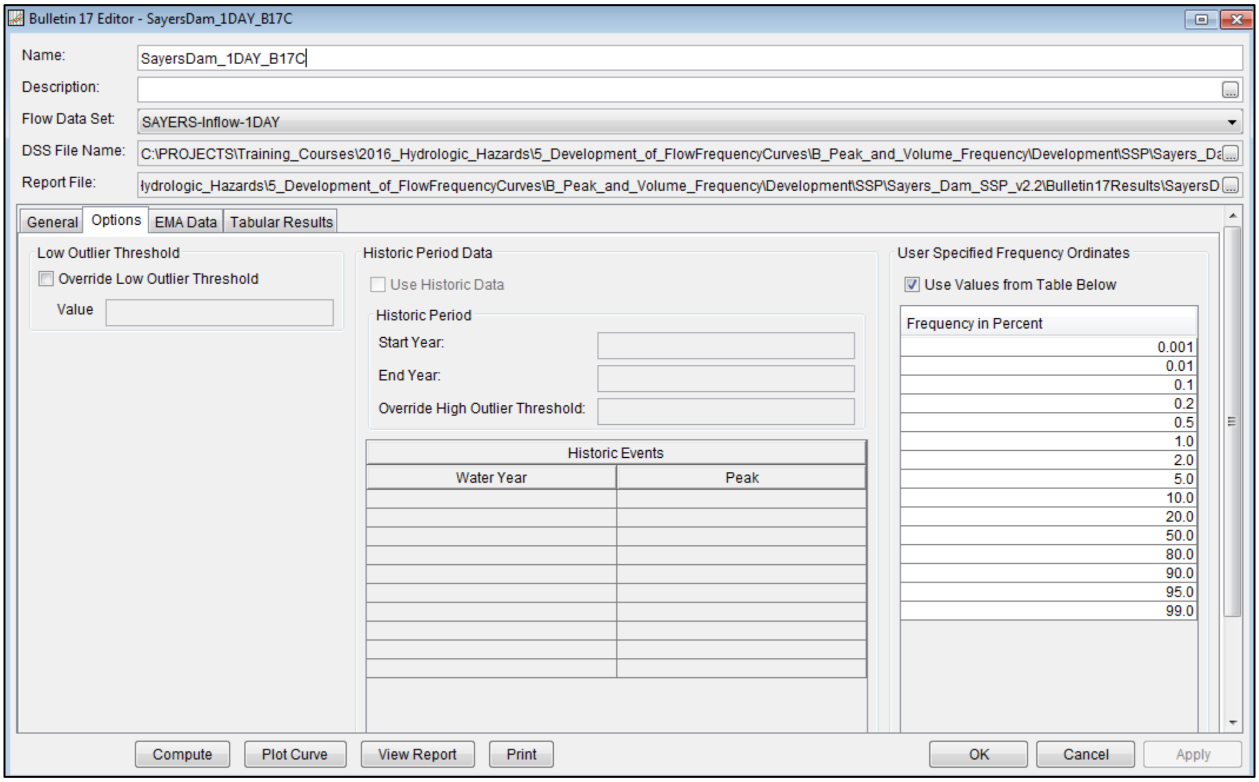
Plotting Position
○ Weibull (A and B = 0)
○ Median (A and B = 0.3)
○ Hazen (A and B = 0.5)
● Hirsch/Stedinger
○ Other (Specify A, B)

Plotting position computed using formula (m-A)/(n+1-A-B)
Where:
m=Rank, 1=Largest
N=Number of Years
A,B=Constants
A:
B:

Confidence Limits
● Defaults (0.05, 0.95)
○ User Entered Values
Upper Limit:
Lower Limit:

Time Window Modification
DSS Range is 17MAR1936 - 10JAN2016
☐ Start Date
☐ End Date

Figure 33: 1-day Duration B17C General Tab



Bulletin 17 Editor - SayersDam_1DAY_B17C

Name: SayersDam_1DAY_B17C
Description:
Flow Data Set: SAYERS-Inflow-1DAY
DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers_Da
Report File: ydrologic_Hazards\5_Development_of_FlowFrequencyCurves\B_Peak_and_Volume_Frequency\Development\SSP\Sayers_Dam_SSP_v2.2\Bulletin17Results\SayersD

Low Outlier Threshold
☐ Override Low Outlier Threshold
Value

Historic Period Data
☐ Use Historic Data
Historic Period
Start Year:
End Year:
Override High Outlier Threshold:

Historic Events

Water Year	Peak

User Specified Frequency Ordinates
☑ Use Values from Table Below

Frequency in Percent
0.001
0.01
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
80.0
90.0
95.0
99.0

Figure 34: 1-day Duration B17C Options Tab

19. Move to the **EMA Data** tab.

    - *Note*: The first row within the Perception Thresholds table will automatically be created to span the entire period of record of the selected Flow Data Set. No evidence is presented within available post-flood reports to indicate whether the March 1936 event contained the largest duration-specific flow rate for any time period prior to 1936. Therefore, ensure that the first row in the **Perception Thresholds** table spans **1936** through **2016**. The low and high perception thresholds for this first row should be left at **0** and "**inf**".

    - For any missing years in the analysis period, perception thresholds other than zero to infinity must be entered after the first row. These missing years are 1937 – 1954, 1969 – 1971, and 1973 – 1984. Therefore, three additional rows must be added to the Perception Thresholds table.

    - Evidence presented in the March 1936 event post-flood report (Bogardus & Ryder, 1936) suggests that the March 1936 event contained the largest 1DAY duration flow rate in the Bald Eagle Creek watershed before June 1972. This implies that had an event larger than the March 1936 event occurred in the timeframe between 1936 and 1972, it would have been documented. Since the March 1936 event had a peak 1DAY duration flow rate of approximately 10,000 cfs, this flow rate can be used as a low threshold for the perception thresholds of missing years.

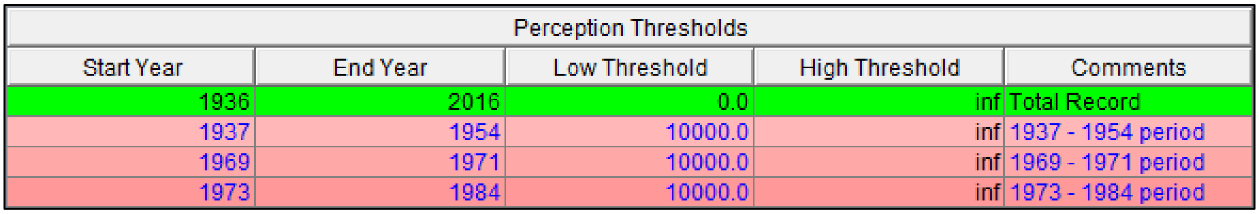
    - In the second row of the Perception Thresholds table, type **1937**, **1954**, and **10000** in the cells corresponding to **Start Year**, **End Year**, and **Low Threshold**.

    - In the **High Threshold** cell, double left-click to begin editing.

    - Then, right-click and select **Set as INF**. This sets the high threshold to infinity.

    - Use the **Comments** column to provide an adequate descriptive note.

    - Continue creating rows in the Perception Thresholds table until all of the missing years in the analysis period are accounted. The Perception Thresholds table should resemble Figure 35.

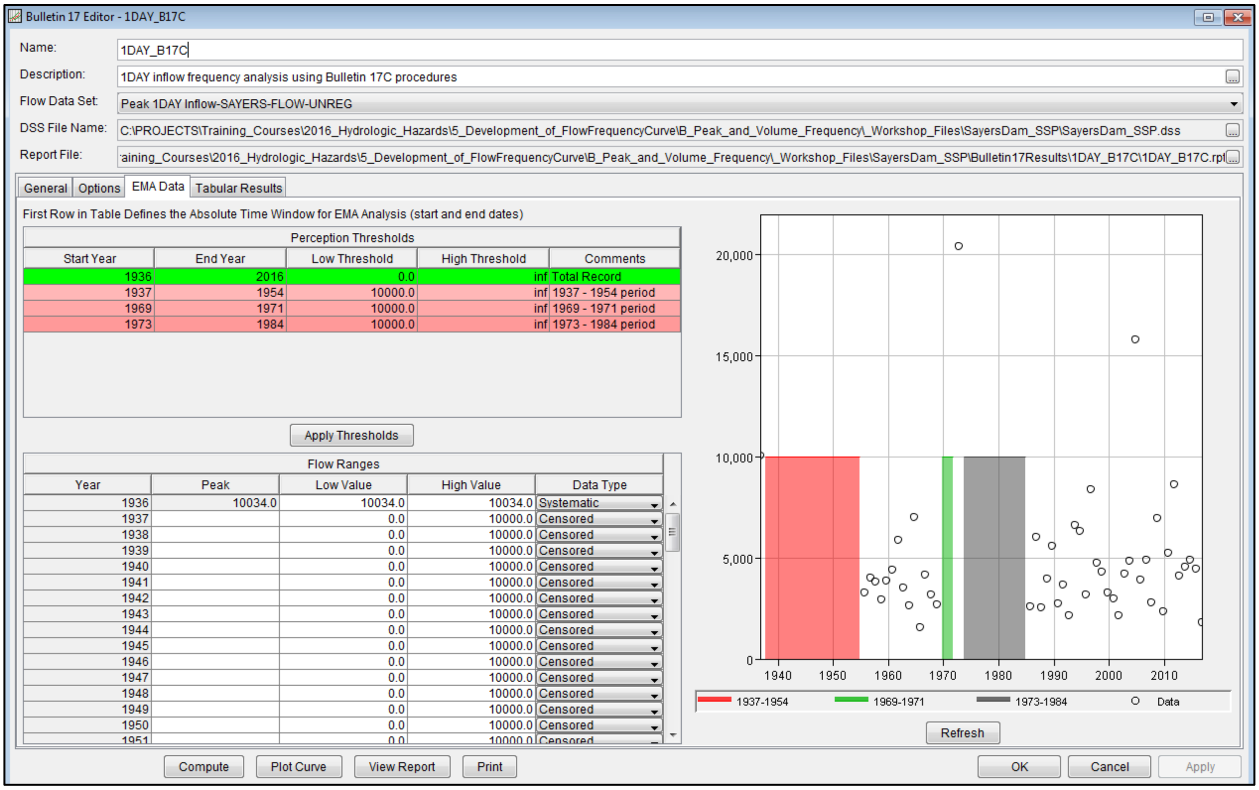


Perception Thresholds				
Start Year	End Year	Low Threshold	High Threshold	Comments
1936	2016	0.0	inf	Total Record
1937	1954	10000.0	inf	1937 - 1954 period
1969	1971	10000.0	inf	1969 - 1971 period
1973	1984	10000.0	inf	1973 - 1984 period

Figure 35: 1-day Duration B17C Perception Thresholds Table

- Once all of the information has been entered to the **Perception Thresholds** table, click **Apply Thresholds**. This will fill out the **Flow Ranges** table with the corresponding information.

- Ensure that the **Flow Ranges** table contains a low and high value for every single year in the analysis period. The completed **EMA Data** tab should resemble Figure 36.



Name: 1DAY_B17C

Description: 1DAY inflow frequency analysis using Bulletin 17C procedures

Flow Data Set: Peak 1DAY Inflow-SAYERS-FLOW-UNREG

DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\SayersDam_SSP.dss

Report File: aining_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\Bulletin17Results\1DAY_B17C\1DAY_B17C.rpt

First Row in Table Defines the Absolute Time Window for EMA Analysis (start and end dates)

Perception Thresholds				
Start Year	End Year	Low Threshold	High Threshold	Comments
1936	2016	0.0	inf	Total Record
1937	1954	10000.0	inf	1937 - 1954 period
1969	1971	10000.0	inf	1969 - 1971 period
1973	1984	10000.0	inf	1973 - 1984 period

Flow Ranges				
Year	Peak	Low Value	High Value	Data Type
1936	10034.0	10034.0	10034.0	Systematic
1937		0.0	10000.0	Censored
1938		0.0	10000.0	Censored
1939		0.0	10000.0	Censored
1940		0.0	10000.0	Censored
1941		0.0	10000.0	Censored
1942		0.0	10000.0	Censored
1943		0.0	10000.0	Censored
1944		0.0	10000.0	Censored
1945		0.0	10000.0	Censored
1946		0.0	10000.0	Censored
1947		0.0	10000.0	Censored
1948		0.0	10000.0	Censored
1949		0.0	10000.0	Censored
1950		0.0	10000.0	Censored
1951		0.0	10000.0	Censored

Figure 36: 1-day Duration B17C EMA Data Tab

20. Compute the analysis then plot and tabulate the flow-frequency curve. Clicking **Plot Curve** produces a plot that should resemble Figure 37.

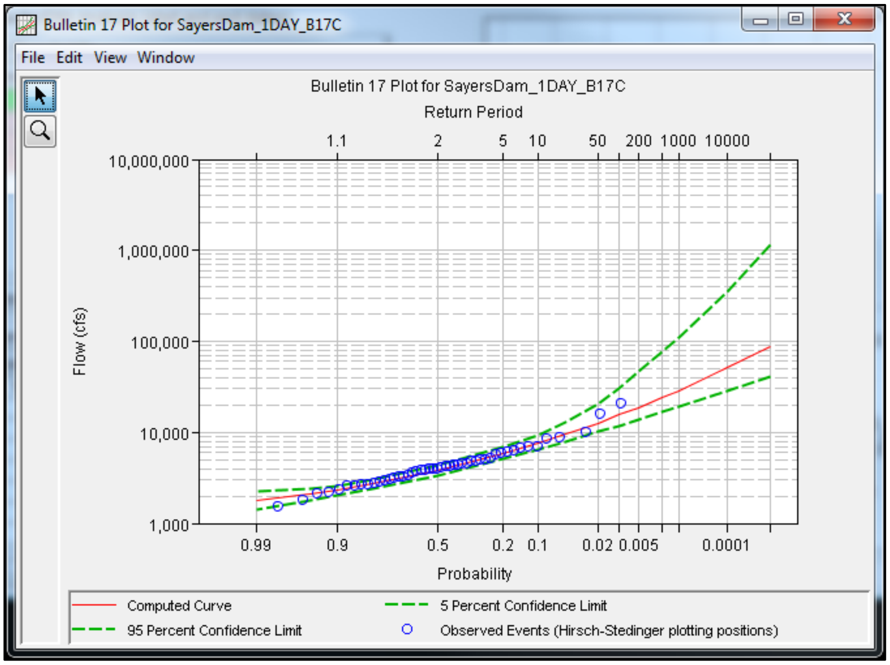
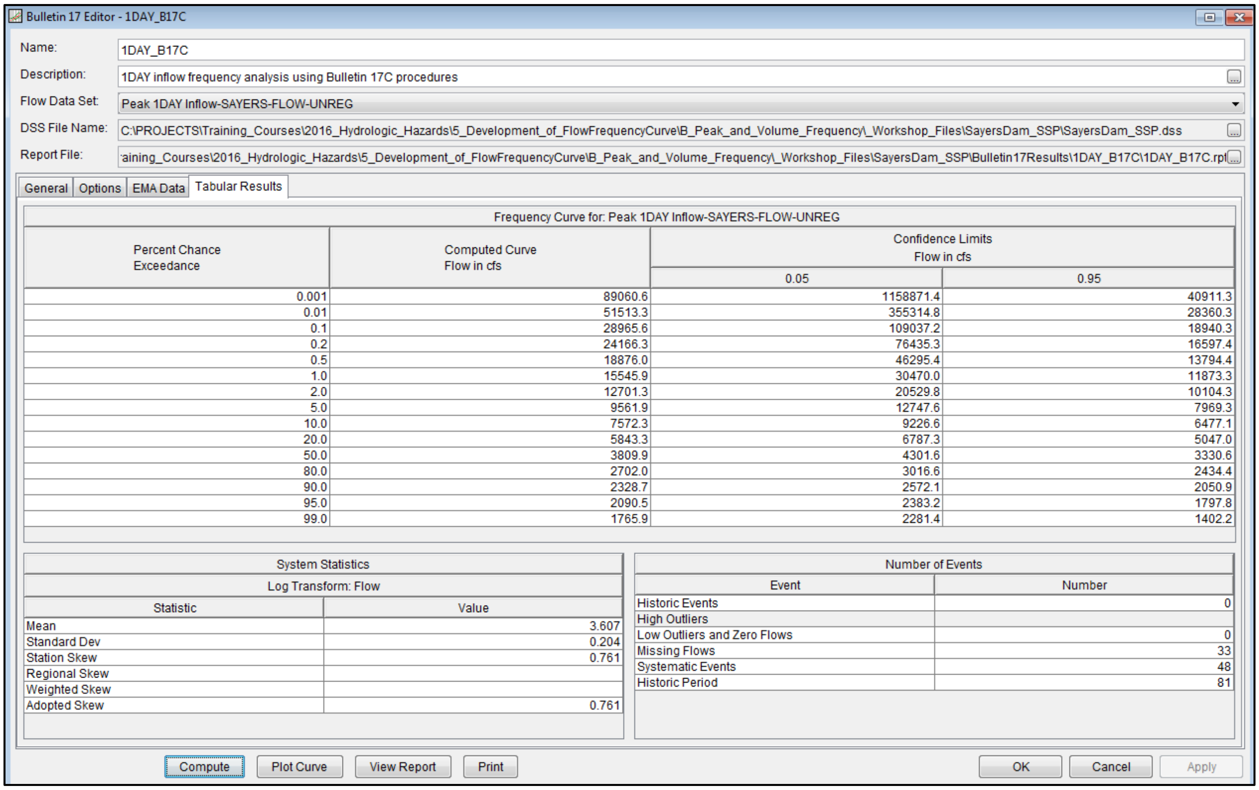


Figure 37: 1-day Duration B17C Plot

21. Move to the **Tabular Results** tab. Note the **Computed Curve**, **5-**, and **95-percent Confidence Limits** for all of the desired frequency ordinates, the moments/parameters of the LPIII fit to the data, and other information related to the analysis. The computed **Tabular Results** tab should resemble Figure 38.



Name: 1DAY_B17C
Description: 1DAY inflow frequency analysis using Bulletin 17C procedures
Flow Data Set: Peak 1DAY Inflow-SAYERS-FLOW-UNREG
DSS File Name: C:\PROJECTS\Training_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\SayersDam_SSP.dss
Report File: :aining_Courses\2016_Hydrologic_Hazards\5_Development_of_FlowFrequencyCurve\B_Peak_and_Volume_Frequency_Workshop_Files\SayersDam_SSP\Bulletin17Results\1DAY_B17C\1DAY_B17C.rpt

Frequency Curve for: Peak 1DAY Inflow-SAYERS-FLOW-UNREG

Percent Chance Exceedance	Computed Curve Flow in cfs	Confidence Limits Flow in cfs	
		0.05	0.95
0.001	89060.6	1158871.4	40911.3
0.01	51513.3	355314.8	28360.3
0.1	28965.6	109037.2	18940.3
0.2	24166.3	76435.3	16597.4
0.5	18876.0	46295.4	13794.4
1.0	15545.9	30470.0	11873.3
2.0	12701.3	20529.8	10104.3
5.0	9561.9	12747.6	7969.3
10.0	7572.3	9226.6	6477.1
20.0	5843.3	6787.3	5047.0
50.0	3809.9	4301.6	3330.6
80.0	2702.0	3016.6	2434.4
90.0	2328.7	2572.1	2050.9
95.0	2090.5	2383.2	1797.8
99.0	1765.9	2281.4	1402.2

System Statistics
Log Transform: Flow

Statistic	Value
Mean	3.607
Standard Dev	0.204
Station Skew	0.761
Regional Skew	
Weighted Skew	
Adopted Skew	0.761

Number of Events

Event	Number
Historic Events	0
High Outliers	
Low Outliers and Zero Flows	0
Missing Flows	33
Systematic Events	48
Historic Period	81

Figure 38: 1-day Duration B17C Tabular Results Tab

22. Continue by creating Bulletin 17 analyses in a similar fashion for the 2-, 3-, and 4-day durations.

    - *Note*: The analysis period for each of the remaining analyses should span **1936 – 2016**. Using the hydrograph for the 1936 event, the 2-day volume was 9,900 cfs, the 3-day volume was 9,250 cfs, and the 4 day volume was 8,150 cfs.

    - For the **2-day** duration, use a low perception threshold of [**9900** cfs – inf] for each missing period.

    - For the **3-day** duration, use a perception threshold of [**9250** cfs – inf] for each missing period.

    - For the **4-day** duration, use a low perception threshold of [**8150** cfs – inf] for each missing period.

23. Smooth the Bulletin 17C computed at-site standard deviations and skews across multiple durations.

    - *Note*: When fitting a family of flow-frequency curves for multiple durations, it is helpful to plot the mean vs. standard deviation, mean vs. skew, and standard deviation vs. skew for each duration (reference EM 1415). Then, best-fit curves should be used to ensure a smooth transition of the moments/parameters/statistics across the multiple durations. This ensures that the flow-frequency curves will not cross one another (i.e. the 1DAY duration curve should always plot above the 2DAY duration curve, etc.). Typically, the instantaneous peak flow statistics are used to inform the selection of appropriate parameters for longer durations.

24. Plot the computed mean vs. standard deviation, mean vs. skew, and standard deviation vs. skew. The plots should look similar to Figure 39. Also, plot the LPIII parameters versus the duration and make sure the trend is consistent as the duration becomes larger.

- *Note*: Notice the relatively smooth transition across the multiple durations within the Mean vs. Standard Deviation plot. However, notice the abrupt change in skew for the 3-day duration within the Mean vs. Skew and Standard Deviation vs. Skew plots. This abrupt change needs to be smoothed if volume frequency curves cross one another.

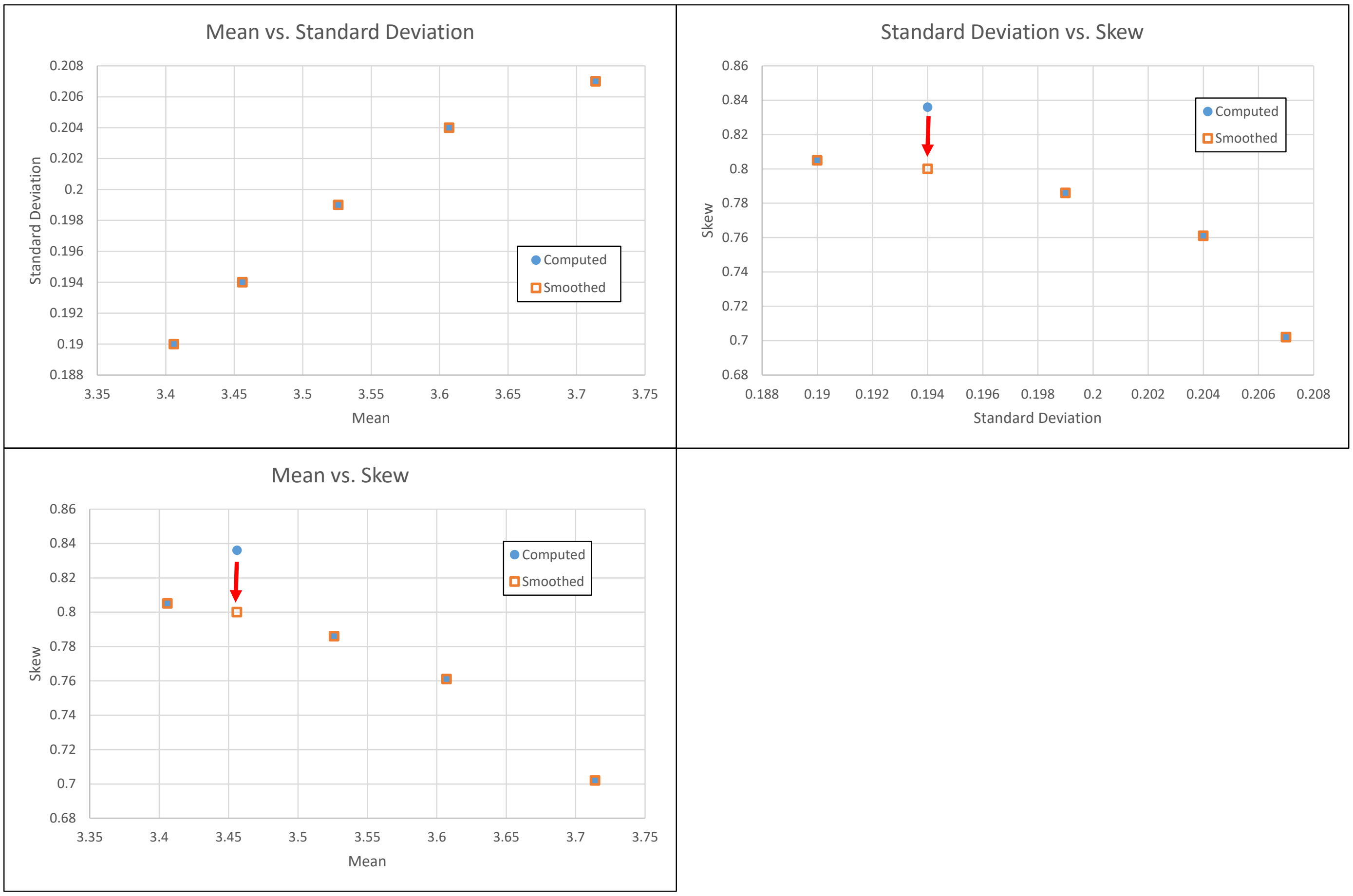


Figure 39: Statistics Smoothing

25. After smoothing the moments/parameters/statistics, the peak flow- and volume-frequency curves must be recomputed to reflect the smoothed statistics, as necessary. In this case, only the 3-day duration needs to be smoothed.

26. Create a new **Bulletin 17** analysis for the 3-day duration by right-clicking on the existing 3-day duration analysis and selecting **Save As…** Enter an appropriate name for the new analysis (i.e. “3day_B17C_smoothed”). On the General tab, select the **Use Regional Skew** option and enter **0.8** and **0.17** for the **Regional Skew** and **Reg. Skew MSE**, respectively. Click **Compute**.

27. The computed curves for each duration need to be combined into a “family” of curves and visualized. The family of curves are plotted to ensure they do not cross one another. The family of curves should look similar to Figure 40.

    - *Note*: This peak flow- and volume-frequency information will be used to inform additional analyses, such as the construction of balanced hydrographs. Also, visualizing the curves together also helps to ensure that the computed moments/parameters of the various analytical distributions are appropriate.

    - These curves and this plot are essential information for dam and levee safety analyses, including Periodic Assessments and SQRAs. The validity of several subsequent analyses and consequently the hydrologic and hydraulic contributions to the SQRA hinge upon the accuracy and validity of this data. Therefore, great care should be taken to include as much valuable information as possible.

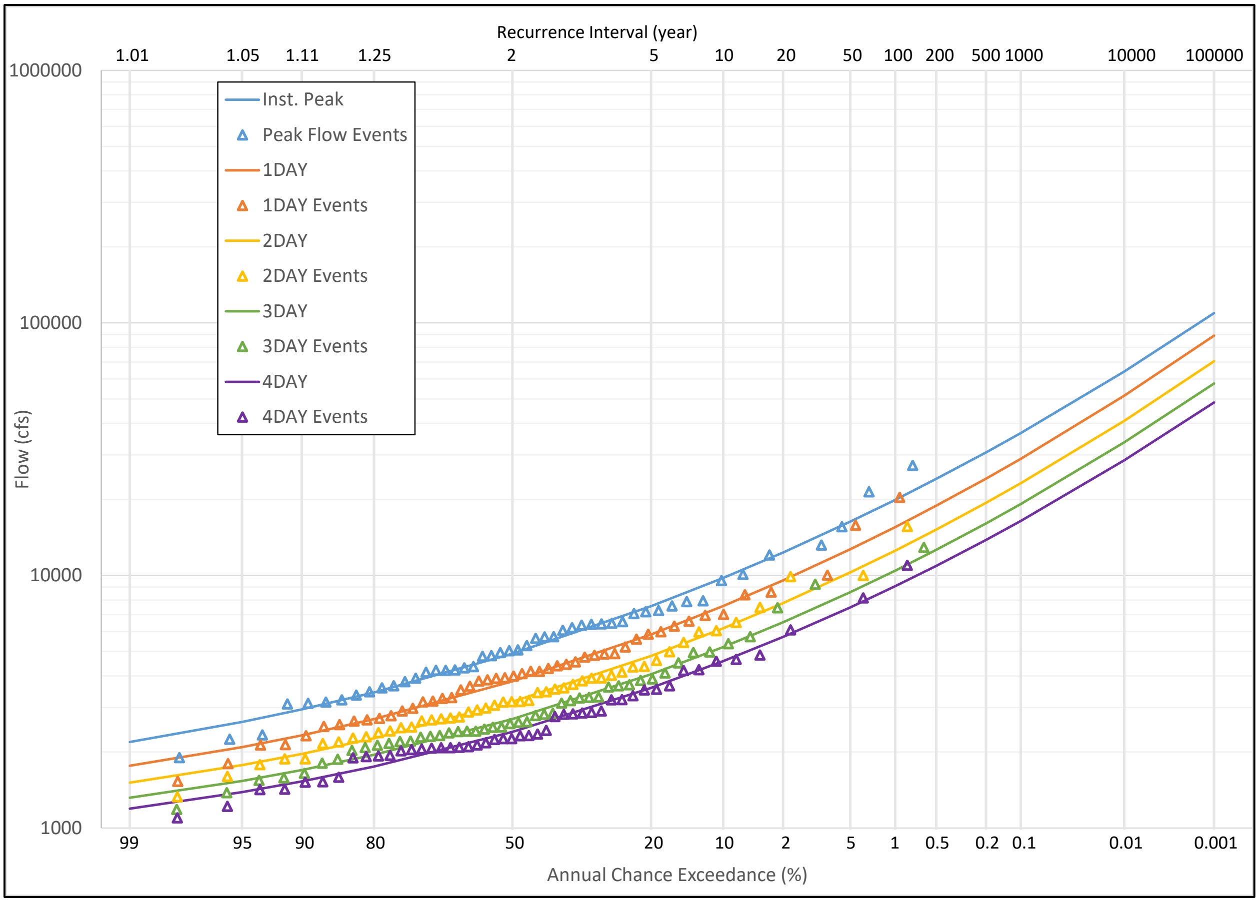


Figure 40: Computed Flow-Frequency Curves

Short Note on Expected Probability

The computed (median) curve represents the uncertainty in due to natural variability, the uncertainty bounds represent the uncertainty due to knowledge uncertainty, whereas the “expected probability of exceedance” curve represents the combined uncertainty due to both natural variability and knowledge uncertainty.

A high degree of knowledge uncertainty due to a short record length results in an asymmetrical distribution for both very high and very low discharges and stages. As a result, the median curve does not adequately represent the long tail of the probability distribution. Therefore, instead of using the median to represent the “best-estimate” probability of exceedance, the mean is used for this analysis. The expected curve is considered the “best-estimate” because it reflects the relative likelihood of all probabilities of a discharge or stage exceeding a certain value, rather than the point where 50% of the exceedance probabilities lie either above or below the median. The expected curve implies that on average the estimated exceedance probability for a given discharge or stage is correct.

Expected probability is expressed as:

$$E[P(X > x_0)] = \lim_{n\to\infty} \frac{\sum 1_{X>x_0}(X)}{n} \qquad \textit{Equation 3}$$

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. *X* is more likely to exceed x_0 for certain combinations of parameters θ of the probability distribution for *X*, which are uncertain because of the limited sample size used to estimate them. For example, the mean, standard deviation and coefficient of skewness of log-transformed streamflow are the parameters of the LPIII distribution. Estimates for these parameters are from a limited sample of annual maximum flows, and so they are uncertain. If they are treated as random variables, then the probability of exceeding a particular flow of x_0 cfs is random. Expected probability is the expected value (or mean) of the probability of exceeding x_0.

USACE policy is that frequency curves used in risk assessment must reflect the expected probability (U.S. Army Corps of Engineers, 1994). Use of the expected curve in a risk analysis ensures that the asymmetry of the sampling uncertainty is properly accounted for and, thus, the resulting expected annual loss of life and expected annual damage are accurate.

An expected probability adjustment was demonstrated in Bulletin 17B; however, the adjustment did not reflect skew uncertainty. At this time it is not appropriate to use the Bulletin 17B expected probability adjustment.

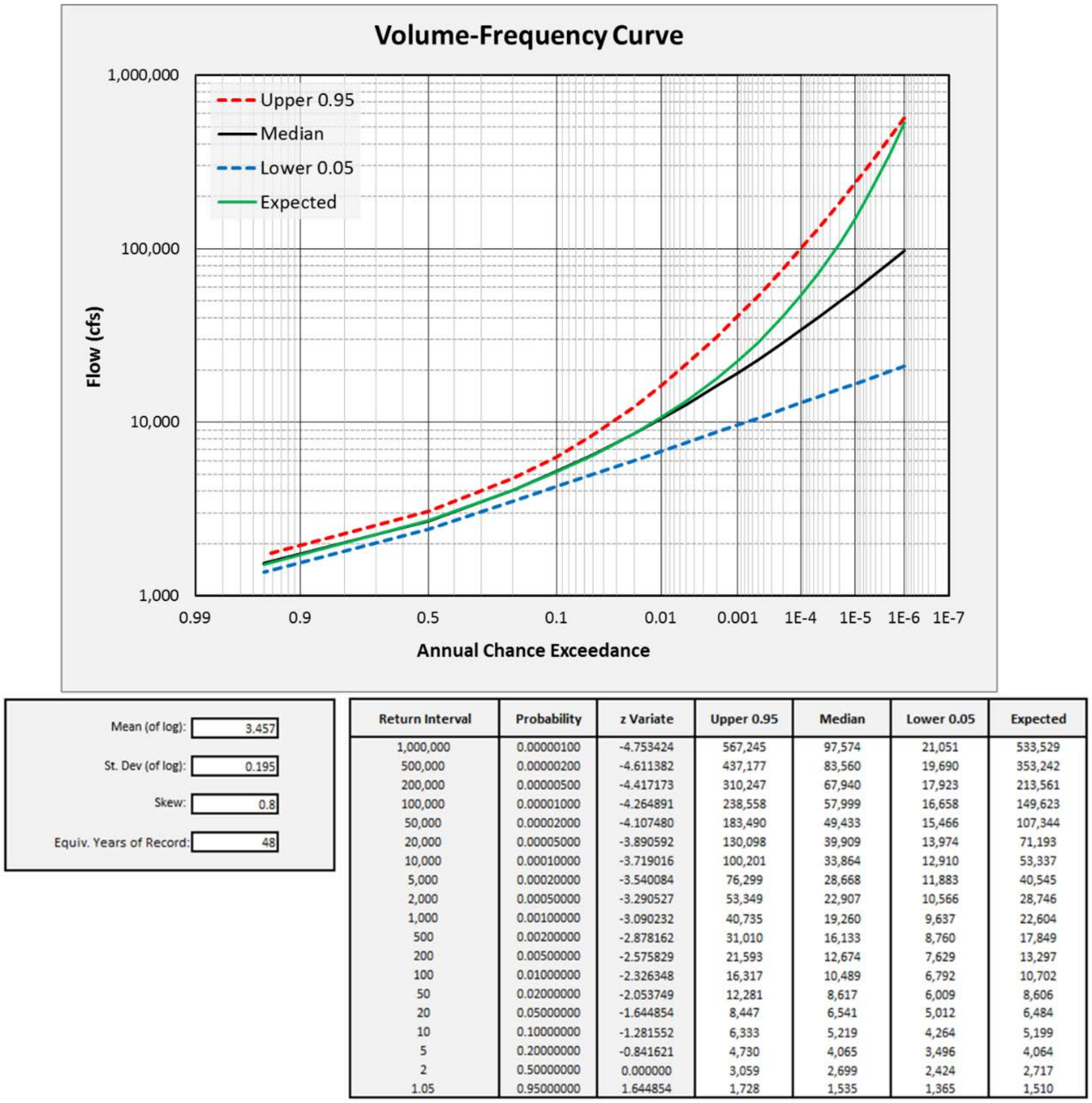
28. The expected probability curves for each duration must be computed using the *STATS_LPIII_ExpectedProbability_v2.0* spreadsheet tool.

29. Input the mean, standard deviation, skew, and equivalent/effective record length for the instantaneous peak duration as computed by HEC-SSP. These should be the smoothed parameters derived above.

30. Click on **Simulate**. The simulation will result in the computation of the **90% Confidence Limits**, **Median**, and **Expected Probability** curves. The entire simulation will require approximately 1 minute to complete. Following completion, the median, upper and lower 90% confidence limits, and expected probability curve will be displayed, as shown in Figure 41.

31. Finally, plot the median curves (as computed using HEC-SSP) and the expected probability curves (as computed using the *STATS_LPIII_ExpectedProbability_v2.0* spreadsheet tool) within the same plot, as shown in Figure 42.

The expected probability curve is the basis for the “best estimate” of the hydrologic hazard for use in the risk estimate for an SQRA. The expected probability curve can be obtained by explicitly modeling the uncertainty in a stochastic or Monte Carlo simulation or it can be obtained by applying an expected probability curve for use in a deterministic model (U.S. Army Corps of Engineers, 1994). Both the median curve (and/or LPIII statistics/moments) and expected probability curves will be used within future analyses. When sampling flow-frequency information within a stochastic analysis, the median curve and/or LPIII statistics with an equivalent record length should be used. However, when computing balanced hydrographs that will then be used in a program that does not consider its uncertainty, such as estimating stage-frequency with a coincident frequency analysis, the expected probability curve should be used in their construction. The expected probability adjustment should be made to flow-, volume-, and/or precipitation-frequency curves when the stage (elevation) frequency relation is derived using the results from deterministic simulations rather than from a stochastic analysis.



Mean (of log):	3.457
St. Dev (of log):	0.195
Skew:	0.8
Equiv. Years of Record:	48

Return Interval	Probability	z Variate	Upper 0.95	Median	Lower 0.05	Expected
1,000,000	0.00000100	-4.753424	567,245	97,574	21,051	533,529
500,000	0.00000200	-4.611382	437,177	83,560	19,690	353,242
200,000	0.00000500	-4.417173	310,247	67,940	17,923	213,561
100,000	0.00001000	-4.264891	238,558	57,999	16,658	149,623
50,000	0.00002000	-4.107480	183,490	49,433	15,466	107,344
20,000	0.00005000	-3.890592	130,098	39,909	13,974	71,193
10,000	0.00010000	-3.719016	100,201	33,864	12,910	53,337
5,000	0.00020000	-3.540084	76,299	28,668	11,883	40,545
2,000	0.00050000	-3.290527	53,349	22,907	10,566	28,746
1,000	0.00100000	-3.090232	40,735	19,260	9,637	22,604
500	0.00200000	-2.878162	31,010	16,133	8,760	17,849
200	0.00500000	-2.575829	21,593	12,674	7,629	13,297
100	0.01000000	-2.326348	16,317	10,489	6,792	10,702
50	0.02000000	-2.053749	12,281	8,617	6,009	8,606
20	0.05000000	-1.644854	8,447	6,541	5,012	6,484
10	0.10000000	-1.281552	6,333	5,219	4,264	5,199
5	0.20000000	-0.841621	4,730	4,065	3,496	4,064
2	0.50000000	0.000000	3,059	2,699	2,424	2,717
1.05	0.95000000	1.644854	1,728	1,535	1,365	1,510

Figure 41: STATS_LPIII_ExpectedProbability_v2.0 Spreadsheet Tool Results for 3-day Duration

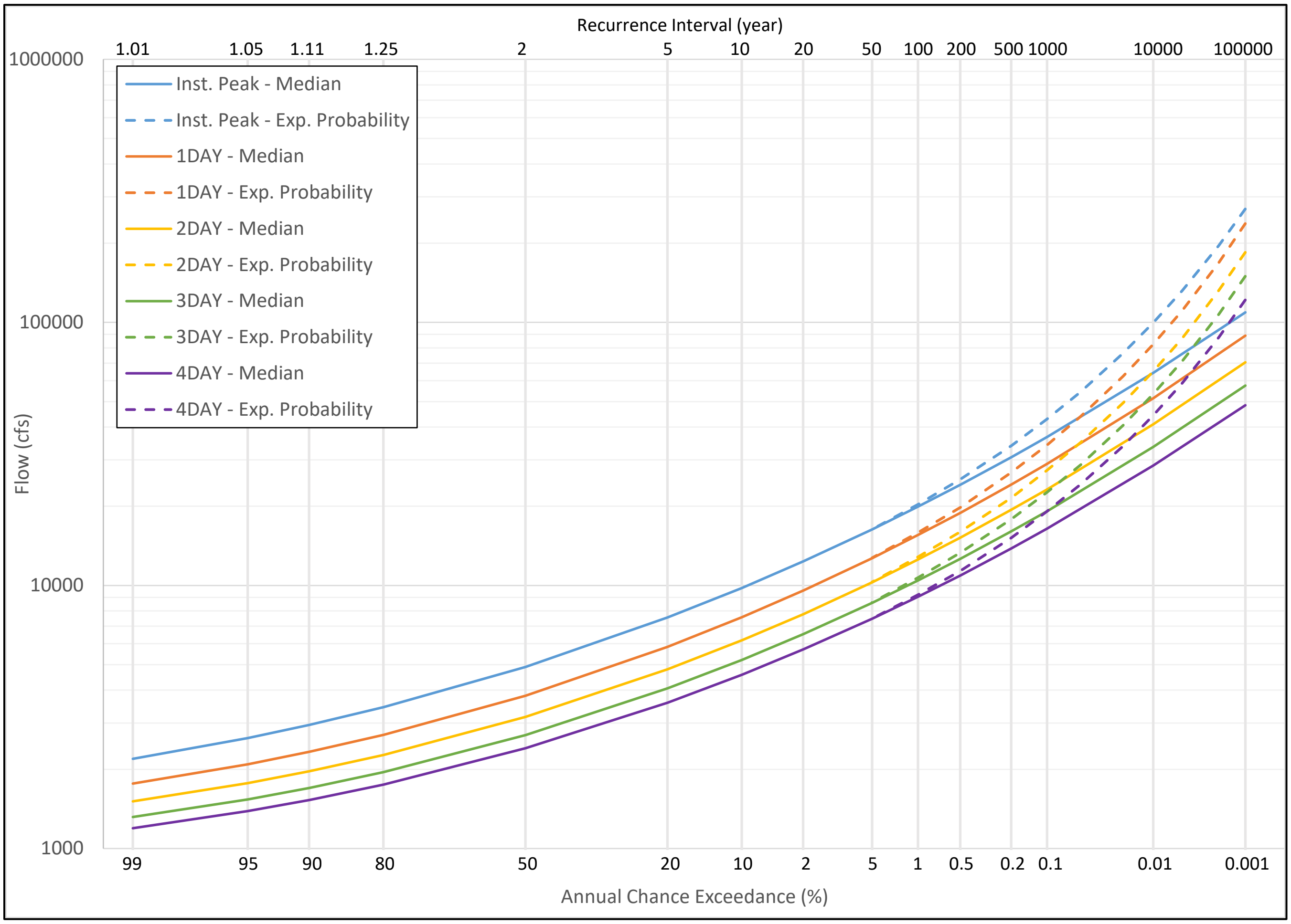


Figure 42: Median vs. Expected Probability

Flood Seasonality Analysis

This chapter discusses the relative frequency of flood events by season, the role it plays in the hydrologic hazard assessment and provides a step-by-step tutorial on determining flood seasonality using the RMC-RFA software.

The term *flood seasonality* is intended to describe the frequency of occurrence of floods on a seasonal basis, where a rare flood is defined as any event where the flow exceeds some user specified threshold for a specified flow duration (MGS Engineering Consultants, Inc., 2009). This approach is commonly referred to as a partial duration series (PDS) or peaks over threshold (POT) method.

Flood seasonality information is required in many applications in hydrology and water resources, such as seasonal streamflow forecasting, flood protection, and water resources infrastructure operations. For the purposes of the hydrologic hazard assessment of dams, flood seasonality information tells us which season an extreme flood event is most likely to occur. The information can also provide insight on mixed populations in meteorology. For example, a reservoir in the west will likely have a snowmelt season and a rainy season.

Flood seasonality information can also be important if the reservoir is operated with seasonal guide curves. In many flood control reservoirs in USACE, the pool is lowered ahead of the rainy season in order to provide more storage ahead of any large flood events. Therefore, the flood seasonality has a significant influence on antecedent reservoir conditions, which will be discuss in the Reservoir Starting Pool Duration Analysis chapter.

Computing Flood Seasonality

The following parameters need to be determined before you can calculate the flood seasonality:

- Threshold Flow
- Critical inflow duration
- Maximum events per year
- Minimum days between events

Threshold flow

The threshold flow defines what magnitude of event will be counted as a flood. With small record lengths, the threshold flow is generally selected as equal to the lowest annual flood so that at least one flood in each year is included (U.S. Geological Survey, 1960). However, in long records, the threshold flow is usually chosen as a flow that corresponds to a specified frequency level (i.e. 2-year, 5-year or 10-year return period) for a specified critical duration to provide a common measure or rareness of the flood.

There are two conflicting goals in selecting a threshold for identifying rare floods:

1) The threshold needs to be high enough so that only primarily large events are considered in the analysis.
2) The threshold needs to be low enough to obtain a dataset large enough to reduce uncertainties arising from sampling error.

Considering the two goals, the threshold needs to be set to as rare a frequency level as possible that will still provide a sufficiently large sample size. Sample sizes of 30-40 flood events are usually adequate.

Determining an appropriate threshold flow to meet this criteria is an iterative process that requires a VDF curve for the critical duration, as described in the previous chapter. An example of this process and the selection of a threshold flow for the Bald Eagle Creek data set can be found below.

Critical inflow duration

The critical inflow duration is discussed in detail in the Critical Inflow Duration Analysis section. The threshold flow corresponds to the critical duration; i.e., the threshold flow represents a moving average flow over a specified duration.

Maximum events per year

This parameter can be used to develop flood seasonality based on an annual maximum series. For example, the threshold flow could be set to zero and the maximum events set to one to derive an annual maximum series.

Minimum days between events

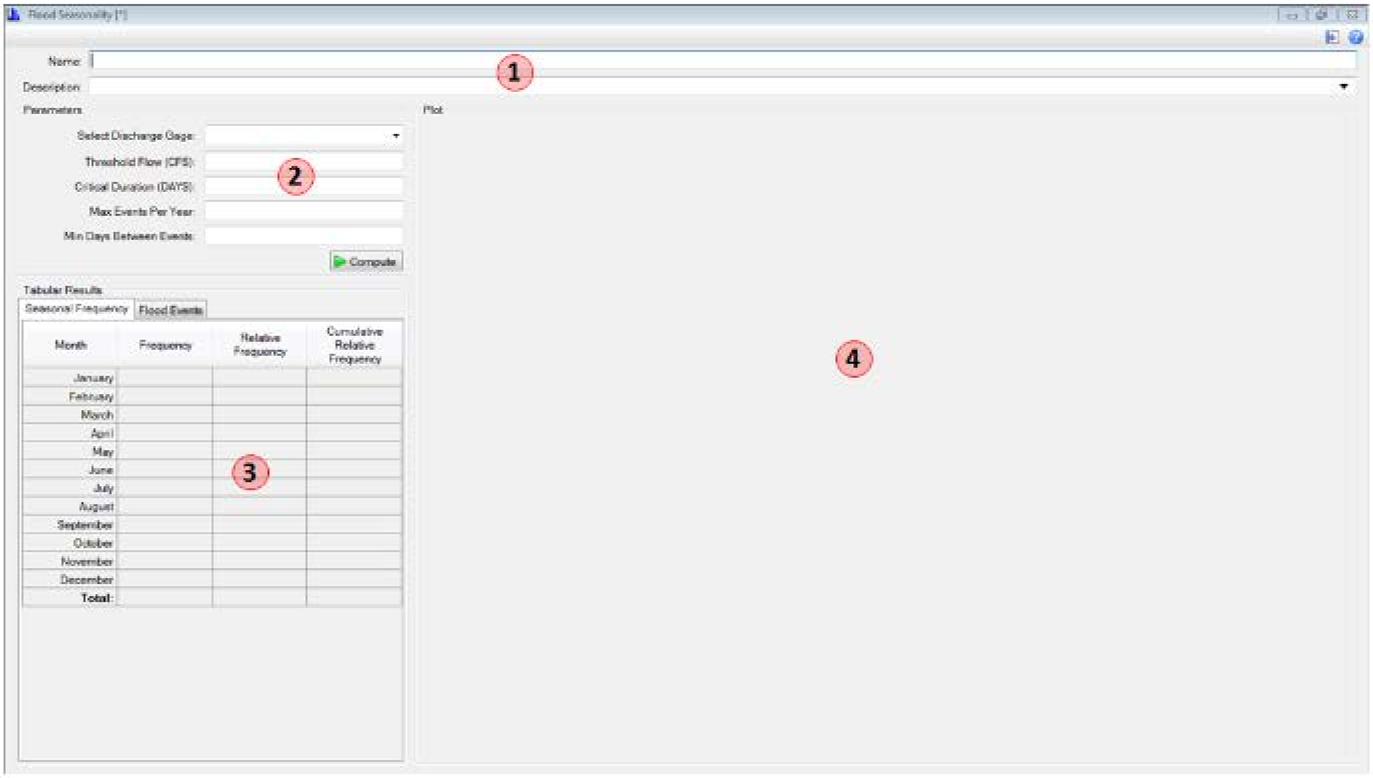
This parameter is used in conjunction with the “Maximum events per year” option. The minimum number of days between events is used to identify independent flood events. For example, if the critical inflow duration is three days, then a minimum of 10 days between events might be sufficient to ensure independence. The minimum number of days between events can be determined by visual inspection of the flow time series to see the typical time between large flow events.

Computing Flood Seasonality Using RMC-RFA

1. Open the RMC-RFA Project File ***Sayers Dam.rfa.sqlite*** and navigate to the Flood Seasonality tab under the analyses folder. Right click and select new.

2. Under the Select Discharge Gage dropdown box select the intended discharge gage reflecting the POR daily average flow to be used for the study.

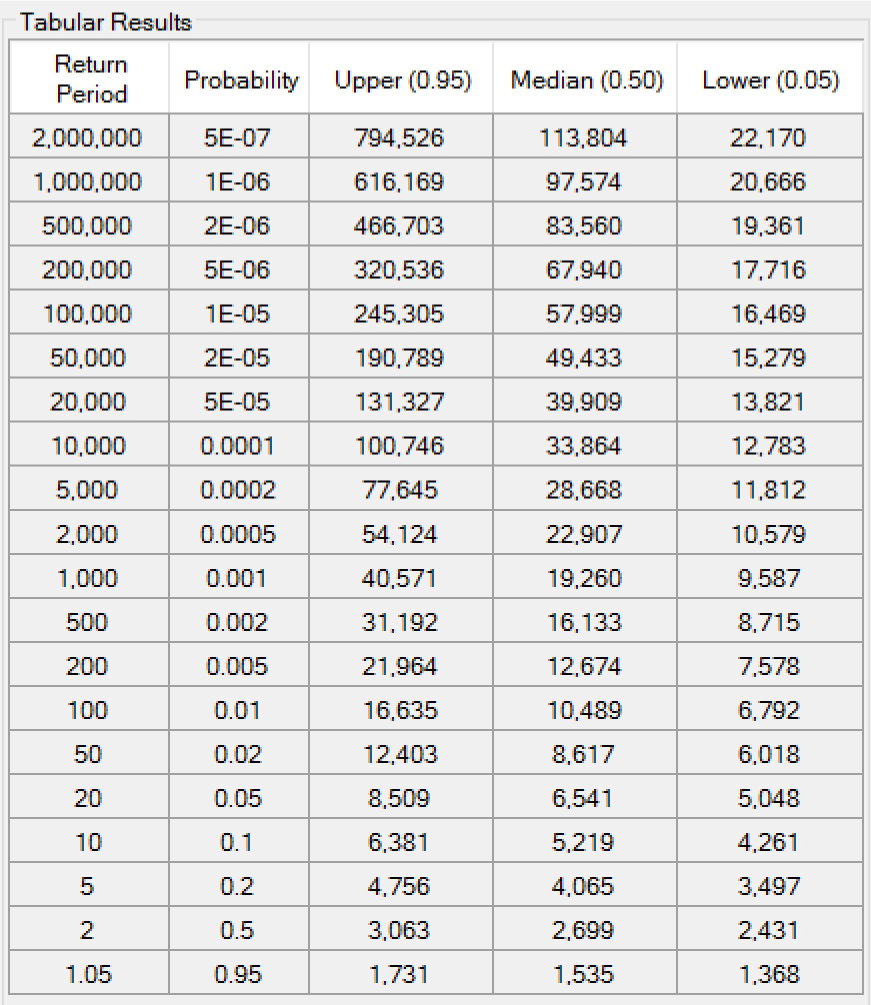
3. Next draw your attention to the remaining four parameters located in the region labeled number 2 as shown in Figure 43 below.



Month	Frequency	Relative Frequency	Cumulative Relative Frequency
January			
February			
March			
April			
May			
June			
July			
August			
September			
October			
November			
December			
Total:			

Figure 43: RMC-RFA Flood Seasonality Analysis Window

4. Determine the **Threshold Flow**.
    - Since the equivalent record length is only 48 years, the 2-yr discharge for the 3-day VDF curve described in the previous section used to establish threshold flow of 2,700 cfs. However, for illustrative purposes our initial guess will be 5,200 cfs, which is the flow that approximately corresponds to the 10% exceedance probability (10-year recurrence flow). Figure 44 shows the probability distribution output for 3-day VDF curve.



Tabular Results

Return Period	Probability	Upper (0.95)	Median (0.50)	Lower (0.05)
2,000,000	5E-07	794,526	113,804	22,170
1,000,000	1E-06	616,169	97,574	20,666
500,000	2E-06	466,703	83,560	19,361
200,000	5E-06	320,536	67,940	17,716
100,000	1E-05	245,305	57,999	16,469
50,000	2E-05	190,789	49,433	15,279
20,000	5E-05	131,327	39,909	13,821
10,000	0.0001	100,746	33,864	12,783
5,000	0.0002	77,645	28,668	11,812
2,000	0.0005	54,124	22,907	10,579
1,000	0.001	40,571	19,260	9,587
500	0.002	31,192	16,133	8,715
200	0.005	21,964	12,674	7,578
100	0.01	16,635	10,489	6,792
50	0.02	12,403	8,617	6,018
20	0.05	8,509	6,541	5,048
10	0.1	6,381	5,219	4,261
5	0.2	4,756	4,065	3,497
2	0.5	3,063	2,699	2,431
1.05	0.95	1,731	1,535	1,368

Figure 44: Volume Frequency Curve Tabular Results

5. Input the **Critical Duration** based on the guidance in the Critical Inflow Duration Analysis section. Critical duration for Sayers Dam is 3 days.

6. Input the **Maximum Events Per Year.** If you are unsure how many data points your initial flow threshold will yield you can start with 5 events per year. However, for a more educated guess you can plot the flow data in HEC-DSS as seen below.

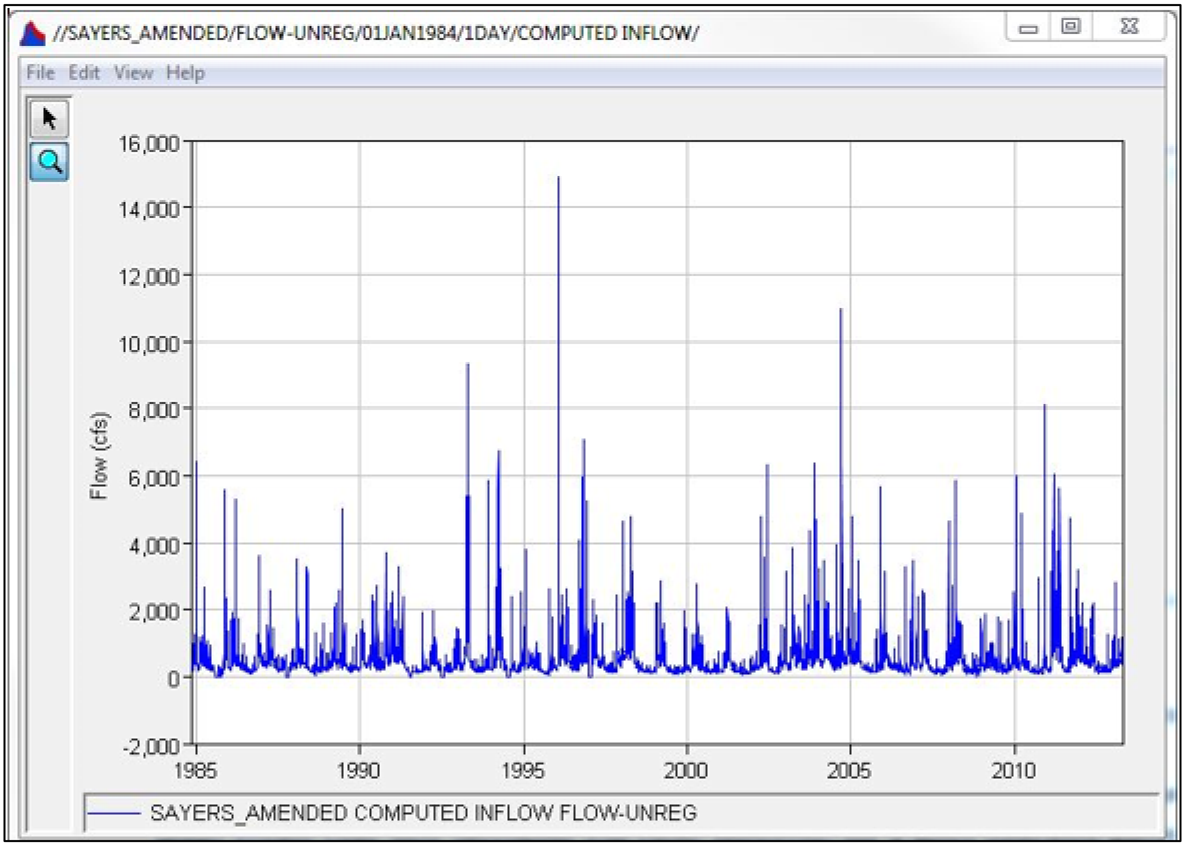
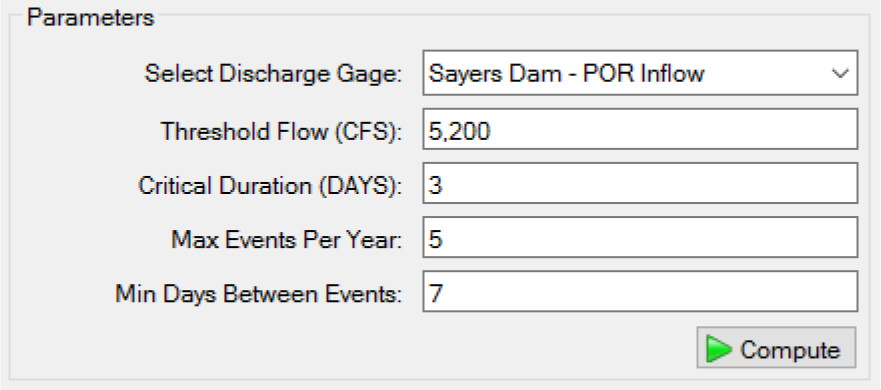


Figure 45: Period of Record Daily Average Flow Data

- Inspect the record. Estimate the number of events per year that are greater than your flow threshold.

7. Input the **Minimum Days Between Events** based on the guidance above.

8. After you have entered all parameters, your input parameter list should look like Figure 46.



Parameters

Select Discharge Gage: Sayers Dam - POR Inflow

Threshold Flow (CFS): 5,200

Critical Duration (DAYS): 3

Max Events Per Year: 5

Min Days Between Events: 7

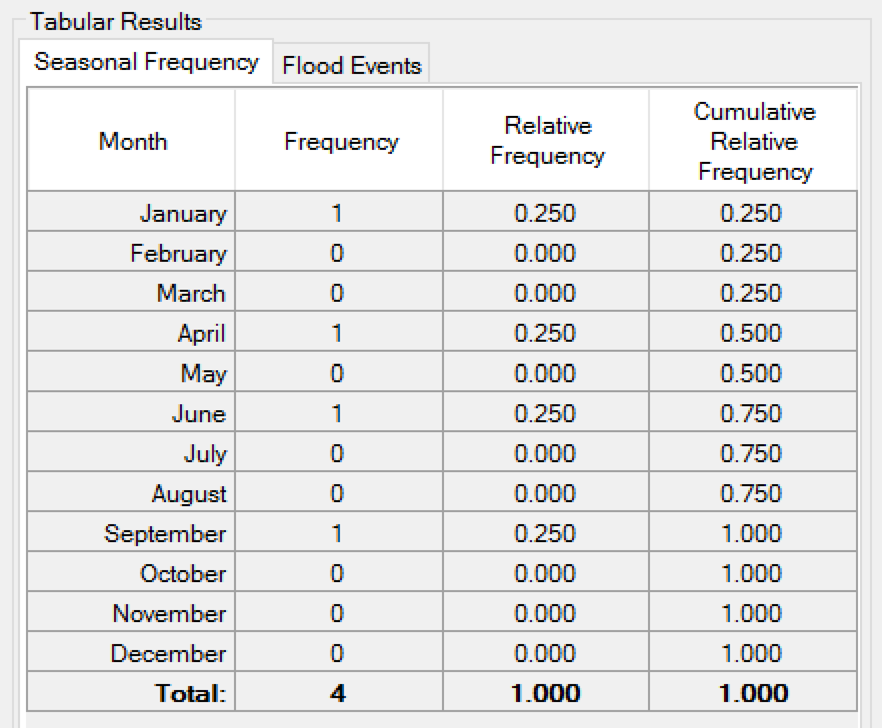
Figure 46: RMC-RFA Flood Seasonality Input Parameters

- Select the **Compute** button, if you are satisfied with your inputs**.** Now you can view the flood seasonality histogram and verify that you have as many events represented as possible (again, at least 30 events is recommended) by reviewing the results.

9. Review your results.

   - The first thing you will notice is that with a flow threshold of 5,200 cfs our analysis only yields four records, which is unacceptable.

   - If the total number of output data points are less than 30 then go back to the **Flow Threshold** parameter and adjust the flow threshold or the number of maximum events per year. Select a more commonly recurring flow threshold such as 2,700 cfs, which is the 2-year recurrence flow (50-percent chance exceedance flow).

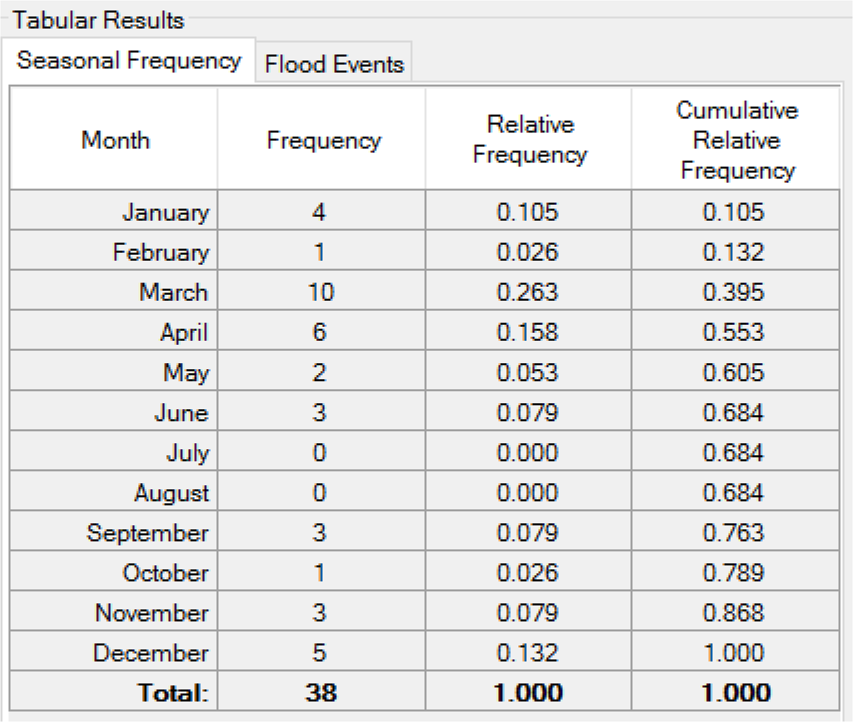


Month	Frequency	Relative Frequency	Cumulative Relative Frequency
January	1	0.250	0.250
February	0	0.000	0.250
March	0	0.000	0.250
April	1	0.250	0.500
May	0	0.000	0.500
June	1	0.250	0.750
July	0	0.000	0.750
August	0	0.000	0.750
September	1	0.250	1.000
October	0	0.000	1.000
November	0	0.000	1.000
December	0	0.000	1.000
Total:	**4**	**1.000**	**1.000**

Figure 47: RMC-RFA Flood Seasonality Stats Using 5,200 cfs for Threshold Flow

   - Notice now that with a flow threshold of 2,700 cfs we have increased our data points to 38. You can view which events were extracted in the **Flood Events tab** (located to the right of the **Seasonal Frequency** tab) and verify that the events listed accurately represent your period of record.

   - Conversely, if the initial parameter estimates produce more than twice the equivalent record length, which would be 100 in this case, you will want to increase the flow threshold to ensure that you are truly representing the largest flow events.



Month	Frequency	Relative Frequency	Cumulative Relative Frequency
January	4	0.105	0.105
February	1	0.026	0.132
March	10	0.263	0.395
April	6	0.158	0.553
May	2	0.053	0.605
June	3	0.079	0.684
July	0	0.000	0.684
August	0	0.000	0.684
September	3	0.079	0.763
October	1	0.026	0.789
November	3	0.079	0.868
December	5	0.132	1.000
Total:	**38**	**1.000**	**1.000**

Figure 48: RMC-RFA Flood Seasonality Analysis Using 2,700 cfs for Threshold

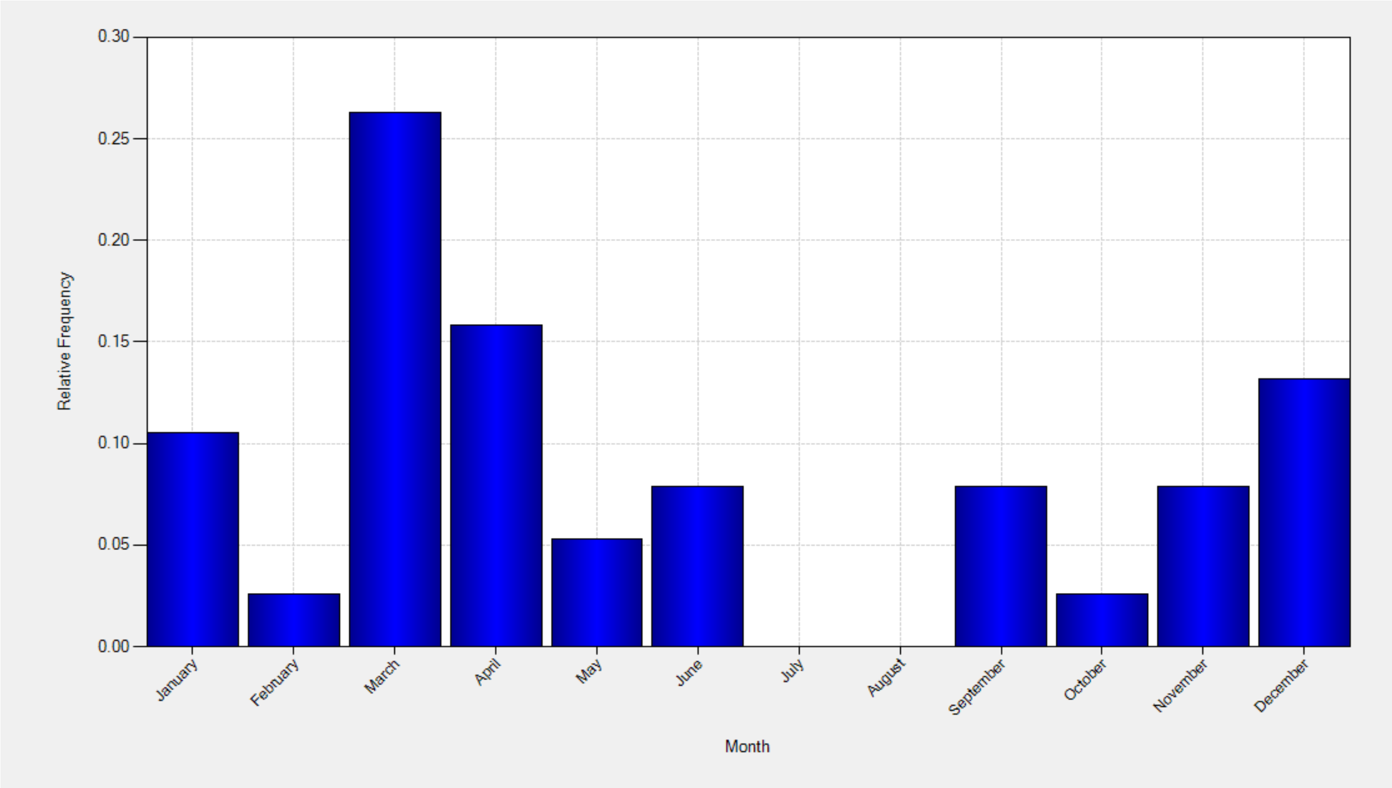


Figure 49: RMC-RFA Flood Seasonality Analysis Histogram Using 2,700 cfs for Threshold

According to the water control manual (U.S. Army Corps of Engineers, 1996), the most notable storms occurred in May 1889, May 1894, March 1936, May 1946, November 1950, August 1955, June 1972, September 1975, and January 1996. The storm of March 1936 produced the greatest flood of record along the upper portions of the West Branch Susquehanna River. Major floods on Bald Eagle Creek can occur at any time during the year. However, most floods are associated with runoff produced by tropical disturbances or by snowmelt concurrent with heavy rainfall in the spring months. Table 4-03 in the water control manual lists the maximum, minimum, and mean monthly runoff statistics for the period of record at the Milesburg gage on Bald Eagle Creek up to 1996, and is provided below in Figure 50 and Figure 51. As can be seen, the flood seasonality results from RMC-RFA are consistent with the climate and flood runoff characteristics of the watershed.

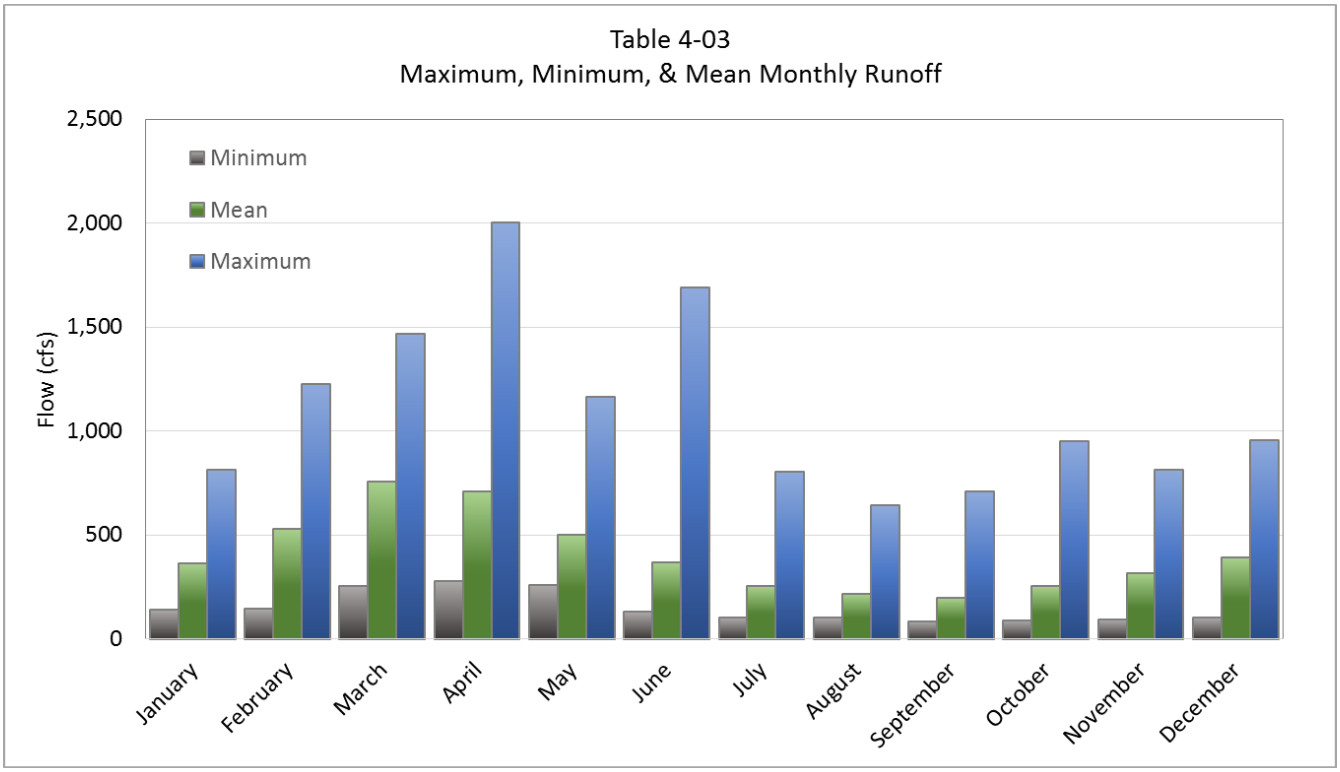


Figure 50: Maximum, Minimum, and Mean Monthly Runoff Statistics at the Milesburg Gage

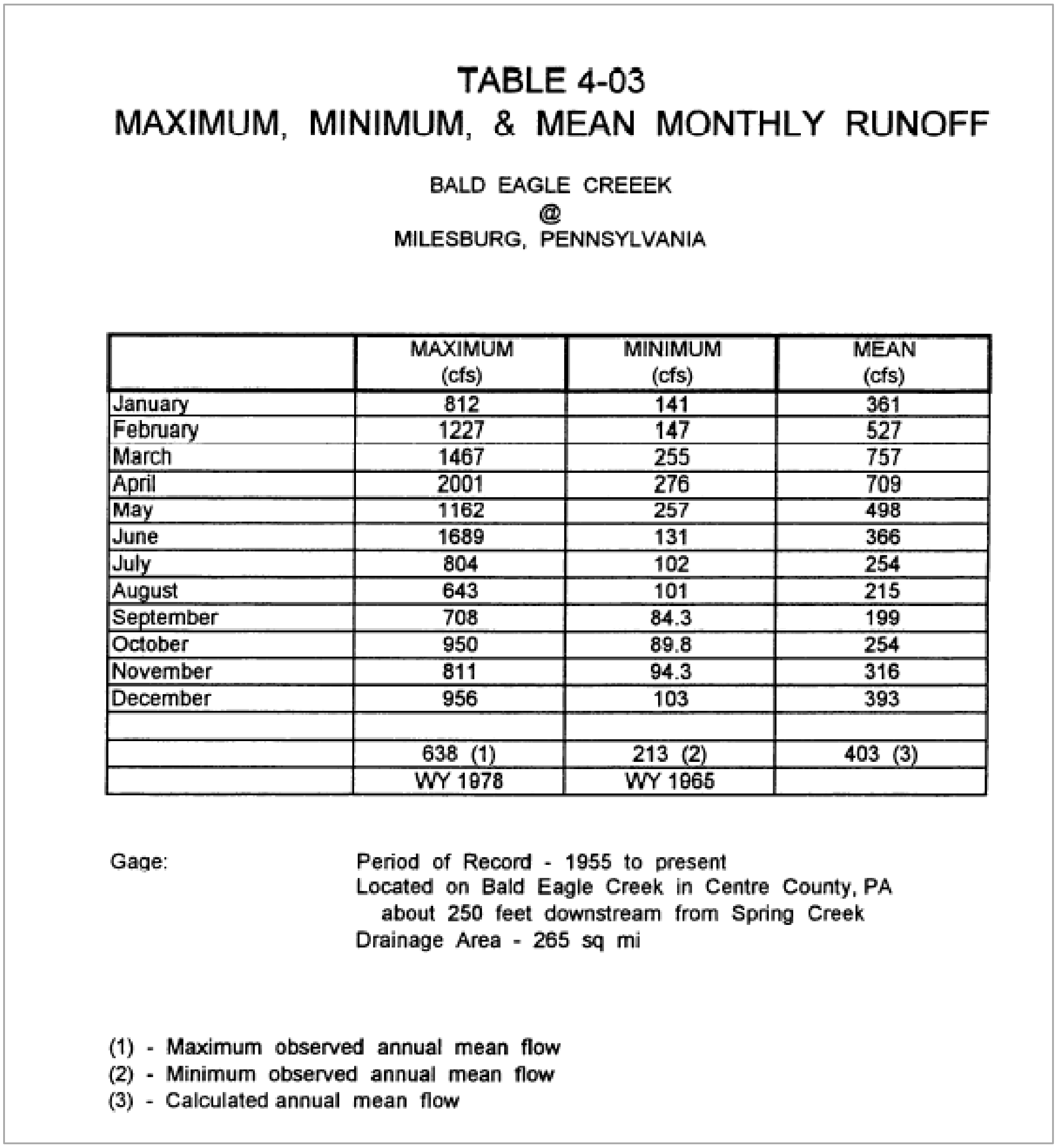


TABLE 4-03
MAXIMUM, MINIMUM, & MEAN MONTHLY RUNOFF

BALD EAGLE CREEEK
@
MILESBURG, PENNSYLVANIA

	MAXIMUM (cfs)	MINIMUM (cfs)	MEAN (cfs)
January	812	141	361
February	1227	147	527
March	1467	255	757
April	2001	276	709
May	1162	257	498
June	1689	131	366
July	804	102	254
August	643	101	215
September	708	84.3	199
October	950	89.8	254
November	811	94.3	316
December	956	103	393
	638 (1)	213 (2)	403 (3)
	WY 1978	WY 1965	

Gage:	Period of Record - 1955 to present Located on Bald Eagle Creek in Centre County, PA about 250 feet downstream from Spring Creek Drainage Area - 265 sq mi

(1) - Maximum observed annual mean flow
(2) - Minimum observed annual mean flow
(3) - Calculated annual mean flow

Figure 51: Table 4-03 from Foster Joseph Sayers Regulation Manual

Reservoir Starting Pool Duration Analysis

This chapter discusses the antecedent reservoir pool conditions, the role it plays in the hydrologic hazard assessment and provides a step-by-step tutorial on determining reservoir starting pool duration curves using the RMC-RFA and HEC-SSP.

Pool duration curves represent the percent of time during which specified reservoir pools are exceeded at a reservoir of interest. Ordinarily, daily variations in pools are inconsequential, so duration curves are typically developed using observed daily average reservoirs pools.

Reservoir starting pool duration curves represent the percent of time during which antecedent reservoir pools are exceeded. Starting pool duration curves are developed by first filtering observed daily average pools associated with historical flood events, so that they only represent typical starting pools. Then, the filtered data set is sorted by month or season.

Pool duration information is required for many applications in the risk assessment of dams. For seismic potential failure modes, duration information is used to estimate the conditional probability of different pool elevations when an earthquake occurs. Annual duration is typically used because it is assumed that the earthquake can occur at any random time during a given year. The risk estimate for seismic PFMs are annualized by the seismic load probability. It is important to note that these estimates are not annual probability estimates, but simply the percentage of time the reservoir has exceeded user-defined elevations.

On the other hand, for the purposes of the hydrologic hazard assessment of dams, reservoir starting pool duration curves are used to derive reservoir stage-frequency curves by combining uncertainty in the inflow flood event with the uncertainty of the pool at the start of the flood event.

Computing Reservoir Starting Pool Duration Curves

In short, pool duration curves are developed by ranking mean-daily stages from largest to smallest, and assigning an empirical plotting position to estimate the percentage of data of record mean-daily stages exceed a specific magnitude (Engineer Manual 1110-2-1420, Hydrologic Engineering Requirements for Reservoirs, 1997).

In this chapter, two methods for computing starting pool duration will be shown: 1) Using RMC-RFA, and 2) using HEC-SSP for use in coincident frequency analysis or seismic potential failure mode analysis.

Computing Starting Stage Duration Using RMC-RFA

The following parameters need to be determined before you can calculate the reservoir starting pool of the period of record in RMC-RFA. The following bulleted items will be described in the following two paragraphs.

- Pool Change Threshold
- Typical High Pool Duration

Pool Change Threshold

The pool change threshold represents the maximum rate of rise of the pool per day. It will allow the starting pool elevation to be populated from daily elevations that are theorized to occur prior to any given flood event by essentially deleting all stage hydrographs that rise or fall faster than the entered threshold as would a flow hydrograph behaving under flood event. If a large threshold value is chosen, you may artificially drive your starting pool too high as it takes in to account flood events where stages tend to rise quickly; i.e., the threshold will capture the larger or flashier floods, but miss the smaller events. An appropriate pool change threshold can by determined by visual inspection of a stage hydrograph from a normal rainfall year; i.e., a year where the reservoir was operated normally because there was no significant flood events. An example of this is described as follows.

First, inspect the period of record. Choose a year without a significant event and inspect the stage hydrograph from that year. You can then estimate the rate of pool change per day from the hydrograph. It may be beneficial to review several normal years and take an average daily rate of rise. The normal rate of rise can be compared to a hydrograph from an event year where the stage should be rising much faster.

For example, the Sayers Dam stage hydrograph show below in Figure 52 is taken from the spring of 1999, a normal precipitation year. The rate of rise per day is shown in Table 5. The maximum rate of rise is about 2 feet per day. After repeating this process for the years 2000 and 2001, also years with normal rainfall, it is determined that approximately 2 feet per day is indeed a good estimation for maximum normal rate of rise for this project. As you can see in Figure 53 and Table 6, the hydrograph taken from the September 2004 shows a much faster rate of rise, consistent with a flood event. Sensitivity runs should be made to determine the appropriate threshold that meets the above criteria.

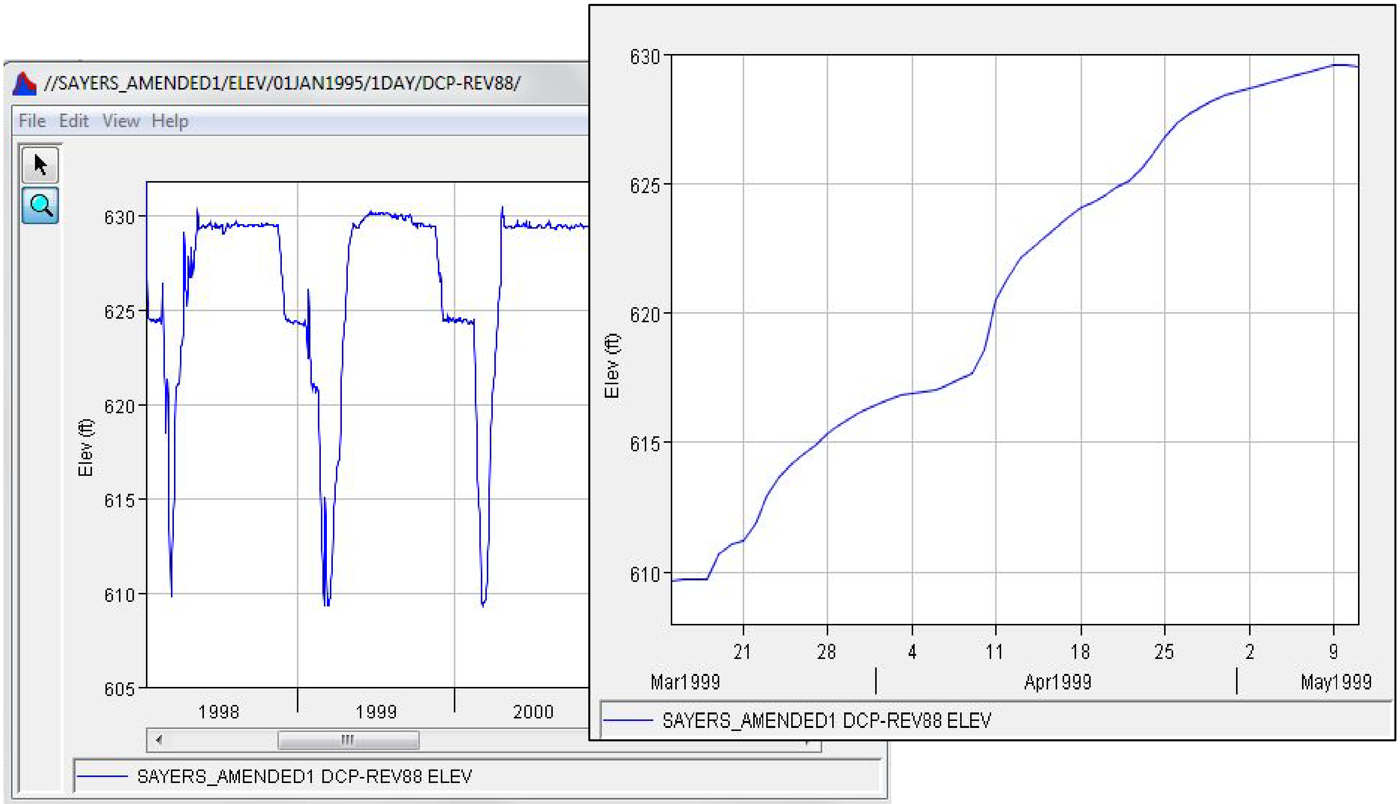


Figure 52: Foster Joseph Sayers Dam Stage Hydrograph for the Spring of 1999

Table 5: Rate of Change in Stage for Spring of 1999

Date	Stage (ft)	Rate of Change
30Mar1999	616.25	0.172
31Mar1999	616.42	0.210
01Apr1999	616.63	0.180
02Apr1999	616.81	0.086
03Apr1999	616.90	0.074
04Apr1999	616.97	0.076
05Apr1999	617.05	0.162
06Apr1999	617.21	0.240
07Apr1999	617.45	0.240
08Apr1999	617.69	0.876
09Apr1999	618.56	1.938
10Apr1999	620.50	0.892
11Apr1999	621.39	0.720

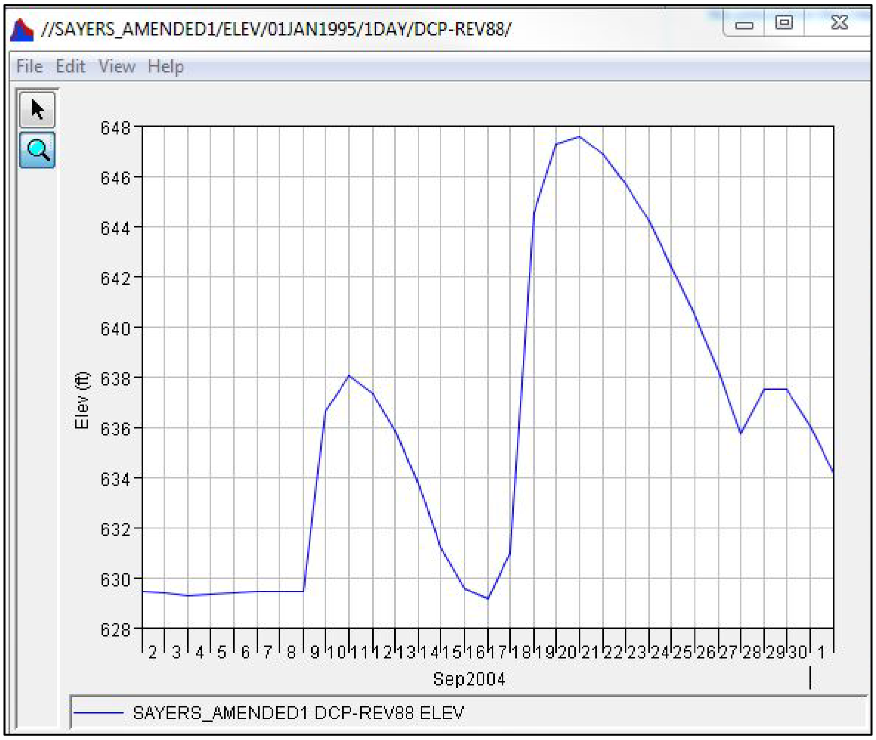


Figure 53: Foster Joseph Sayers Dam Stage Hydrograph for the Fall of 2004

Table 6: Rate of Change in Stage for Fall of 2004

Date	Stage (ft)	Rate of Change
16Sep2004	629.14	1.830
17Sep2004	630.97	13.535
18Sep2004	644.51	2.755
19Sep2004	647.26	0.270
20Sep2004	647.53	-0.675

High Pool Duration

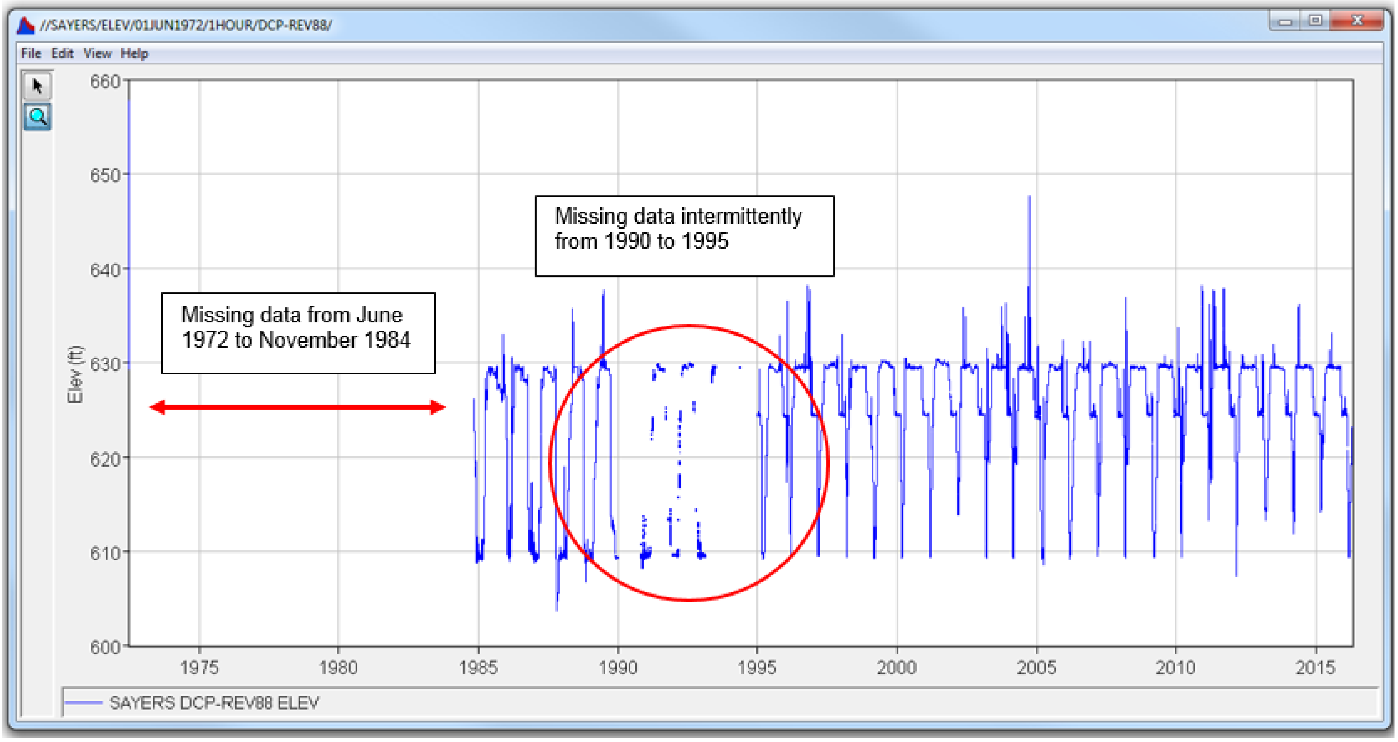
Similar to the pool change threshold, the high pool duration is another parameter used to filter out large events for the purpose of distilling the record to only the typical starting pool elevations. This parameter is needed to avoid clipping out long durations of higher pools that are associated with normal changes in guide curves. This **Typical High Pool Duration** parameter can be determined by visual inspection. In this case, chose an event stage hydrograph and visually inspect how many days the high pool typically lasts following a flood event. Again, it may be beneficial to analyze several event hydrographs, if they are available, and take an average of the high pool durations. From inspection of historical events, it is determined that the high pool duration for Foster Joseph Sayers Dam is 10 days.

Using RMC-RFA

1. Open the RMC-RFA Project File ***Sayers Dam.rfa.sqlite*** *and navigate to the Reservoir Starting Pool Duration tab*. Right click and select new.

2. Select the Stage Gage containing the correct daily elevation data being used for the analysis, which in this case is ***Sayers Dam – POR Stage***.

    - As discussed in the Initial Data Analysis chapter, the period of record stage data had missing data from June 1972 to November 1984. In addition, there was missing data intermittently from 1990 to 1995 as shown below in Figure 54. As such, the period of record data used for the stage duration analysis only uses data from January 1995 to 2016.

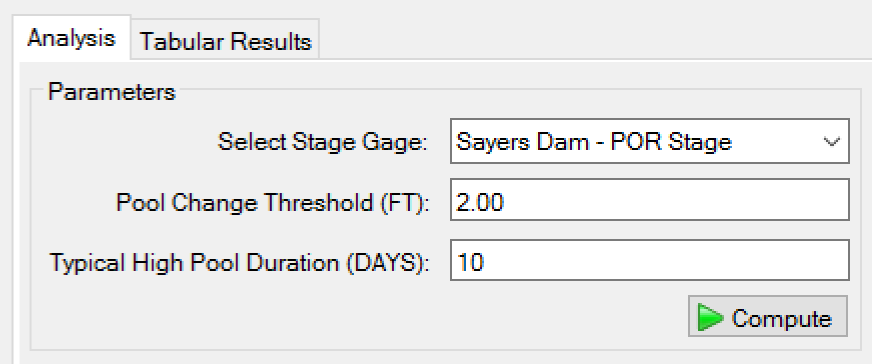


Missing data from June 1972 to November 1984

Missing data intermittently from 1990 to 1995

Figure 54: Plot of Hourly Period of Record Stage Data for Foster Joseph Sayers Dam

3. Enter the pool change threshold of 2 feet per day, and enter the high pool duration of 10 days as shown in Figure 55.



Select Stage Gage: Sayers Dam - POR Stage

Pool Change Threshold (FT): 2.00

Typical High Pool Duration (DAYS): 10

Figure 55: Reservoir Starting Stage Duration Parameters.

4. Select the **Compute** button. To the right of the parameters you will see a plot of the starting stage data plotted with the original, unfiltered stage data as shown in Figure 56. Figure 57 shows a zoomed in plot for the fall and winter of 2003. You can see how effective the input parameters are for removing the stage data associated with floods.

    - *Note:* You can zoom in on any part of the graph by right clicking and selecting zoom. Additionally, any elevation data point can be recalled by selecting the “cross hairs” button as well.

    - You can view **Tabular Result output** data on the next tab just to the right of the Analysis tab.

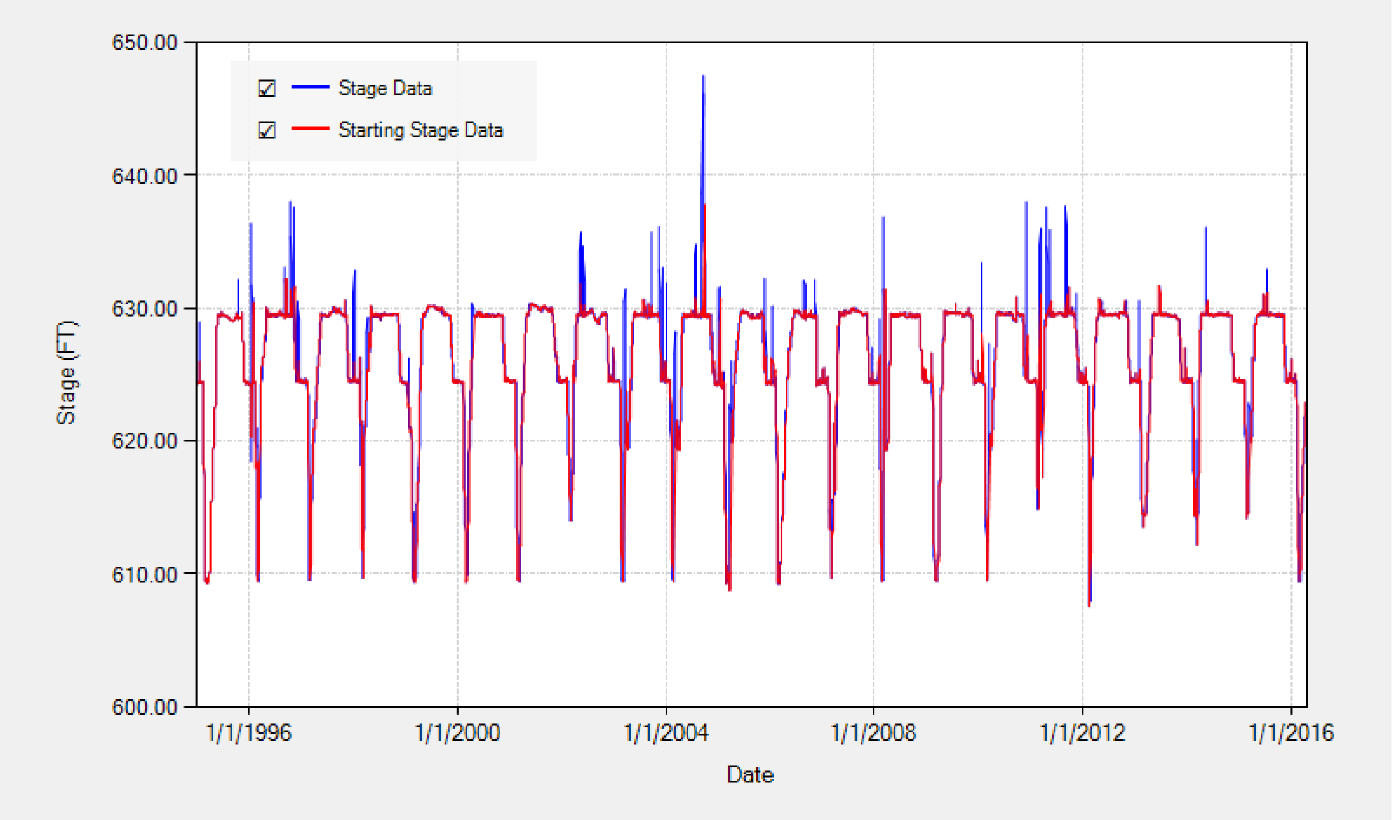


Figure 56: Reservoir Starting Stage Duration Analysis Result Plot

Figure 57: Zoomed Reservoir Starting Stage Duration Analysis Result Plot

5. Select the **Duration Curves** tab located within the Plot window.

   - View the **Duration Curves**. It is recommended that you view all seasonal curves independently and simultaneously by toggling between the months in the box within the plot. Ensure that your curve elevations are consistent with the seasonal reservoir operations found in the water control manual.

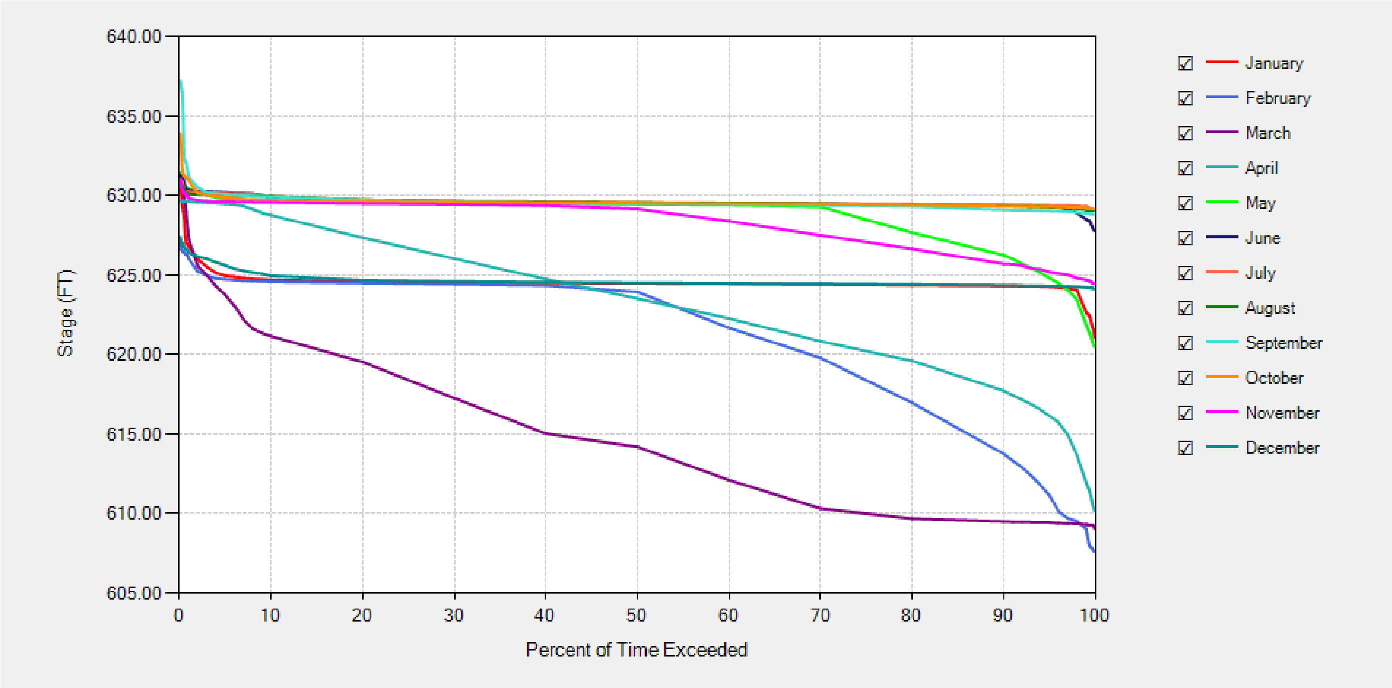


Figure 58: Duration Curves Output Plot

The reservoir elevation guide curve for Foster Joseph Sayers Dam is shown on Plate 7-01 of the water control manual (U.S. Army Corps of Engineers, 1996) and is shown below in Figure 59. Looking at the duration curve results above, you will notice that March produces the lowest pool duration curve. This makes sense because, as you can see from the guide curves below, the lake is lowered to elevation 610 to provide the full flood control capacity of the project. The lake remains at elevation 610 through most of March in anticipation of the spring snowmelt runoff and the associated risk in flooding.

This is important because as we saw in the Flood Seasonality Analysis chapter, floods are most likely to occur in March. However, the dam is operated with consideration of this flood seasonality. Therefore, large events are most likely to occur in March, but they are also most likely to have low reservoir starting pools, mitigating some of the risk for large peak stage events in the spring season.

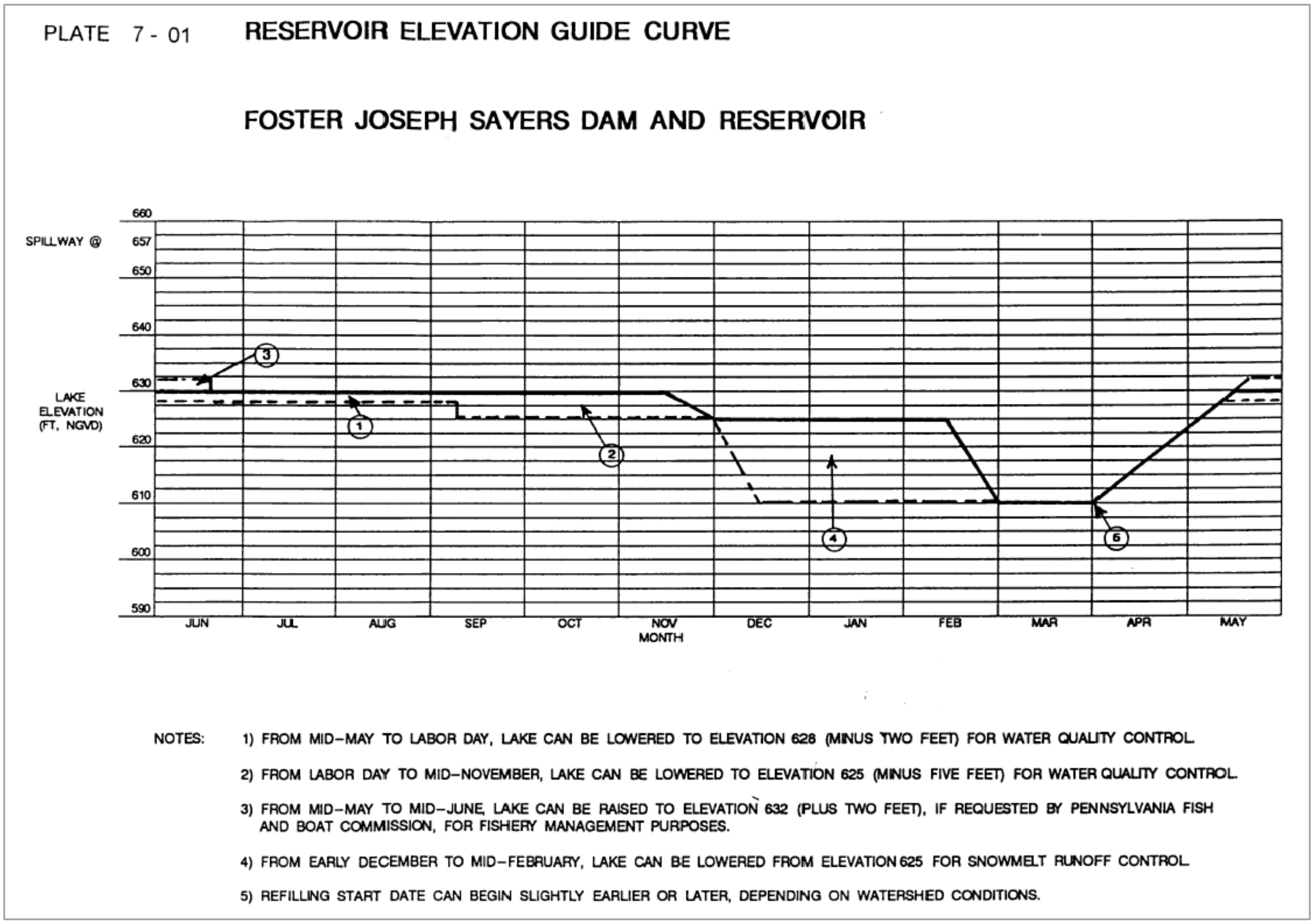


PLATE 7 - 01 **RESERVOIR ELEVATION GUIDE CURVE**

FOSTER JOSEPH SAYERS DAM AND RESERVOIR

NOTES:

1) FROM MID–MAY TO LABOR DAY, LAKE CAN BE LOWERED TO ELEVATION 628 (MINUS TWO FEET) FOR WATER QUALITY CONTROL.

2) FROM LABOR DAY TO MID–NOVEMBER, LAKE CAN BE LOWERED TO ELEVATION 625 (MINUS FIVE FEET) FOR WATER QUALITY CONTROL.

3) FROM MID–MAY TO MID–JUNE, LAKE CAN BE RAISED TO ELEVATION 632 (PLUS TWO FEET), IF REQUESTED BY PENNSYLVANIA FISH AND BOAT COMMISSION, FOR FISHERY MANAGEMENT PURPOSES.

4) FROM EARLY DECEMBER TO MID–FEBRUARY, LAKE CAN BE LOWERED FROM ELEVATION 625 FOR SNOWMELT RUNOFF CONTROL.

5) REFILLING START DATE CAN BEGIN SLIGHTLY EARLIER OR LATER, DEPENDING ON WATERSHED CONDITIONS.

Figure 59: Plate 7-01 from Foster Joseph Sayers Regulation Manual

Computing Pool Duration Curves Using HEC-SSP

This section demonstrates how to compute an all season pool duration curve using HEC-SSP for use in coincident frequency analysis or seismic potential failure mode analysis, using the starting pool output from RMC-RFA.

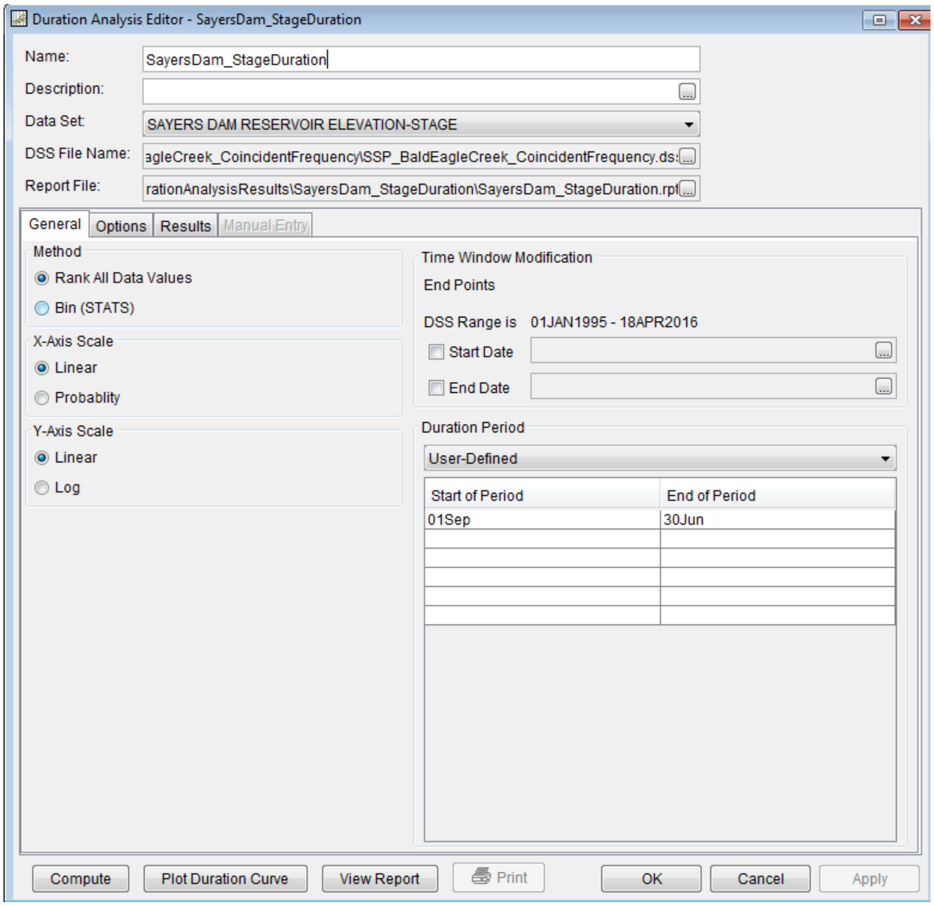
1. Create a new HEC-SSP project, or use the project where peak flow and volume frequency curves were already computed. Import the starting pool values found in **the Stage Data Table** from the RMC-RFA starting stage duration analysis as a new data source into HEC-SSP. Use the **Data Importer** to import the stage values from a HEC-DSS file or manually import by pasting the information from the Excel spreadsheet to the Data Importer, Manual Entry table, or copying and pasting the data directly from RMC-RFA.

2. Created a new Duration Analysis by right clicking on the Duration Analysis folder in the project tree and selecting the **New…** option.

3. As shown in Figure 60, enter a **Name** for the duration analysis and select a **Data Set**. On the **General** tab, make sure the “Rank All Data Values” method is selected. Select the “Linear” option for both x and y axes since reservoir stage data is being analyzed.

4. The **Time Window Modification** option can be used to screen unwanted values from inconsistent reservoir operations. If the stage data set only includes stage values from the current reservoir control manual then no time window modification is needed; however, if the reservoir operations have changed, then a time window should be entered for the period representing the most current reservoir operation scheme.

5. The **Duration Period** option can be used to select only the flood season. As shown in Figure 60, the typical flood season (historically when large floods have occurred) for the Sayers Dam watershed is from September 1 through June 30. HEC-SSP will only use stage values within this time period when computing the duration curve.


Duration Analysis Editor - SayersDam_StageDuration

Name: SayersDam_StageDuration
Description:
Data Set: SAYERS DAM RESERVOIR ELEVATION-STAGE
DSS File Name: agleCreek_CoincidentFrequency\SSP_BaldEagleCreek_CoincidentFrequency.ds
Report File: rationAnalysisResults\SayersDam_StageDuration\SayersDam_StageDuration.rpt

Method
● Rank All Data Values
○ Bin (STATS)

X-Axis Scale
● Linear
○ Probablity

Y-Axis Scale
● Linear
○ Log

Time Window Modification
End Points
DSS Range is 01JAN1995 - 18APR2016
☐ Start Date
☐ End Date

Duration Period
User-Defined

Start of Period	End of Period
01Sep	30Jun

Figure 60: HEC-SSP Duration Analysis Editor, General Tab

6. The **Options** tab contains a few additional options for the Duration Analysis. You can enter the data type and units if this information was not correctly defined in the HEC-DSS record (HEC-SSP reads the information in the HEC-DSS file and automatically populates the data type and units). The **User Defined Exceedance Ordinates** table is used for reporting the computed duration curve. In most cases, the default values are adequate.

7. Click the **Compute** button and then press the **Plot** button to see the computed reservoir stage duration curve. The computed curve for Foster Joseph Sayers Dam reservoir elevation is shown in Figure 61. The "interpolated" curve is the duration curve interpolated to the user defined exceedance ordinate values, and the "computed" curve is the duration curve using all data points (the data points are ranked, sorted, and then percent of time exceeded is computed based on the Weibull plotting position discussed in the Initial Data Analysis chapter).

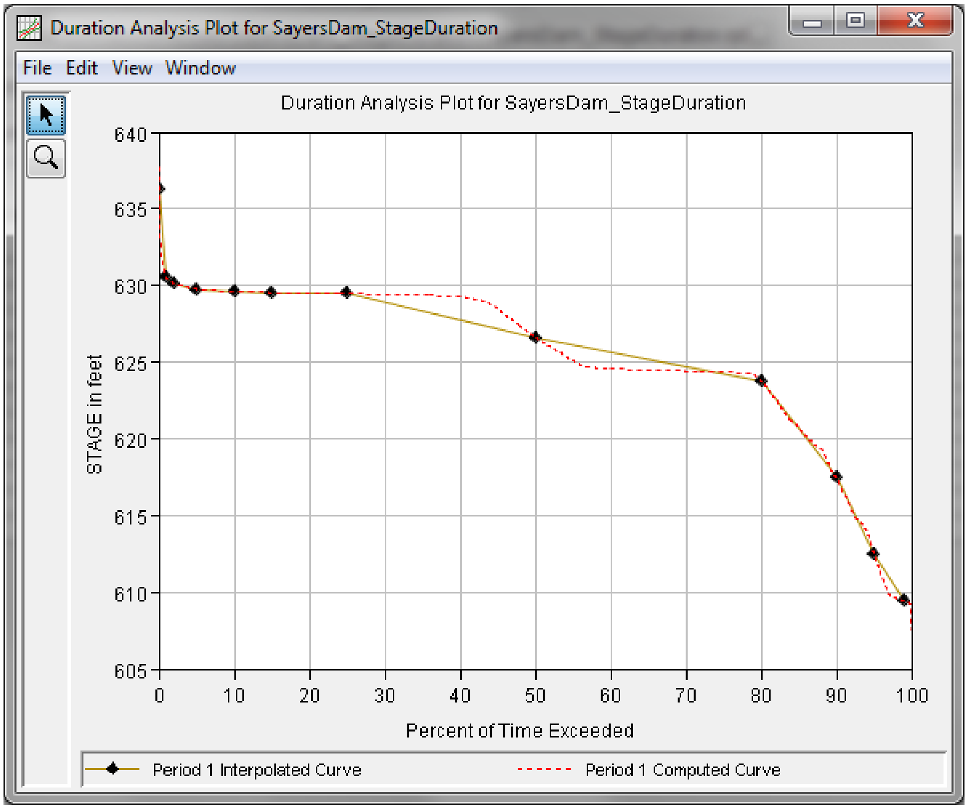


Figure 61: Computed Reservoir Stage Duration Curve

Reservoir Model Development

This chapter provides an overview of reservoir routing concepts and discusses the inputs required to develop a reservoir model for a hydrologic hazard assessment. In addition, this chapter provides a step-by-step tutorial for developing stage-storage-discharge relationships and creating a reservoir model using RMC-RFA and HEC-HMS.

Reservoir Routing Concepts

A reservoir routing model is used to determine pool stages and discharges by routing a flood hydrograph through the reservoir pool and outlets. The reservoir routing model requires information about the reservoir, such as the elevation-storage relationship, and information about physical structures, like spillways and other outlets. These regulating outlets are commonly simplified through use of a stage-storage-discharge relationship.

Reservoir routing in RMC-RFA and HEC-HMS is based on a hydrologic routing method, which is concentrated on the concept of storage for the flood water and does not directly include effects of resistance to the flow. The routing of a flood by using a hydrologic method in a reservoir is based on the continuity equation which equates the rate of change of the storage, $\frac{dS}{dt}$, in the reservoir to the difference between the inflow, *I*, and the outflow, *O:*

$$\frac{dS}{dt} = I - O$$

Equation 4

Specifically, RMC-RFA and HEC-HMS both use a finite difference approximation of the continuity equation called the *Modified Puls* routing method, also known as storage-indication routing or level-pool routing. Using a simple backward differencing scheme and rearranging the continuity equation to isolate the unknown values gives:

$$\left(\frac{S_t}{dt} + \frac{O_t}{2}\right) = \left(\frac{I_{t-1} + I_t}{2}\right) + \left(\frac{S_{t-1}}{dt} - \frac{O_{t-1}}{2}\right)$$

Equation 5

Where I_{t-1} and I = inflow hydrograph ordinates at times *t*-1 and *t*, respectively; O_{t-1} and O = outflow hydrograph ordinates at times *t*-1 and *t*, respectively; and S_{t-1} and S = storage in the reservoir at times *t*-1 and *t*, respectively.

The Modified Puls method has some limitations, which includes, among others, rivers with significant backwater effects, tributary inflows, and flat to mild channel slopes. If the dam being assessed has a long and narrow reservoir or has a potential for significant backwater effects, the Modified Puls routing method may not provide accurate results for peak stage. However, the method is considered appropriate for use in an SQRA.

Developing a Reservoir Model Using RMC-RFA

The Modified Puls reservoir routing method requires stage versus storage and stage versus discharge relationships as reservoir model inputs. The following subsections describe what those inputs are and how to develop them for an SQRA. Before developing a reservoir model, it is important to understand the reservoir water control plan and how the dam is operated. In addition, the vertical datum (Project Construction Datum, NGVD29, or NAVD88) must be determined and used consistently throughout. It is current USACE policy to use NAVD88 and therefore it is required to use this datum for hydrologic hazard analyses.

Stage versus Storage

A stage versus storage relationship (also referred to as a stage-storage function) relates water surface elevation to the volume of water stored. It provides a geometric description of the reservoir that is used during routing to determine the rise or fall of the water surface elevation given a change in the volume of stored water. In most cases, a stage-storage curve will be provided in the project water control manual or can be attained from the District Water

Management Branch. The stage-storage relationship for Foster Joseph Sayers Dam is provide in Plate 7-02 of the regulation manual and can be seen in Figure 62. The data was digitized by the District and the stage-storage function is provided in Table 7.

It is important that the stage increments in the stage-storage function are such that the critical reservoir elevations, such as the spillway and top of dam are adequately captured. If the elevation-storage curve provided in the water control manual is limited to the maximum pool volume, it is recommended that the stage-storage function be extrapolated to a few feet above the top of dam elevation. It is important that the stage-storage function is extended beyond the top of dam to include overtopping information. Please see the Overtopping Discharge section below for more details.

- *Note*: Both the stage-storage and stage-discharge functions must be monotonically increasing and the values should extend beyond the top of the dam to model potential overtopping events. RMC-RFA and HEC-HMS do not extrapolate during a routing simulation.

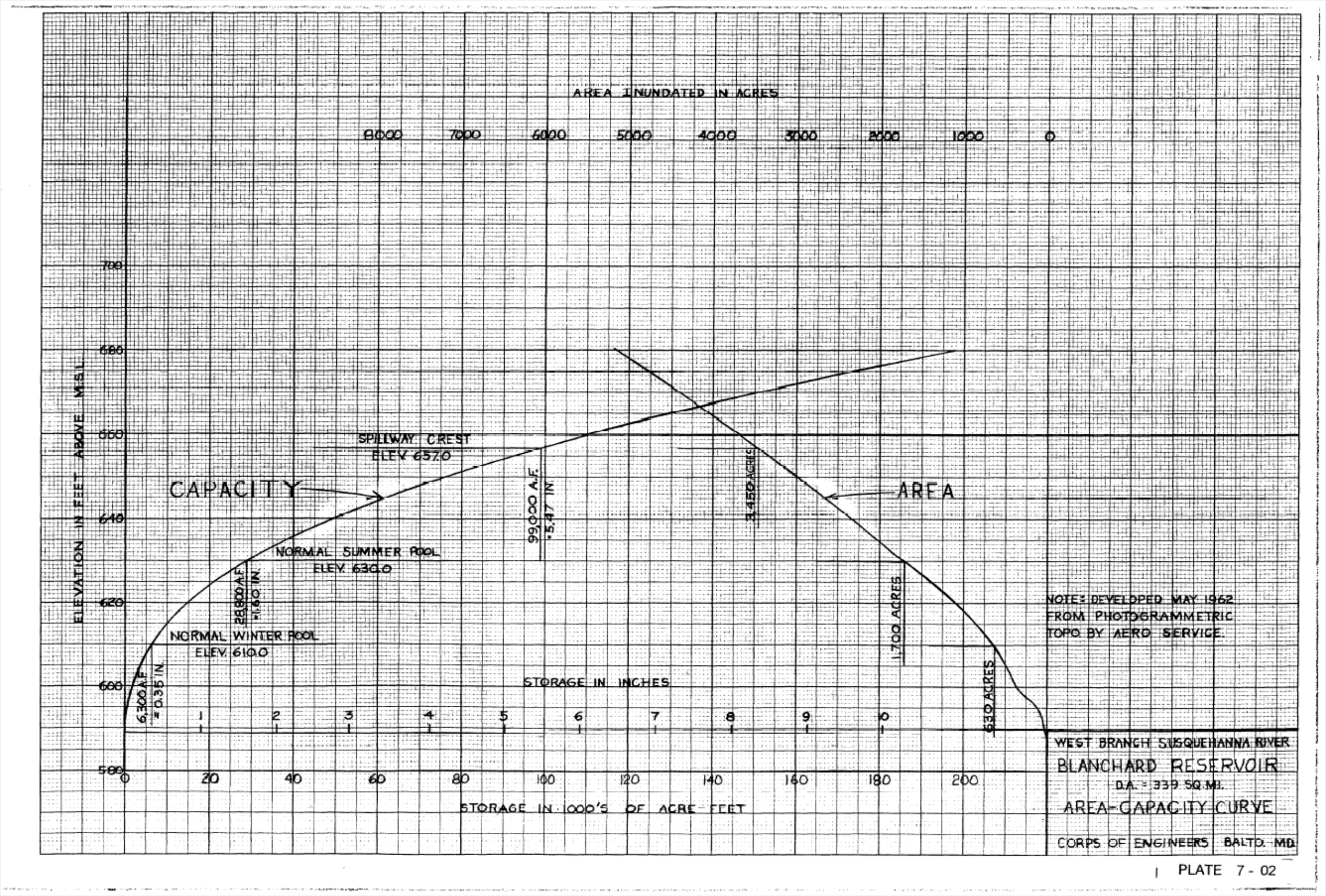


Figure 62: Plate 7-02 from Foster Joseph Sayers Regulation Manual

Table 7: Stage-Storage Relationship for Foster Joseph Sayers Dam

Stage (FT)	Storage (AC-FT)
587.00	1
592.00	69
597.00	801
602.00	2,481
607.00	4,715
612.00	7,727
617.00	11,909
622.00	17,676
627.00	25,174
629.00	28,621
631.00	32,266
633.00	36,127
635.00	40,212
637.00	44,533
639.00	49,103
641.00	53,901
643.00	58,933
645.00	64,245
647.00	69,843
649.00	75,705
651.00	81,841
653.00	88,239
655.00	94,880
657.00 (Spillway Crest)	101,765
659.00	108,896
661.00	116,290
663.00	123,973
665.00	131,926
667.00	140,174
669.00	148,722
671.00	157,569
673.00	166,717
675.00	176,165
677.00	185,913
679.00	195,961
681.00	206,309
682.26 (Top of Dam)	212,990
683.00	216,959
685.00	227,687
687.00	238,415

If a stage-storage function is not readily available, one may need to be derived from the surveyed topography of the reservoir. If a Digital Elevation Model (DEM) is available then there are a number of approximations that can be used to derive storage. Using GIS raster processing tools you can planimeter the DEM area. Compute the average-end area of each section then sum the incremental storage values for each section for a series of known stages to yield the stage-storage relationship. If the project Water Control Manual only provides an Elevation-Area (ft-ac) curve it will need to be converted to elevation (stage) versus storage. Similarly, you can multiply the area given in the curve by the depth increments found at each elevation in the DEM.

Stage versus Discharge

A stage versus discharge relationship (also referred to as a stage-discharge function) relates water surface elevation to the required discharge associated with the outlet works, spillway, and overtopping. Stage-discharge information will be provided in the project water control manual. The stage-discharge relationship should encompass any releases from the dam, including outlet works, spillways, and overtopping if necessary. Overtopping discharges should be included in the stage-discharge relationship in order to properly route extreme flood events that result in overtopping stages and discharges.

Outlet Works Discharge

The primary purpose of the Foster Joseph Sayers Dam and Reservoir is to minimize the adverse impacts of downstream flooding. When not operating for flood damage reduction, project releases are adjusted to provide a stable lake level for recreation, provide in-lake and downstream water quality control, and maintain healthy in-lake and downstream aquatic environments (U.S. Army Corps of Engineers, 1996).

During normal, non-flood periods, Sayers Reservoir is maintained near the levels specified by the elevation guide curve. This ensures that a significant flood control capacity is available should flooding occur. The reservoir elevation guide curve for Foster Joseph Sayers Dam is shown on Plate 7-01 of the regulation manual.

The outlet works for Sayers Dam consist of two hydraulic wheel gates (7’ by 15’ each). For small gate openings, outflow through the service gates can be estimated using the outlet rating curve on Plate 7-04 of the regulation manual. For larger gate openings, outflow through the service gates can be estimated using the outlet rating curve on Plate 7-05. When reservoir inflow increases, releases through the outlet gates are gradually increased to keep outflows equal to inflows as long as downstream conditions permit.

The top five flood events for Sayers Dam were plotted in the Critical Inflow Duration Analysis section, and the October of 1996 event is shown again in Figure 63 below. Notice that releases from the outlet works are limited during the inflow event. During high water situations, such as the 1996 event, project releases are often limited based on downstream river stages. Excess reservoir inflow is then stored for release at a later time when downstream river stages have receded.

Many flood control dams are operated with consideration to downstream constraints and “rate of release” constraints. Consequently, it can be challenging to construct a simple stage-discharge relationship for outlet works.

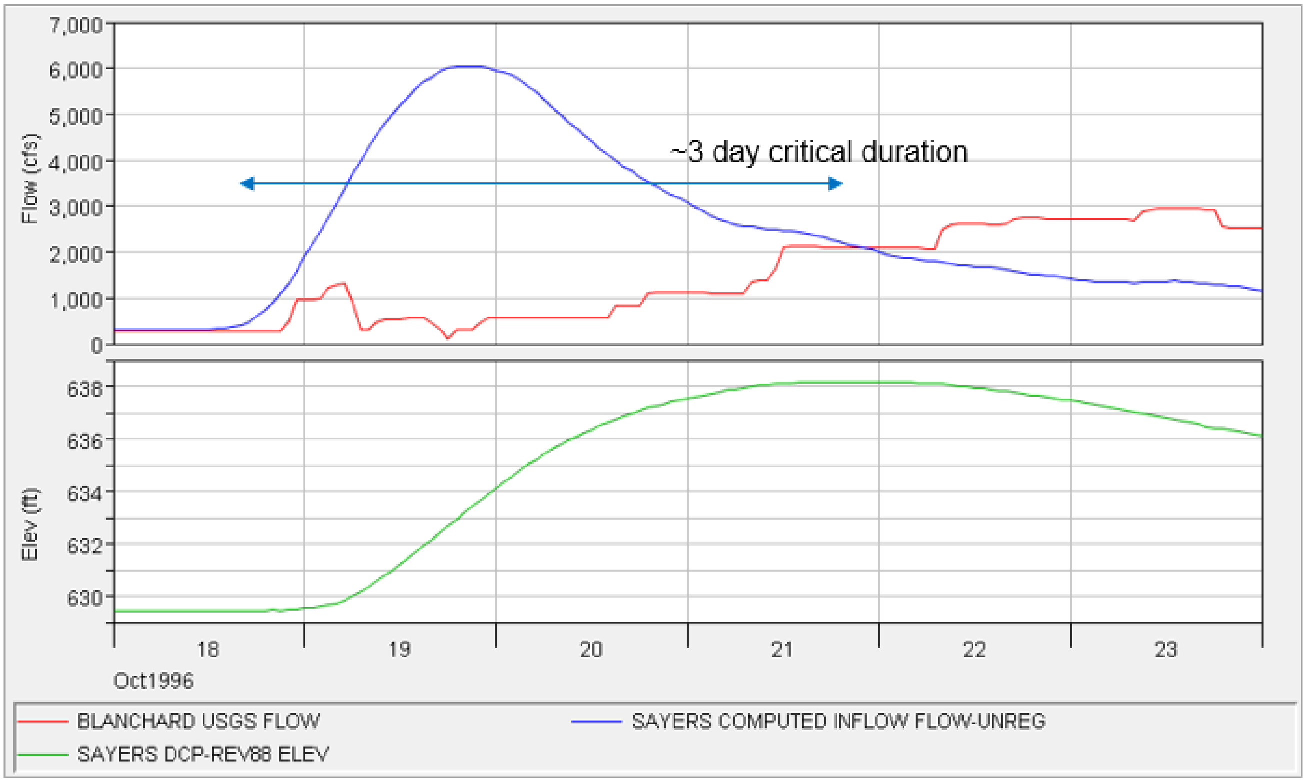


Figure 63: October 1996 Flood Event

Example for Developing a Stage-Discharge Function for Outlet Works

The following discussion is intended to provide an example of how to develop the stage-discharge rating curve for outlet works. One example will be shown here; however, three separate stage-discharge rating curves for outlet works will be evaluated in the Reservoir Stage-Frequency Analysis chapter.

1. The simplest way to begin formulating a relationship between stage and outlet work releases is to plot as many years of daily regulated discharge and observed stage data as are available. If you can fit a trend line to the plot you may have a good starting point for your curve. However, in many cases, the relationship will not be immediately clear and no trend line will be applicable. If this is the case then your data may need further processing. Thus, the development of the outlet rating curve is an iterative process that may take several iterations before finalizing a curve.

2. Consider the following example for Sayers Dam. First, the observed daily reservoir stage and the regulated discharge from 1995 to 2013 and the 1972 flood event are plotted against each other as shown below in Figure 64, with stage, as the independent variable plotted on the X-axis and discharge as the dependent variable, plotted on the Y-axis.

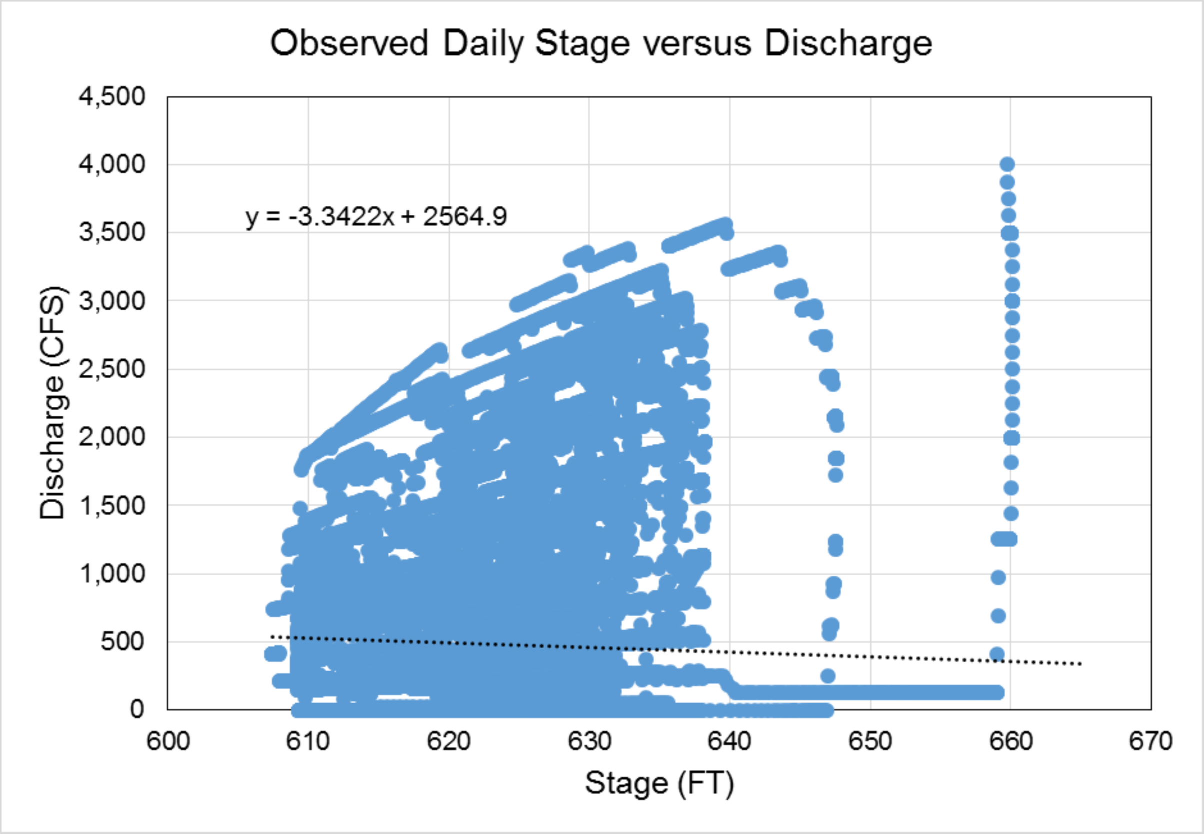
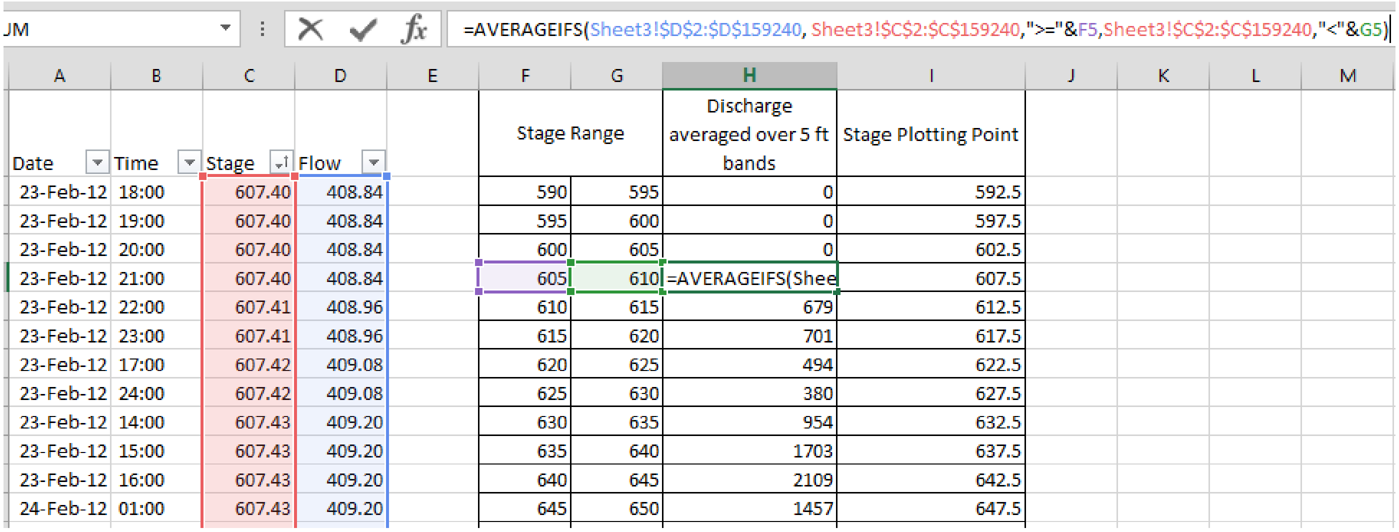


Figure 64: Observed Daily Stage-Discharge X-Y Plot

3. If at this point the data for your project yields a distinguishable relationship between stage and flow, then all you will need to do is either compute or hand-fit a curve to the data. However, as you can see in Figure 64, there is some semblance of a pattern forming at higher elevations, but the overall pattern of the data makes it difficult to define a meaningful relationship between stage and discharge. Therefore, some additional data processing is needed. This can be accomplished with minimal additional effort in Microsoft Excel.

4. First, the X-Y data should be sorted from smallest to largest by stage. Next, take the average discharges over incremental stage bands. This can be done using the AVERAGEIFS() function in Microsoft Excel. In this example, discharges were averaged over five foot stage bands from the lowest elevation data available to the highest. An example of the spreadsheet calculations are shown in Figure 65.



```
=AVERAGEIFS(Sheet3!$D$2:$D$159240, Sheet3!$C$2:$C$159240,">="&F5,Sheet3!$C$2:$C$159240,"<"&G5)
```

A	B	C	D	E	F	G	H	I
Date	Time	Stage	Flow		Stage Range		Discharge averaged over 5 ft bands	Stage Plotting Point
23-Feb-12	18:00	607.40	408.84		590	595	0	592.5
23-Feb-12	19:00	607.40	408.84		595	600	0	597.5
23-Feb-12	20:00	607.40	408.84		600	605	0	602.5
23-Feb-12	21:00	607.40	408.84		605	610	=AVERAGEIFS(Shee	607.5
23-Feb-12	22:00	607.41	408.96		610	615	679	612.5
23-Feb-12	23:00	607.41	408.96		615	620	701	617.5
23-Feb-12	17:00	607.42	409.08		620	625	494	622.5
23-Feb-12	24:00	607.42	409.08		625	630	380	627.5
23-Feb-12	14:00	607.43	409.20		630	635	954	632.5
23-Feb-12	15:00	607.43	409.20		635	640	1703	637.5
23-Feb-12	16:00	607.43	409.20		640	645	2109	642.5
24-Feb-12	01:00	607.43	409.20		645	650	1457	647.5

Figure 65: Spreadsheet Example of AVERAGEIFS Equation

5. Figure 66 shows the resulting stage-discharge relationship. Discharge values were plotted in the center of the elevation band. As you can see, there is now a clearly distinguishable relationship between stage and discharge. You can now fit a trend line to your curve and calculate the equation of the line. The outlet works stage-discharge function is provided in Table 8.

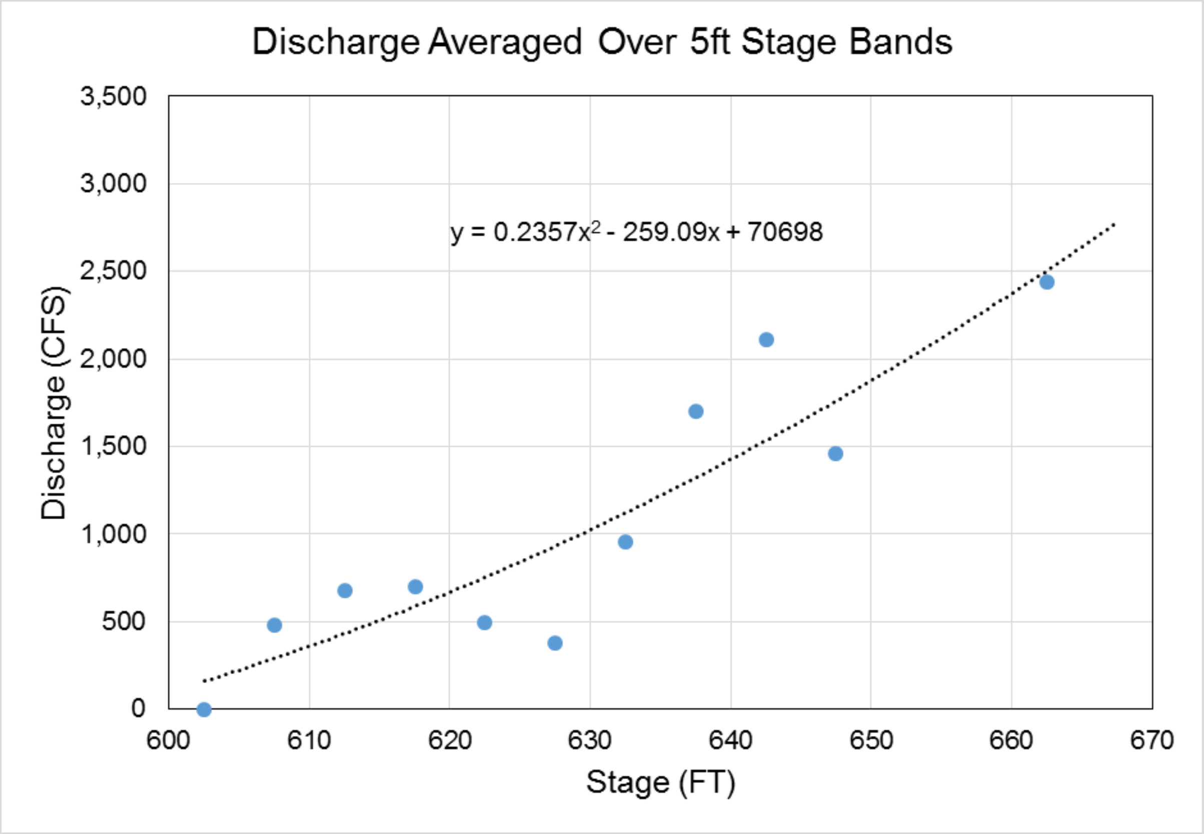


Figure 66: Stage versus Discharge Averaged Over 5ft Stage Bands

Table 8: Stage-Discharge for Outlet Works Relationship for Foster Joseph Sayers Dam

Stage (FT)	Outlet Works Discharge (CFS)
587.00	0
592.00	0
597.00	27
602.00	144
607.00	274
612.00	415
617.00	568
622.00	733
627.00	909
629.00	983
631.00	1,059
633.00	1,136
635.00	1,216
637.00	1,297
639.00	1,381
641.00	1,466
643.00	1,553
645.00	1,642
647.00	1,733
649.00	1,826
651.00	1,920
653.00	2,017
655.00	2,115
657.00	2,216
659.00	2,318
661.00	2,422
663.00	2,528
665.00	2,636
667.00 (Spillway Crest)	2,745
669.00	2,857
671.00	2,970
673.00	3,086
675.00	3,203
677.00	3,322
679.00	3,443
681.00	3,566
682.26 (Top of Dam)	3,645
683.00	3,691
685.00	3,818
687.00	3,946

Spillway Discharge

The uncontrolled spillway for Sayers Dam consists of a concrete ogee weir with a design capacity of 200,000 cfs under a total surcharge of 20.8 feet. Flow over the spillway occurs if the reservoir level exceeds elevation 657.0 feet. The spillway flow as a function of stage can be estimated using the spillway rating curve on Plate 7-03 shown in Figure 67. The stage-spillway discharge function is provided in Table 9.

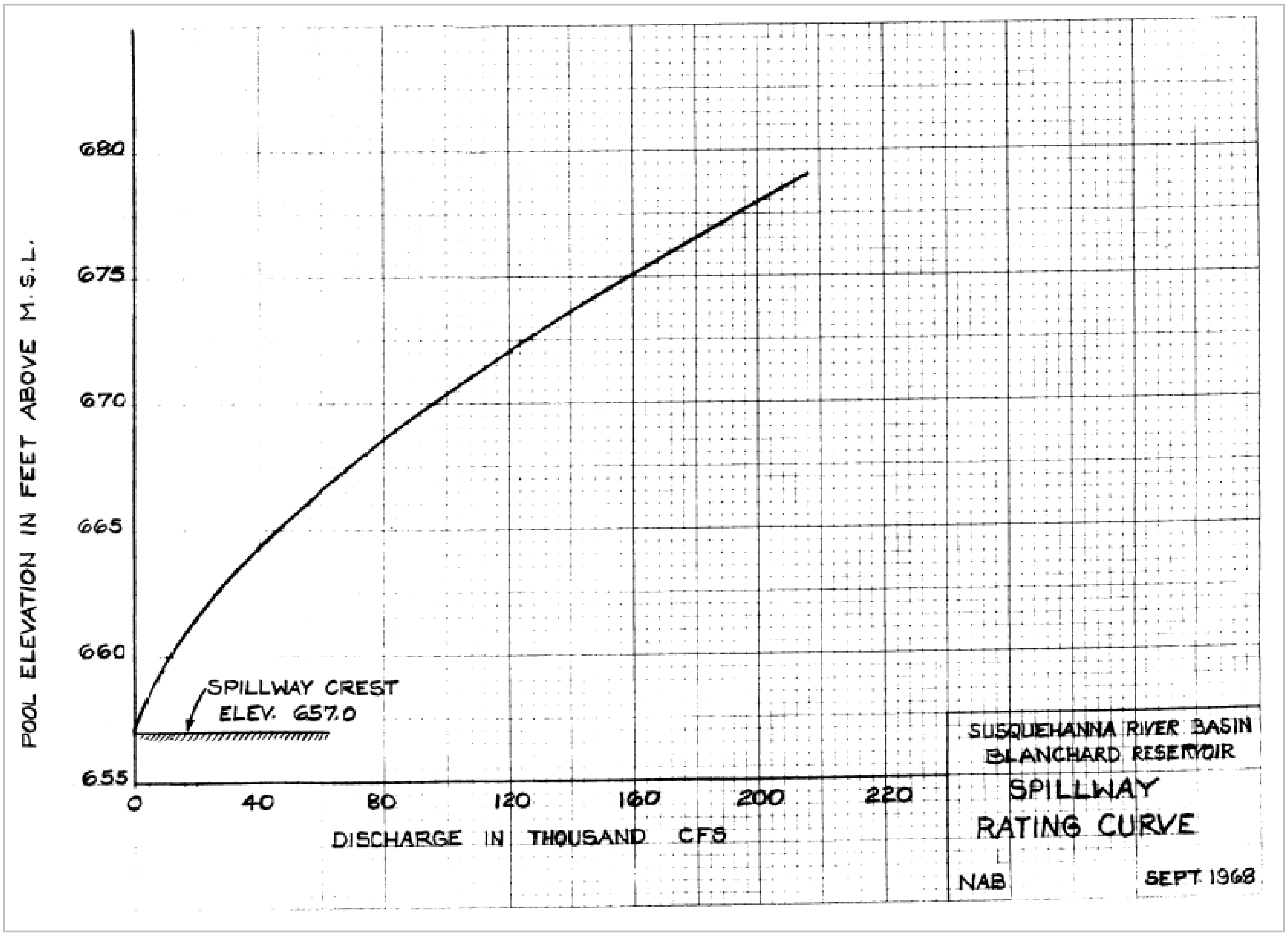


Figure 67: Plate 7-03 from the Foster Joseph Sayers Regulation Manual

Table 9: Spillway Discharge Relationship for Foster Joseph Sayers Dam

Stage (FT)	Spillway Discharge (CFS)
657 (Spillway Crest)	0
659	8,000
661	18,400
663	31,200
665	44,000
667	64,800
669	85,600
671	108,800
673	134,400
675	160,000
677	188,000
679	216,000
681	244,000
682.26 (Top of Dam)	261,640
683	272,000
685	300,000
687	328,000

Overtopping Discharge

It is important that the stage-storage-discharge function is extended beyond the top of dam to include overtopping discharge information. Extreme overtopping flood events will likely be sampled in the stochastic simulation described in the next chapter for Reservoir Stage-Frequency Analysis. Therefore, reservoir stage-overtopping discharge relationships need to be developed to ensure that the model is capable of routing the extreme flood events. Extending the stage-storage-discharge function above the top of dam by three to five feet will likely be adequate for the purposes of an SQRA.

The simplest way to determine the stage-discharge relationships for overtopping, is to first determine the lowest crest elevation and the crest length of the dam. For Foster Joseph Sayers Dam, this is 682.26 ft and 6,835 ft, respectively. Next, using the weir equation shown below, compute overtopping discharge for a series of elevations above the dam crest. The overtopping discharge rating curve is provided in Table 10.

$$Q = CLH^{3/2} \qquad \textit{Equation 6}$$

Where *Q* is the discharge in cfs; C is the unitless discharge constant (2.65 is usually selected for broad-crested weirs); *L* is the length of the crest in feet; and *H* is the water height over the structure (head, in feet).

Table 10: Overtopping Discharge Relationship for Foster Joseph Sayers Dam

Stage (FT)	Overtopping Discharge (CFS)
682.26 (Top of Dam)	0
683	11,530
685	82,151
687	186,918

Total Discharge

The total discharge is derived by simply summing all sources of discharge capacity. The complete stage-storage-discharge relationship for Sayers Dam is provided in Table 11 below.

Short Note on Complex Reservoir Operations

There are different reservoir routing models available for use on USACE studies, including RMC-RFA, HEC-HMS, HEC-RAS, and HEC-ResSim. The reservoir routing capability in RMC-RFA and HEC-HMS are somewhat limited as operation for downstream flow constraints is not possible. Conversely, the reservoir routing capabilities in HEC-ResSim allows for downstream constraints and other complex operations. If hydraulic variables are required, HEC-RAS can be used to perform one- and two-dimensional hydraulic computations for a full network of natural and constructed channels, overbank/floodplains, and leveed areas, amongst others. Also, reservoir routing can be performed within HEC-RAS using the same routing routines if the user determines that hydraulic routing approaches are necessary. However, this level of model complexity is not normally required during an SQRA. In most cases, the reservoir routing needed for a SQRA can be easily met by the capabilities in RMC-RFA and HEC-HMS as complex operations of the reservoir and outlet works are not necessary. When estimating the hydrologic hazard curve for large to extreme floods, the surcharge operating schedule is the primary driver of the resulting peak stages. Therefore, downstream controls are rarely relevant, and furthermore, spillway ratings for gated spillways can be approximated from the surcharge operations curves and some calibration routings.

If it is determined that a complex reservoir routing model, such as HEC-ResSim or HEC-RAS, is required, then balanced hydrographs and coincident frequency analysis should be used to develop the reservoir stage-frequency curve. See Appendix A: Balanced Hydrograph Analysis and Appendix B: Coincident Frequency Analysis for details.

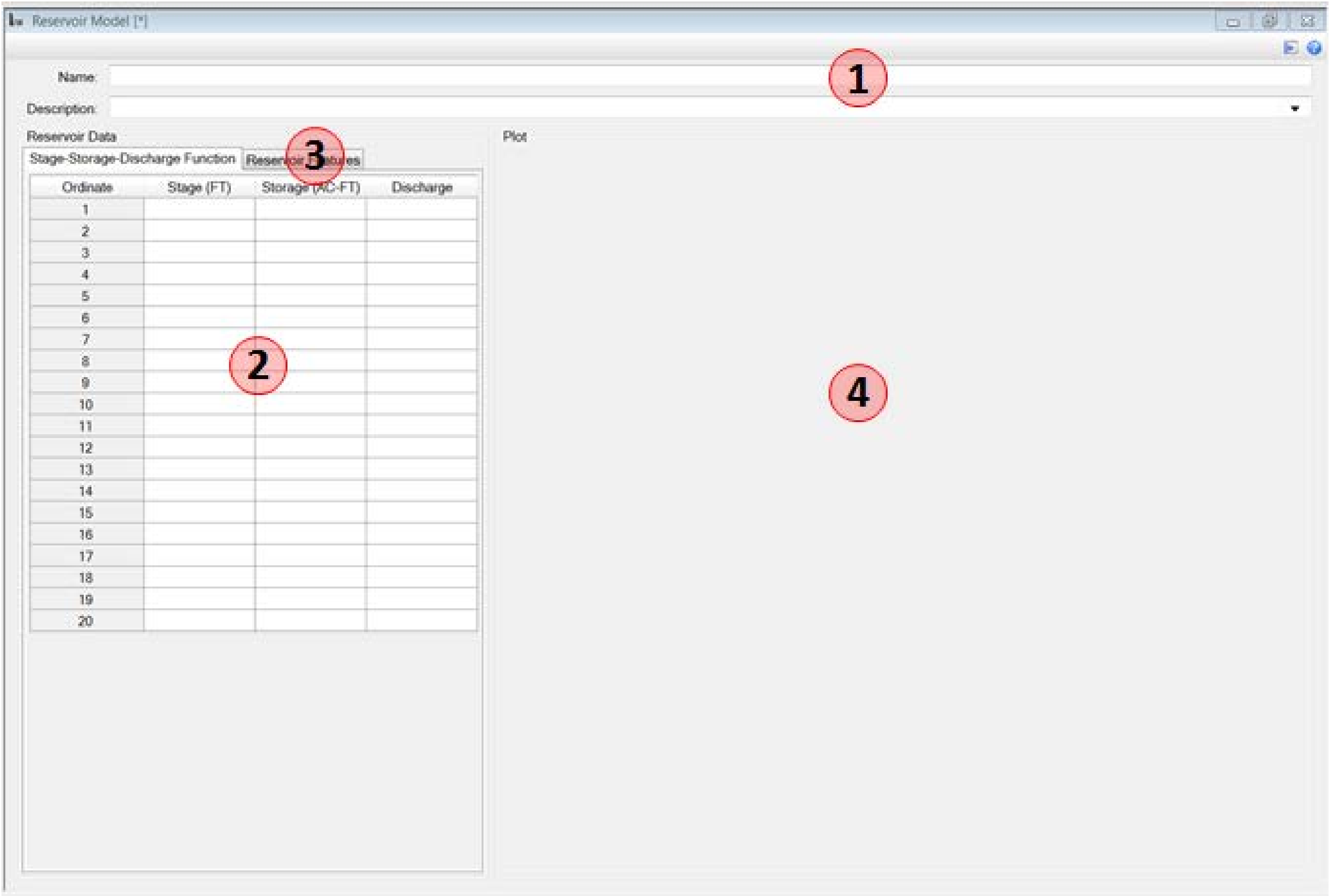
Table 11: Total Stage-Storage-Discharge Relationship for Foster Joseph Sayers Dam

Stage (FT)	Storage (AC-FT)	Outlet Works Discharge (CFS)	Spillway Discharge (CFS)	Overtopping Discharge (CFS)	Total Discharge (CFS)
587.00	1	0	0	0	0
592.00	69	0	0	0	0
597.00	801	27	0	0	27
602.00	2,481	144	0	0	144
607.00	4,715	274	0	0	274
612.00	7,727	415	0	0	415
617.00	11,909	568	0	0	568
622.00	17,676	733	0	0	733
627.00	25,174	909	0	0	909
629.00	28,621	983	0	0	983
631.00	32,266	1,059	0	0	1,059
633.00	36,127	1,136	0	0	1,136
635.00	40,212	1,216	0	0	1,216
637.00	44,533	1,297	0	0	1,297
639.00	49,103	1,381	0	0	1,381
641.00	53,901	1,466	0	0	1,466
643.00	58,933	1,553	0	0	1,553
645.00	64,245	1,642	0	0	1,642
647.00	69,843	1,733	0	0	1,733
649.00	75,705	1,826	0	0	1,826
651.00	81,841	1,920	0	0	1,920
653.00	88,239	2,017	0	0	2,017
655.00	94,880	2,115	0	0	2,115
656.26	99,196	2,178	0	0	2,178
657.00	101,765	2,216	0	0	2,216
659.00	108,896	2,318	8,000	0	10,318
661.00	116,290	2,422	18,400	0	20,822
663.00	123,973	2,528	31,200	0	33,728
665.00	131,926	2,636	44,000	0	46,636
667.00	140,174	2,745	64,800	0	67,545
669.00	148,722	2,857	85,600	0	88,457
671.00	157,569	2,970	108,800	0	111,770
673.00	166,717	3,086	134,400	0	137,486
675.00	176,165	3,203	160,000	0	163,203
677.00	185,913	3,322	188,000	0	191,322
679.00	195,961	3,443	216,000	0	219,443
681.00	206,309	3,566	244,000	0	247,566
682.26	212,990	3,645	261,640	0	265,285
683.00	216,959	3,691	272,000	11,530	287,221
685.00	227,687	3,818	300,000	82,151	385,968
687.00	238,415	3,946	328,000	186,918	518,865

Using RMC-RFA

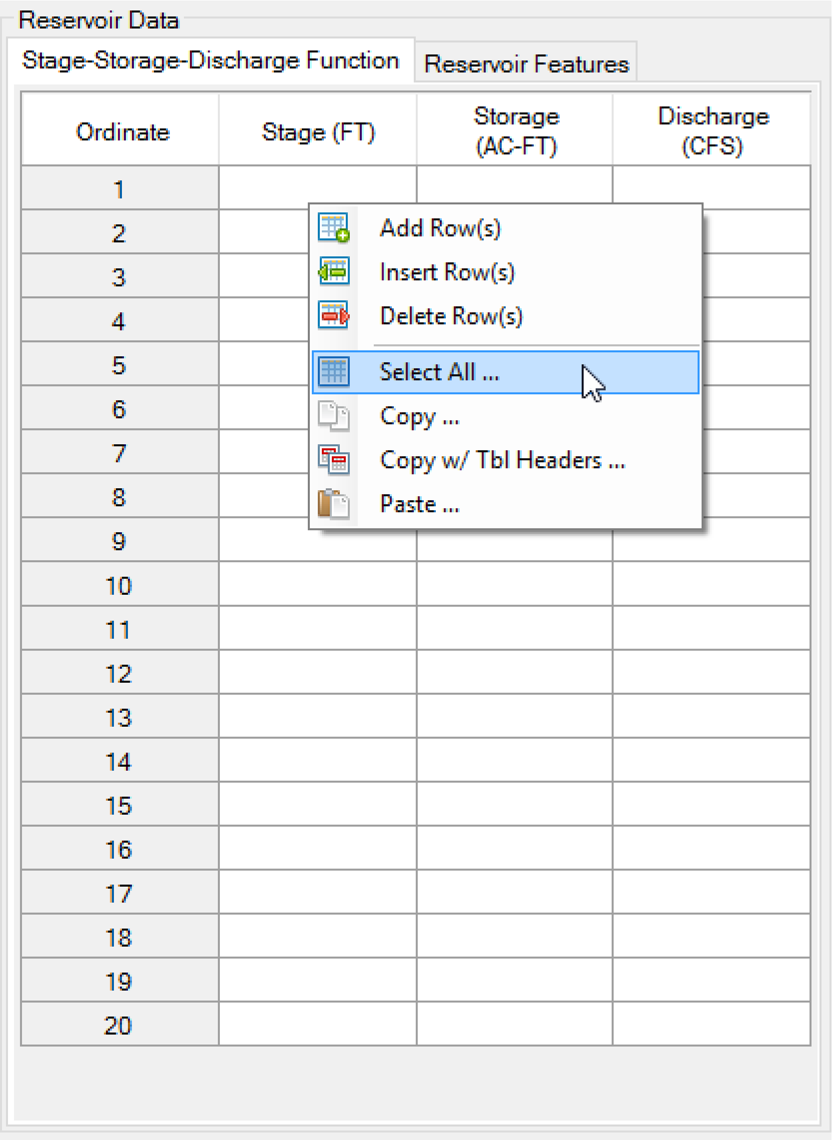
1. Open the RMC-RFA Project File ***Sayers Dam.rfa.sqlite*** and navigate to the Reservoir Models tab. Right click and select new. The RMC-RFA reservoir model window is shown in Figure 68.

    - *Note*: In the stage-storage-discharge table, the user can add rows, insert rows, delete rows, select all, copy, copy with table headers and paste by right clicking within the table as shown in Figure 69.



Ordinate	Stage (FT)	Storage (AC-FT)	Discharge
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			

Figure 68: Reservoir Model Window in RMC-RFA



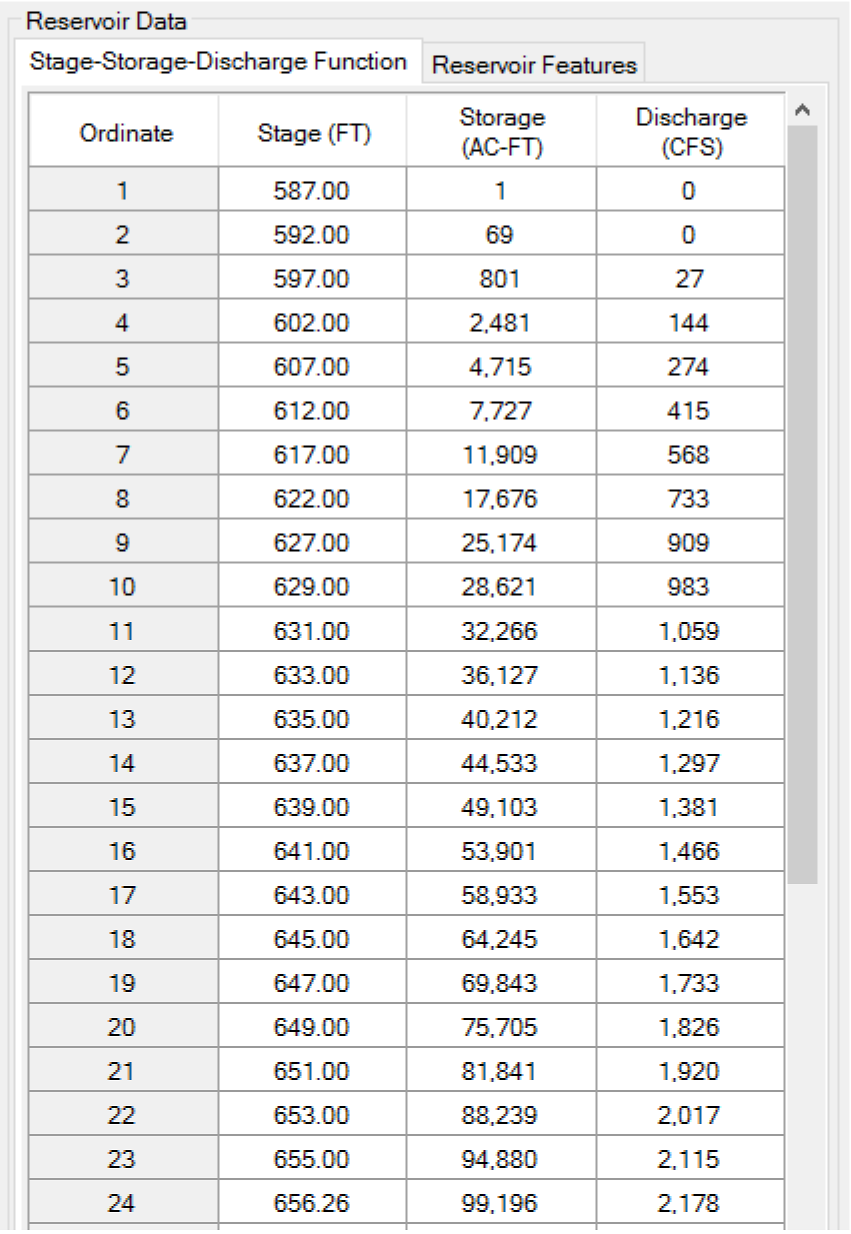
Ordinate	Stage (FT)	Storage (AC-FT)	Discharge (CFS)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			

Figure 69: Options available when right clicking within stage-storage-discharge table

2. Copy and paste the stage-storage and total discharge data from Table 11 into RMC-RFA as shown in Figure 70.

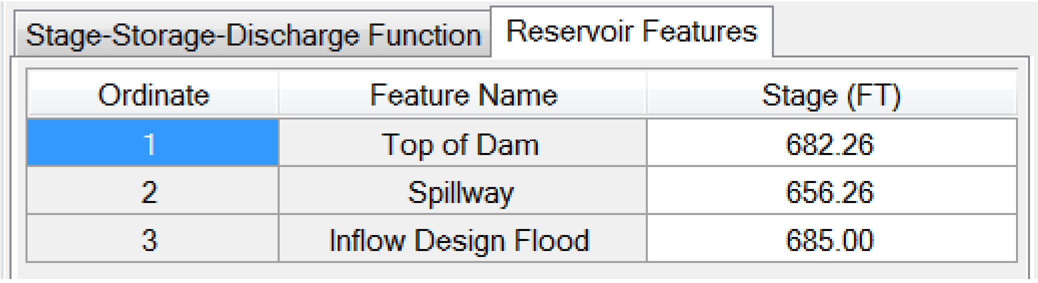
3. Finally, enter the stage for the top of dam, spillway, and inflow design flood as shown in Figure 71. These reservoir features are used as reference points to aid with interpretation of simulation results.

    - *Note*: The default plot in the Reservoir Model is the stage-storage relationship. It also displays the reservoir features. Right clicking within the plot allows the user to select the stage-discharge function plot. The stage-storage and stage-discharge plots are shown in Figure 72 and Figure 73, respectively.



Ordinate	Stage (FT)	Storage (AC-FT)	Discharge (CFS)
1	587.00	1	0
2	592.00	69	0
3	597.00	801	27
4	602.00	2,481	144
5	607.00	4,715	274
6	612.00	7,727	415
7	617.00	11,909	568
8	622.00	17,676	733
9	627.00	25,174	909
10	629.00	28,621	983
11	631.00	32,266	1,059
12	633.00	36,127	1,136
13	635.00	40,212	1,216
14	637.00	44,533	1,297
15	639.00	49,103	1,381
16	641.00	53,901	1,466
17	643.00	58,933	1,553
18	645.00	64,245	1,642
19	647.00	69,843	1,733
20	649.00	75,705	1,826
21	651.00	81,841	1,920
22	653.00	88,239	2,017
23	655.00	94,880	2,115
24	656.26	99,196	2,178

Figure 70: Reservoir Data Table for Foster Joseph Sayers Dam in RMC-RFA



Ordinate	Feature Name	Stage (FT)
1	Top of Dam	682.26
2	Spillway	656.26
3	Inflow Design Flood	685.00

Figure 71: Reservoir Features in RMC-RFA

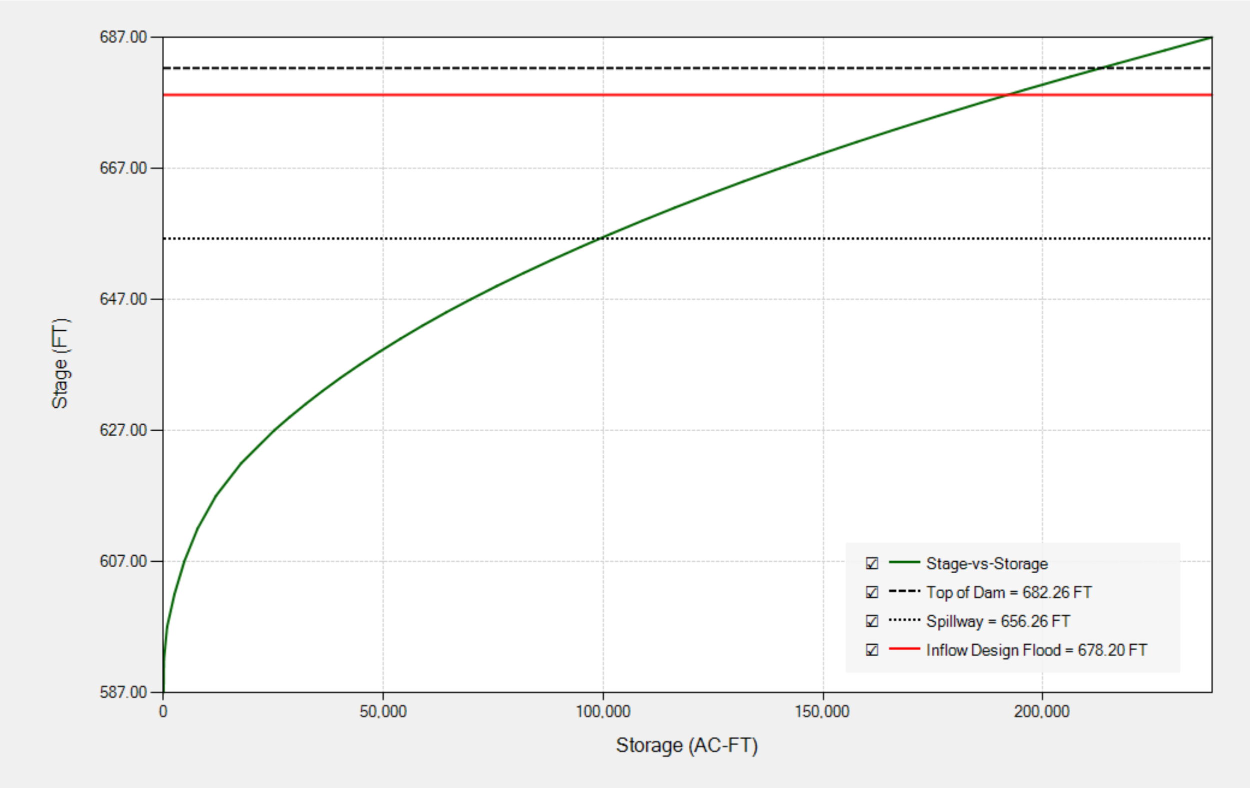


Figure 72: Stage-Storage Function Plot in RMC-RFA

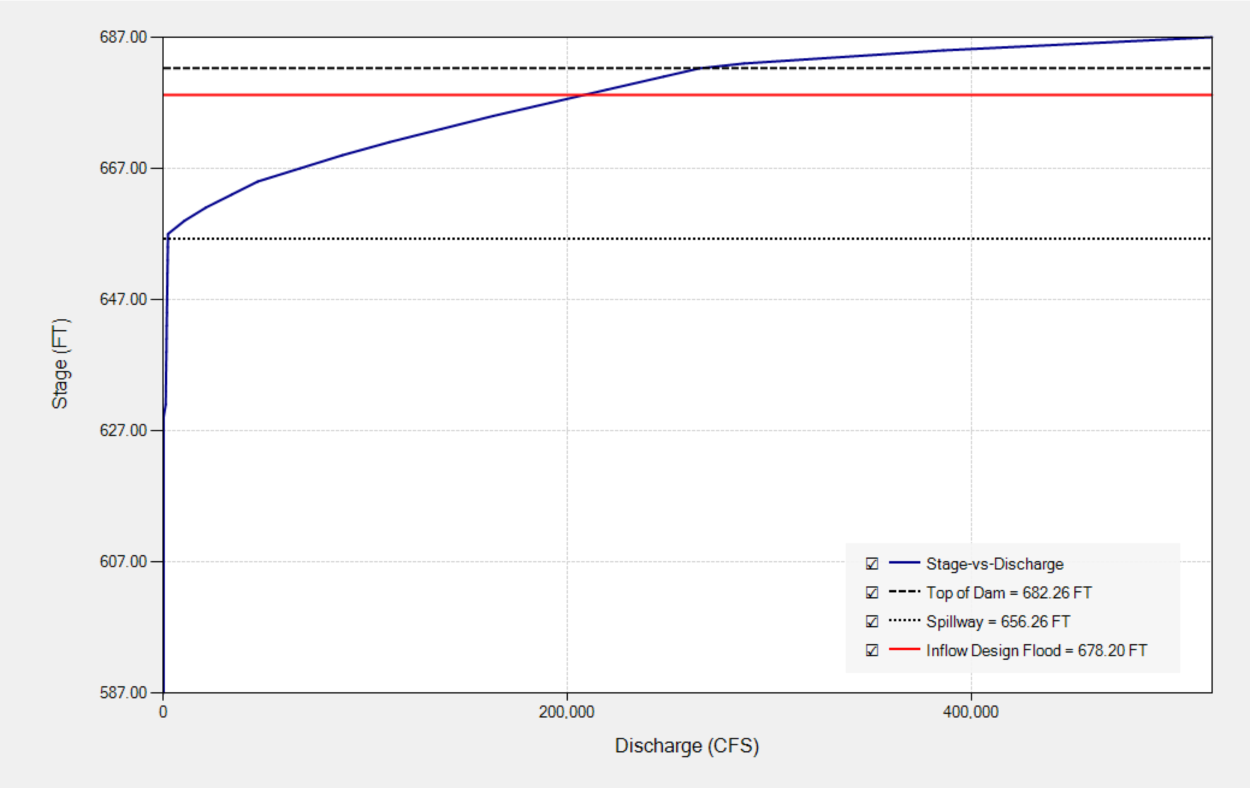


Figure 73: Stage-Discharge Function Plot in RMC-RFA

Developing a Reservoir Model Using HEC-HMS

The general steps to develop a reservoir routing model in HEC-HMS are described herein. HEC-HMS provides a computationally efficient and reliable means for determining the peak pool elevation given an inflow hydrograph when the influence of complex downstream control operations on the peak pool elevation is generally negligible.

The following key steps provide guidance for developing the major components of a reservoir routing model using HEC-HMS:

1. Create a simple HEC-HMS basin model that only includes a source element connected to a reservoir element, as shown in Figure 74. Configure the source element to use a Discharge Gage (created in later steps), and then configure the reservoir element as discussed below.

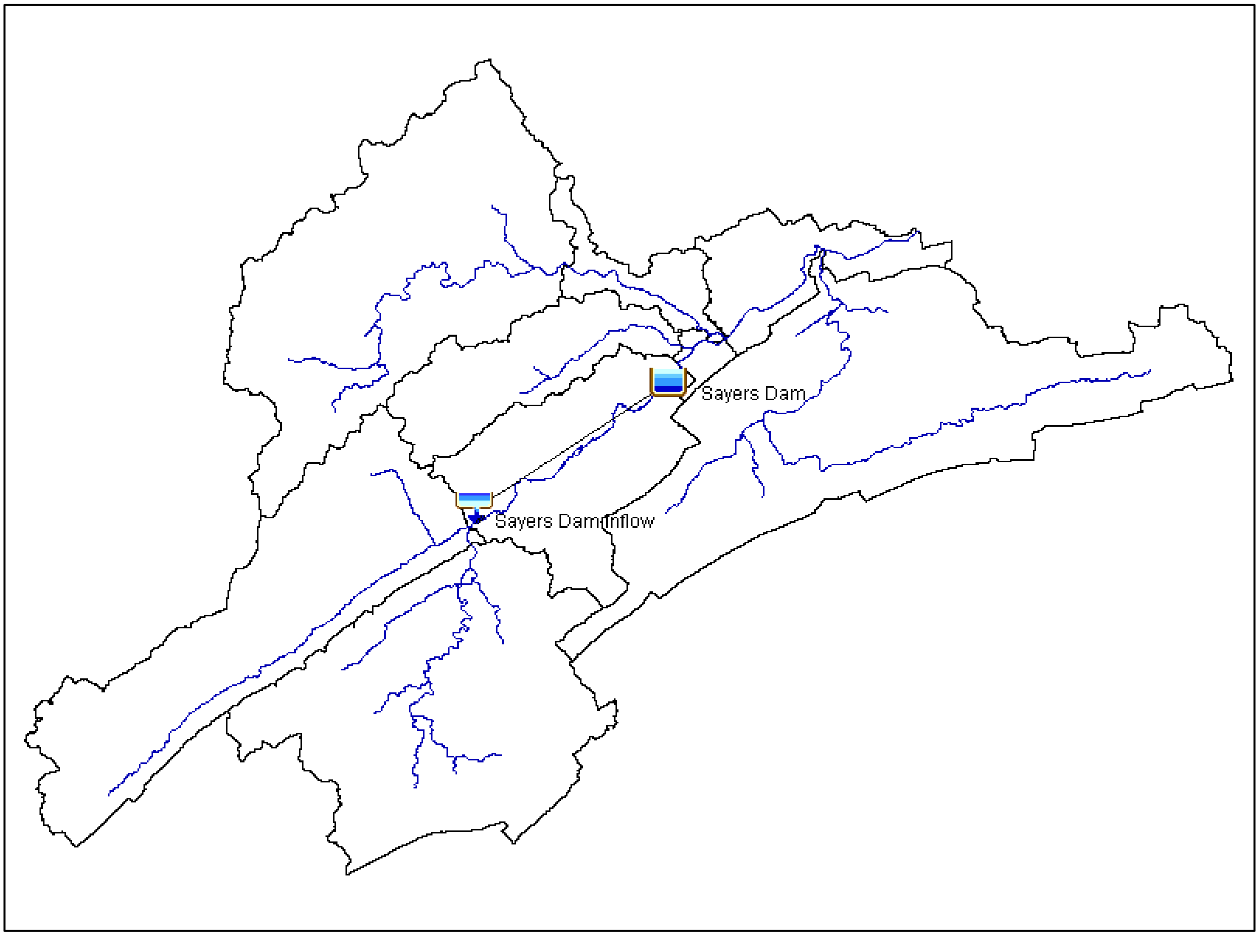
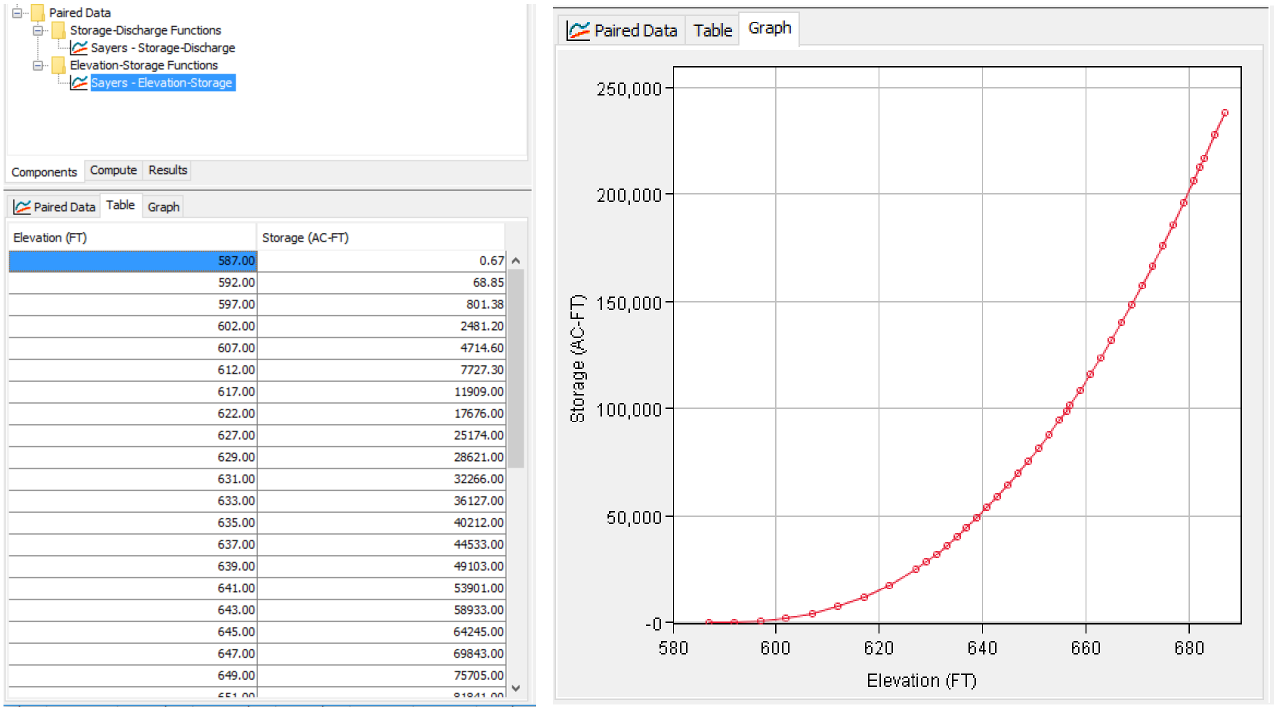


Figure 74: Simple HEC-HMS Basin Model Used to Route One-Half PMF Hydrograph

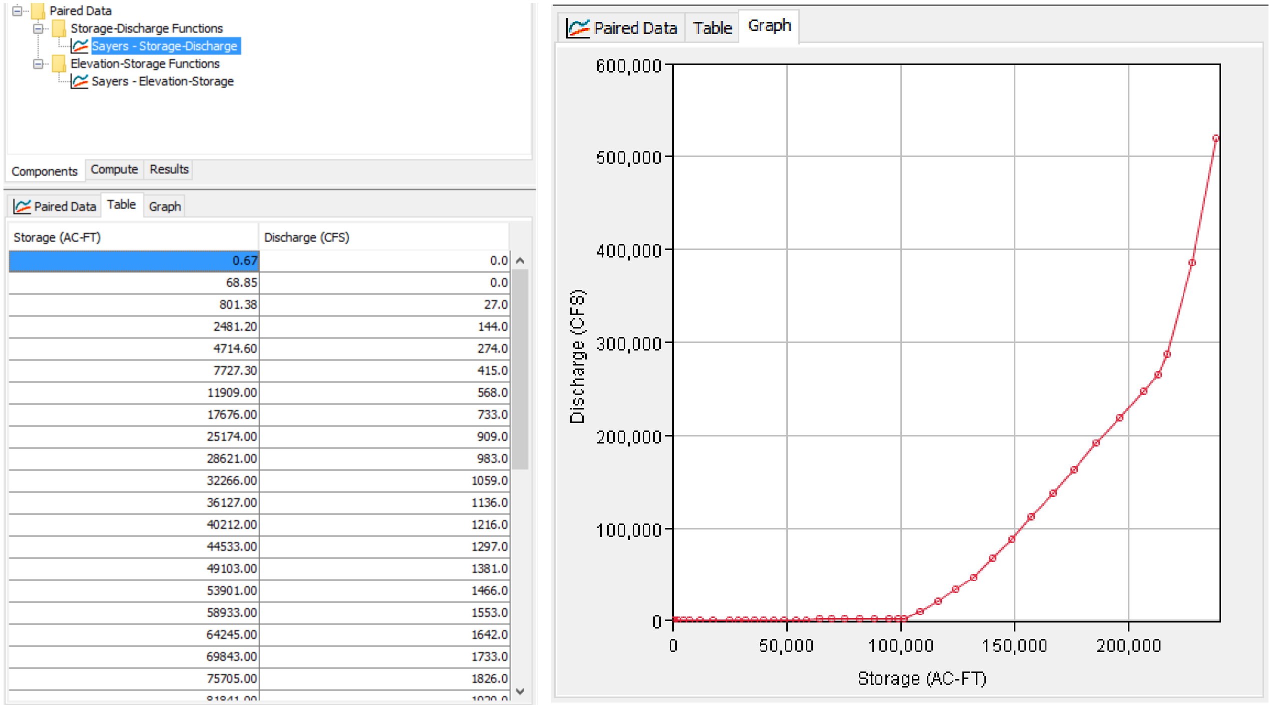
2. Create an Elevation-Storage and Storage-Discharge function within the HEC-HMS project. The elevation-storage-discharge relationship should be developed using the same techniques as demonstrated above.

    - *Note*: These functions must be monotonically increasing and the values should extend beyond the top of the dam to model potential overtopping events. HEC-HMS does not extrapolate. The elevation-storage relationship and storage-discharge relationship for Sayers Dam, as entered within HEC-HMS is shown in Figure 75 and Figure 76, respectively.



Elevation (FT)	Storage (AC-FT)
587.00	0.67
592.00	68.85
597.00	801.38
602.00	2481.20
607.00	4714.60
612.00	7727.30
617.00	11909.00
622.00	17676.00
627.00	25174.00
629.00	28621.00
631.00	32266.00
633.00	36127.00
635.00	40212.00
637.00	44533.00
639.00	49103.00
641.00	53901.00
643.00	58933.00
645.00	64245.00
647.00	69843.00
649.00	75705.00

Figure 75: Elevation-Storage Curve in HEC-HMS



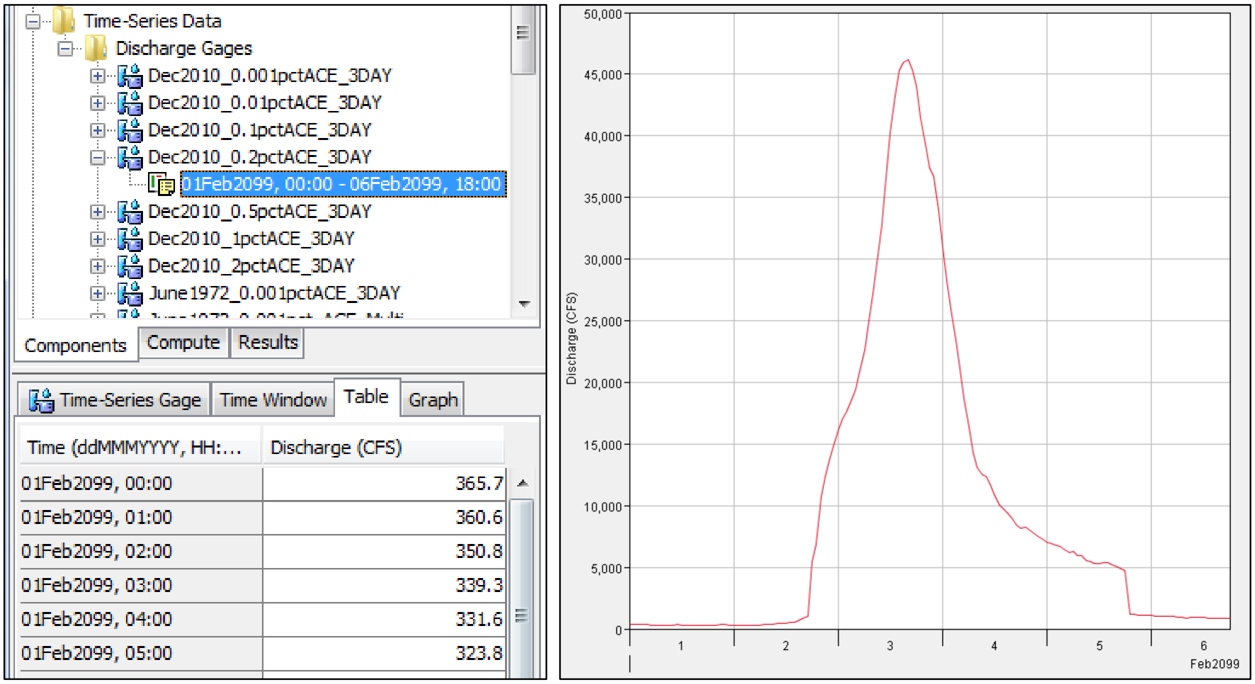
Storage (AC-FT)	Discharge (CFS)
0.67	0.0
68.85	0.0
801.38	27.0
2481.20	144.0
4714.60	274.0
7727.30	415.0
11909.00	568.0
17676.00	733.0
25174.00	909.0
28621.00	983.0
32266.00	1059.0
36127.00	1136.0
40212.00	1216.0
44533.00	1297.0
49103.00	1381.0
53901.00	1466.0
58933.00	1553.0
64245.00	1642.0
69843.00	1733.0
75705.00	1826.0

Figure 76: Storage-Discharge Curve in HEC-HMS

3. Create a Discharge Gage using the Time-Series Data Manager in the HEC-HMS project. Discharge Gages will be used to store synthetic inflow events, such as balanced hydrographs, which are discussed in Appendix A: Balanced Hydrograph Analysis.

    - *Note*: The time window of the inflow events are not critical. However, the time window for the events should be should be consistent. An example of a balanced hydrograph being input as a Discharge

Gage is plotted within Figure 77. Additional discharge gages should be added to include supplementary balanced hydrographs using other probabilities, durations, and hydrograph shapes.



- Time-Series Data
  - Discharge Gages
    - Dec2010_0.001pctACE_3DAY
    - Dec2010_0.01pctACE_3DAY
    - Dec2010_0.1pctACE_3DAY
    - Dec2010_0.2pctACE_3DAY
      - 01Feb2099, 00:00 - 06Feb2099, 18:00
    - Dec2010_0.5pctACE_3DAY
    - Dec2010_1pctACE_3DAY
    - Dec2010_2pctACE_3DAY
    - June1972_0.001pctACE_3DAY

Time (ddMMMYYYY, HH:...	Discharge (CFS)
01Feb2099, 00:00	365.7
01Feb2099, 01:00	360.6
01Feb2099, 02:00	350.8
01Feb2099, 03:00	339.3
01Feb2099, 04:00	331.6
01Feb2099, 05:00	323.8

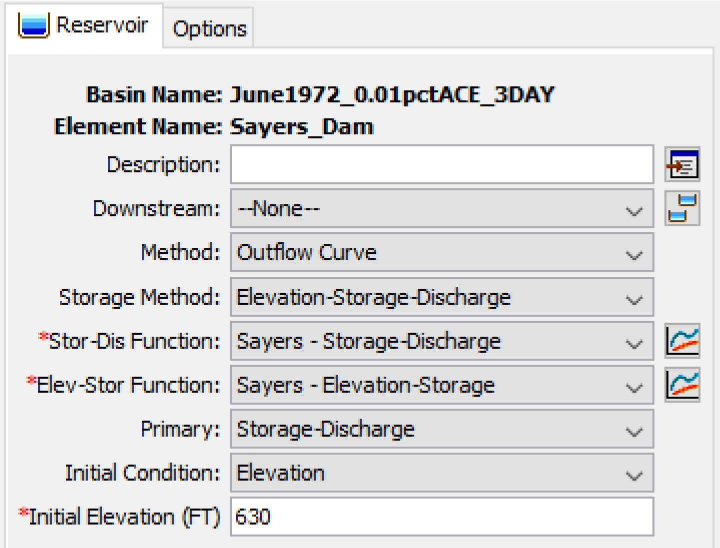
Figure 77: Discharge Gage Time Series in HEC-HMS

4. The reservoir element should be configured to use the **Outflow Curve** reservoir routing method.

   - *Note*: The previously created **Elevation-Storage** and **Storage-Discharge** functions should be selected. Also, the primary curve for interpolation should be set to **Storage-Discharge**. The use of the Outflow Curve method assumes that all pertinent release information (including the physical structures as well as release decisions) are represented by the storage-discharge function.

   - The initial condition should be set using an elevation. The initial elevation corresponds to the value used at the beginning of the simulation. Normally, the initial elevation can be set to the average pool stage (in this case, 630 ft).

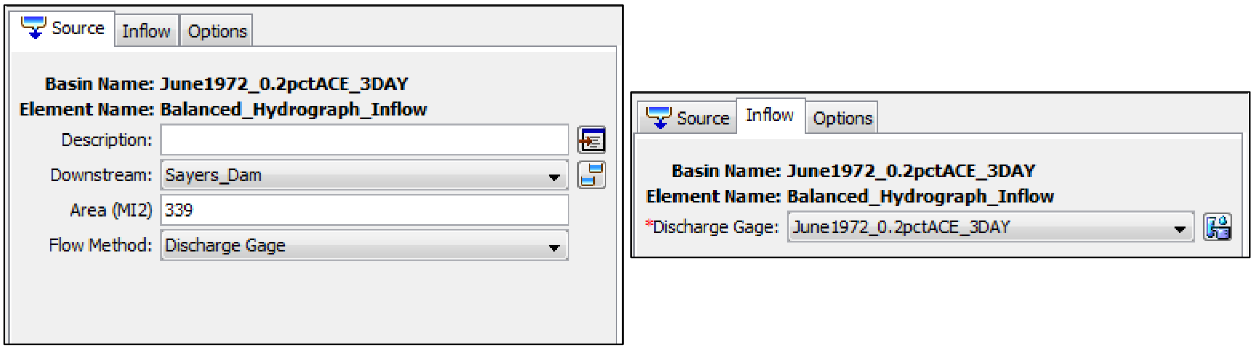
   - Figure 78 shows the Reservoir editor populated with the required data.



Basin Name: June1972_0.01pctACE_3DAY
Element Name: Sayers_Dam
Description:
Downstream: --None--
Method: Outflow Curve
Storage Method: Elevation-Storage-Discharge
*Stor-Dis Function: Sayers - Storage-Discharge
*Elev-Stor Function: Sayers - Elevation-Storage
Primary: Storage-Discharge
Initial Condition: Elevation
*Initial Elevation (FT) 630

Figure 78: HEC-HMS Reservoir Editor

5. The Source element should be configured to use the **Discharge Gage** flow method. Also, the contributing drainage area should be entered within the **Area** field.
    - *Note*: The previously created **Discharge Gage** should be selected on the **Inflow** tab.
    - The completed Source element editor populated with the required data is shown in Figure 79.

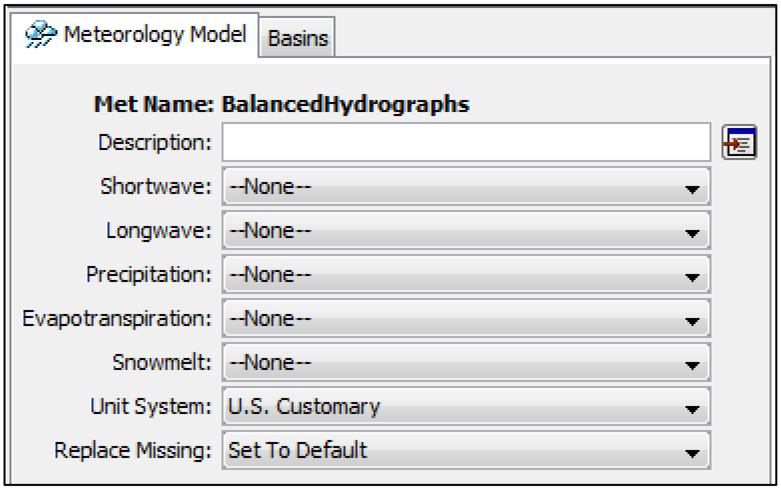


Basin Name: June1972_0.2pctACE_3DAY
Element Name: Balanced_Hydrograph_Inflow
Description:
Downstream: Sayers_Dam
Area (MI2) 339
Flow Method: Discharge Gage

Basin Name: June1972_0.2pctACE_3DAY
Element Name: Balanced_Hydrograph_Inflow
*Discharge Gage: June1972_0.2pctACE_3DAY

Figure 79: HEC-HMS Source Element Editor

6. Create a new meteorologic model.
    - *Note*: Set all of the hydro-meteorologic inputs/methods to “None” and set the replace missing option to **Set to Default**. Link the new meteorologic model to the basin model.
    - The completed meteorologic model editor is shown in Figure 80.



Met Name: BalancedHydrographs

Description:

Shortwave: --None--

Longwave: --None--

Precipitation: --None--

Evapotranspiration: --None--

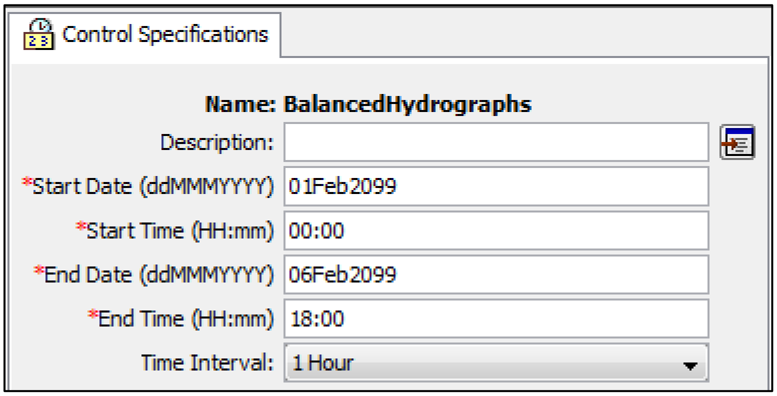
Snowmelt: --None--

Unit System: U.S. Customary

Replace Missing: Set To Default

Figure 80: HEC-HMS Meteorologic Model Editor

7. Create a control specification that contains the time window for model simulations.
    - *Note*: The time window should correspond to the time window(s) used for the flood event hydrograph(s). However, the time window may need to be extended to fully capture the peak pool elevation as the hydrograph is routed through the dam/reservoir in question.
    - The control specification parameters are shown in Figure 81.



Name: BalancedHydrographs

Description:

*Start Date (ddMMMYYYY) 01Feb2099

*Start Time (HH:mm) 00:00

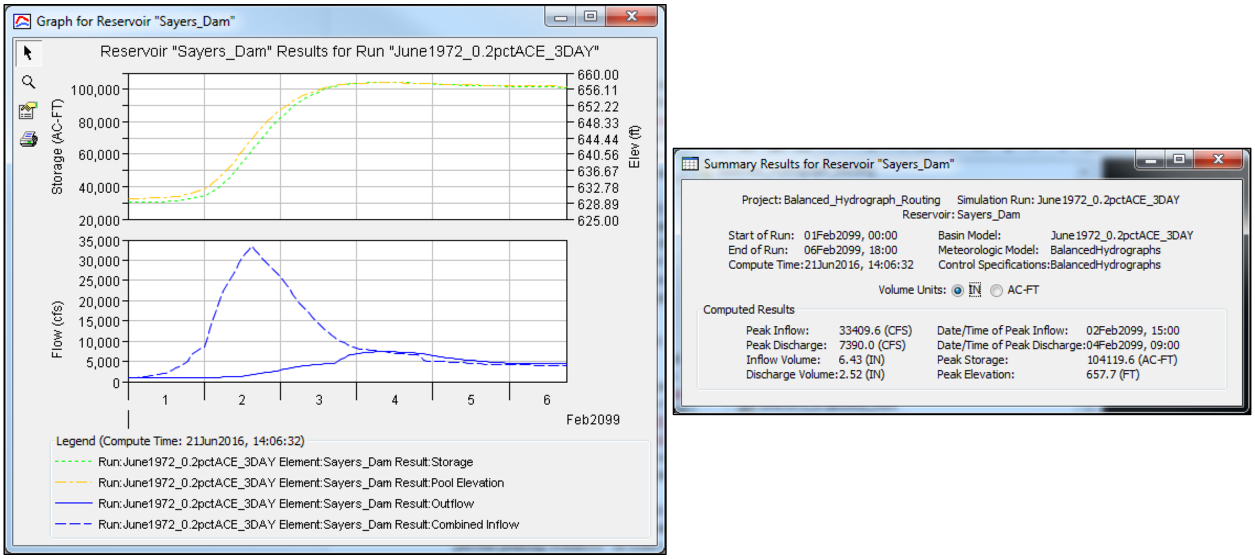
*End Date (ddMMMYYYY) 06Feb2099

*End Time (HH:mm) 18:00

Time Interval: 1 Hour

Figure 81: HEC-HMS Control Specifications Editor

8. Create a simulation that links the basin model, meteorologic model, and control specification.
    - *Note*: Additional simulations should be added to include additional flood hydrograph shapes.
9. Compute the simulation.
10. Examine the peak pool elevation obtained from the HEC-HMS model using both the Graph and Summary Table. The Graph and Summary Table are shown in Figure 82.



Project: Balanced_Hydrograph_Routing Simulation Run: June1972_0.2pctACE_3DAY
Reservoir: Sayers_Dam

Start of Run: 01Feb2099, 00:00
End of Run: 06Feb2099, 18:00
Compute Time: 21Jun2016, 14:06:32
Basin Model: June1972_0.2pctACE_3DAY
Meteorologic Model: BalancedHydrographs
Control Specifications: BalancedHydrographs

Volume Units: ● IN ○ AC-FT

Computed Results

Peak Inflow: 33409.6 (CFS)
Peak Discharge: 7390.0 (CFS)
Inflow Volume: 6.43 (IN)
Discharge Volume: 2.52 (IN)
Date/Time of Peak Inflow: 02Feb2099, 15:00
Date/Time of Peak Discharge: 04Feb2099, 09:00
Peak Storage: 104119.6 (AC-FT)
Peak Elevation: 657.7 (FT)

Figure 82: HEC-HMS Graph and Summary Table

Reservoir Stage-Frequency Analysis

This chapter describes how to estimate a reservoir stage-frequency curve with uncertainty bounds using the reservoir frequency analysis software, RMC-RFA. Because risk analysis focuses on decision making under uncertainty, quantifying uncertainty is a critical component of any risk analysis. Separating what is known from what is not known is a primary responsibility of the risk assessor. A major purpose of a SQRA is to motivate risk assessors and risk managers to be intentional in how they address uncertainty in analysis and decision making.

There are two primary components of randomness in inflow volume and reservoir stage exceedance probabilities: natural variability and knowledge uncertainty. Natural variability is best described as the effect of randomness and is a function of the system (Vose, 2008). It is not reducible through either study or further measurement. For example, a peak flow-frequency curve describes the natural variability in peak flow.

Knowledge uncertainty is the lack of knowledge about parameters that characterize the system being modeled. Knowledge uncertainty can be reduced through further measurement or study. For example, the confidence intervals, or uncertainty bounds, around a flood frequency curve describe the knowledge uncertainty in the statistical parameters of the flood frequency curve.

For the purposes of RMC-RFA, the most important distinction is that natural variability cannot be reduced with more or better information. Whereas, knowledge uncertainty can be reduced with more and better information through means of additional measurement, more detailed studies, data collection, data quality control, filling gaps in missing gage data, and record extension through the inclusion of historical, regional, and/or paleoflood data. Recall, that historical flood events and paleoflood data can be used to effectively extend the period of record. Knowledge uncertainty decreases as the effective record length increases.

Overview of the RMC-RFA Methodology

The USACE Risk Management Center (RMC) developed the RMC-RFA software to facilitate hydrologic hazard assessments within the USACE Dam Safety Program. RMC-RFA produces a reservoir stage-frequency curve with uncertainty 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. Knowledge uncertainty in the inflow volume frequency distribution is simulated in the outer loop, which comprises many realizations. The basic construct of the simulation procedure employed by RMC-RFA is illustrated in Figure 83. The model parameters that are treated as random variables in RMC-RFA are listed in Table 12. For more information on the RMC-RFA methodology please see (RMC-RFA User's Manual, 2017) and (Smith & England, 2017).

Table 12: Model Parameters Treated as Random Variables

Input Parameter	Dependency	Statistical Distribution	Sampling Approach
Inflow Volume	Independent	Analytical	Importance/Stratified
Inflow Hydrograph Shape	Independent	Empirical	Monte Carlo
Flood Season	Independent	Empirical	Monte Carlo
Reservoir Starting Stage	Flood Season	Empirical	Monte Carlo

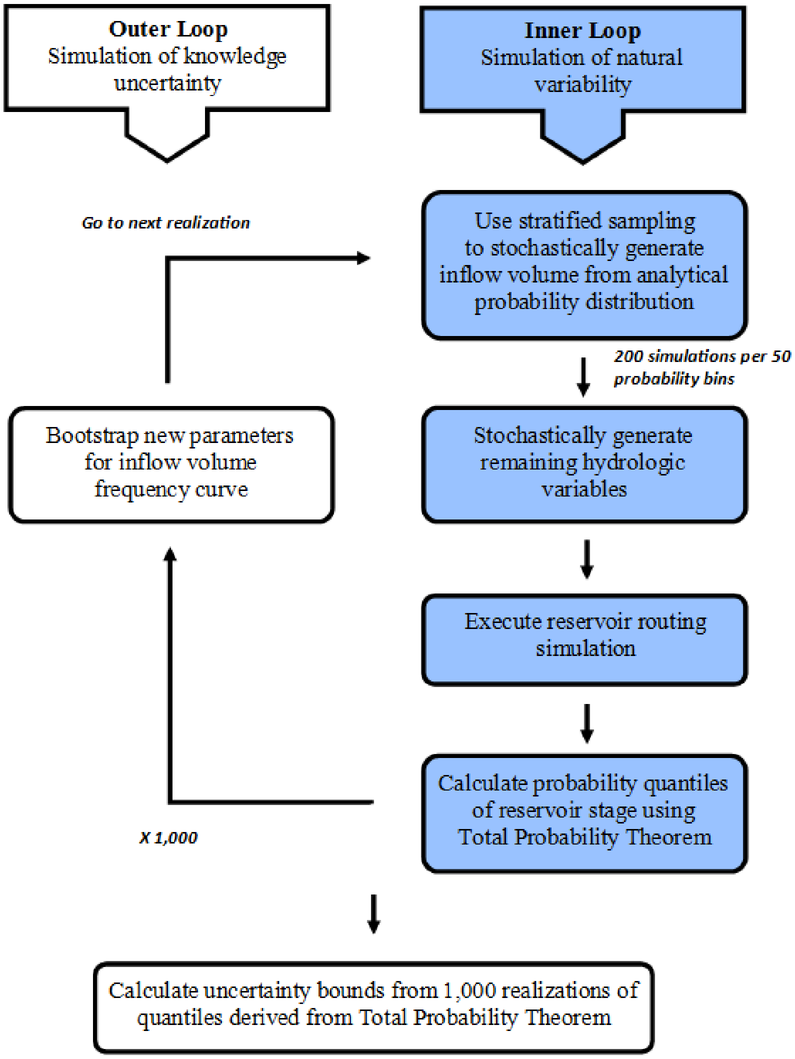


Figure 83: Flowchart of the Steps Involved in the RMC-RFA Simulation

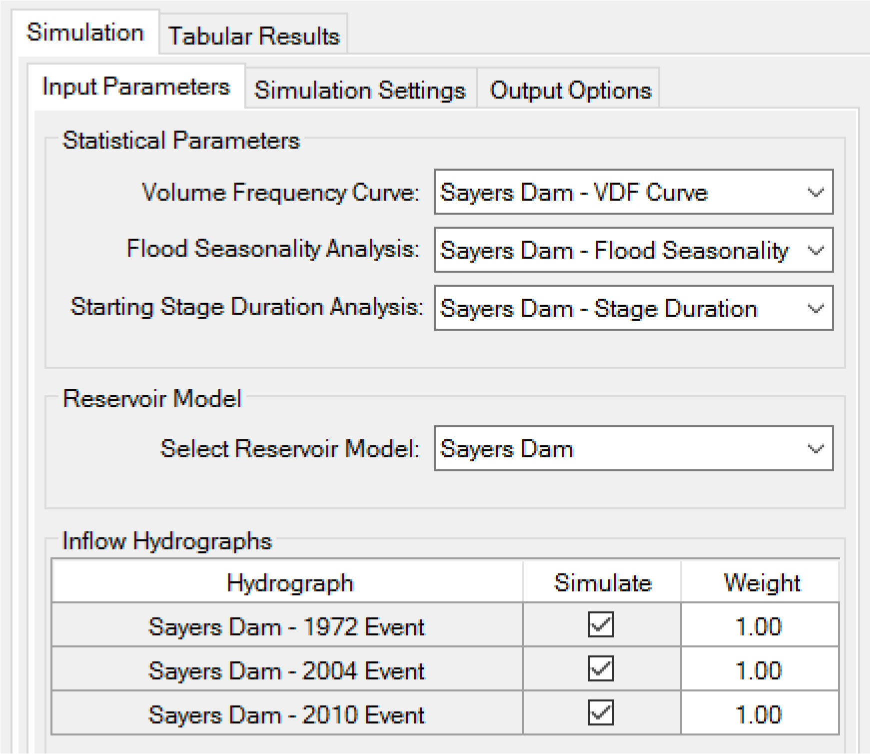
Computing Reservoir Stage-Frequency Using RMC-RFA

The RMC-RFA User’s Manual provides an excellent step-by-step guide for setting up a project and simulation (RMC-RFA User's Manual, 2017). This section will only provide an overview of the model inputs and simulation settings that are required for computing a reservoir stage-frequency analysis using RMC-RFA for an SQRA.

RMC-RFA Model Inputs

An RMC-RFA simulation requires the six primary model inputs listed below and shown in Figure 84. The previous chapters in this document described how to develop all necessary inputs for RMC-RFA.

- Inflow Volume-Frequency Curve
- Flood Seasonality Analysis
- Reservoir Starting Stage Duration Analysis
- Reservoir Model
- Inflow Hydrograph Shapes
- Empirical Stage-Frequency Curve



Simulation | Tabular Results

Input Parameters | Simulation Settings | Output Options

Statistical Parameters

Volume Frequency Curve: Sayers Dam - VDF Curve

Flood Seasonality Analysis: Sayers Dam - Flood Seasonality

Starting Stage Duration Analysis: Sayers Dam - Stage Duration

Reservoir Model

Select Reservoir Model: Sayers Dam

Inflow Hydrographs

Hydrograph	Simulate	Weight
Sayers Dam - 1972 Event	☑	1.00
Sayers Dam - 2004 Event	☑	1.00
Sayers Dam - 2010 Event	☑	1.00

Figure 84: RMC-RFA Simulation Input Parameters

Inflow Volume-Frequency Curve

The critical inflow duration was determined to be 3-days. The volume-duration-frequency curve was derived as described in the Inflow Volume-Frequency Analysis chapter. The volume-frequency curve was fit using a Log Pearson Type III distribution with a mean (of log) of 3.457, a standard deviation (of log) of 0.195, a skew (of log) of 0.800, and an effective record length of 48.

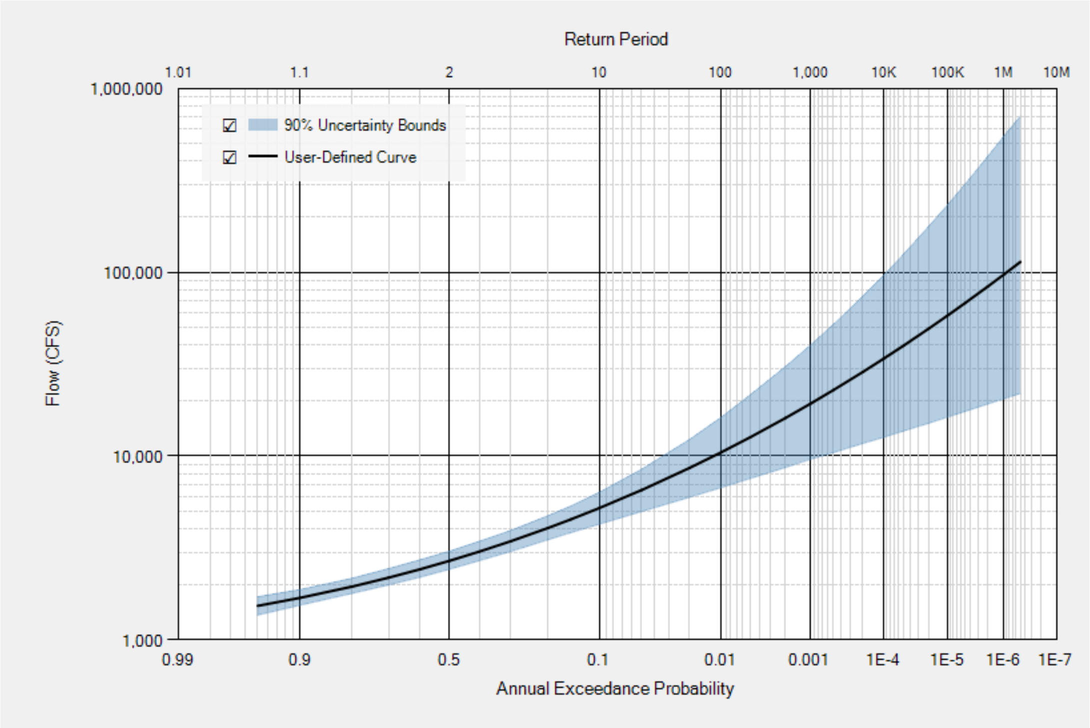


Figure 85: Volume-frequency Curve as Plotted in RMC-RFA.

Flood Seasonality Analysis

The flood seasonality was estimated as described in the Flood Seasonality Analysis chapter and showed strong agreement with the climate and flood runoff characteristics of the watershed as described in the water control manual.

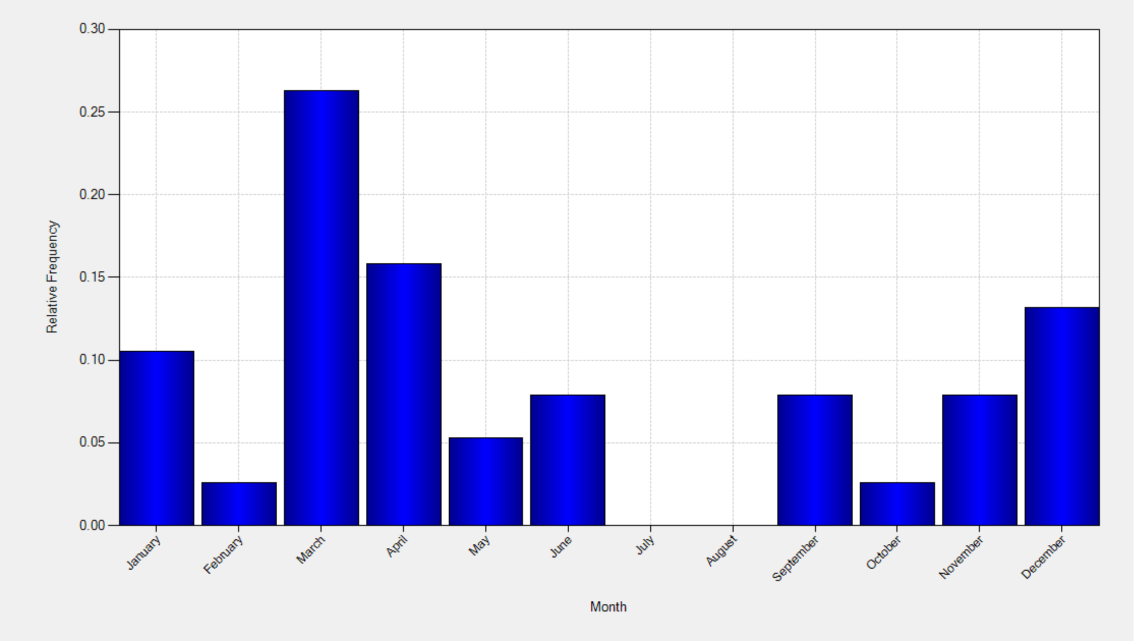


Figure 86: RMC-RFA Flood Seasonality Analysis

Starting Stage Duration Analysis

The starting stage duration curves were estimate as described in Reservoir Starting Pool Duration Analysis chapter and illustrate the impacts of the seasonal guide curves used for reservoir operations.

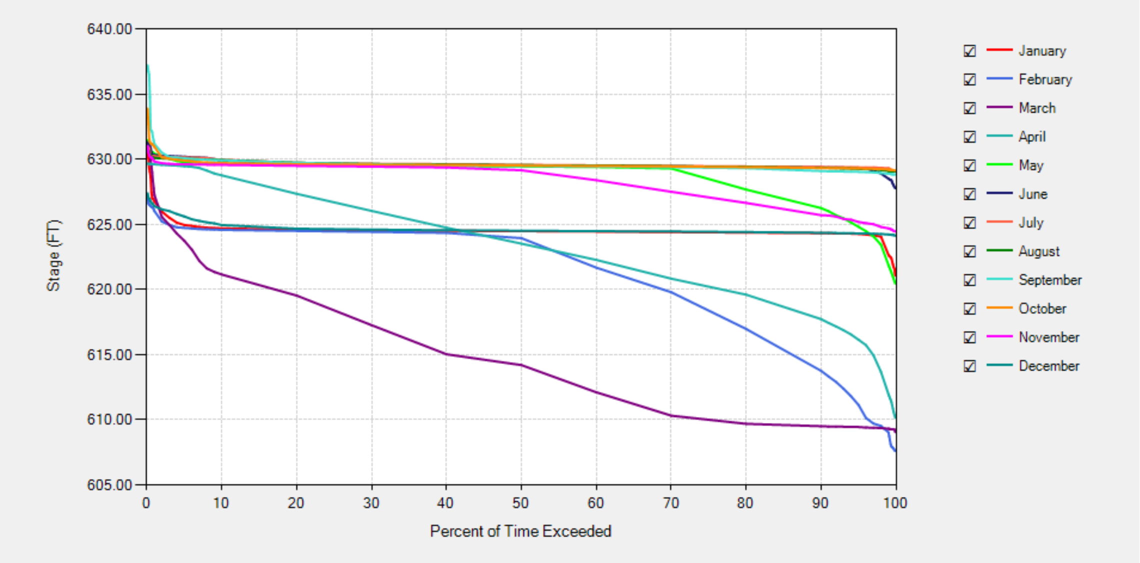


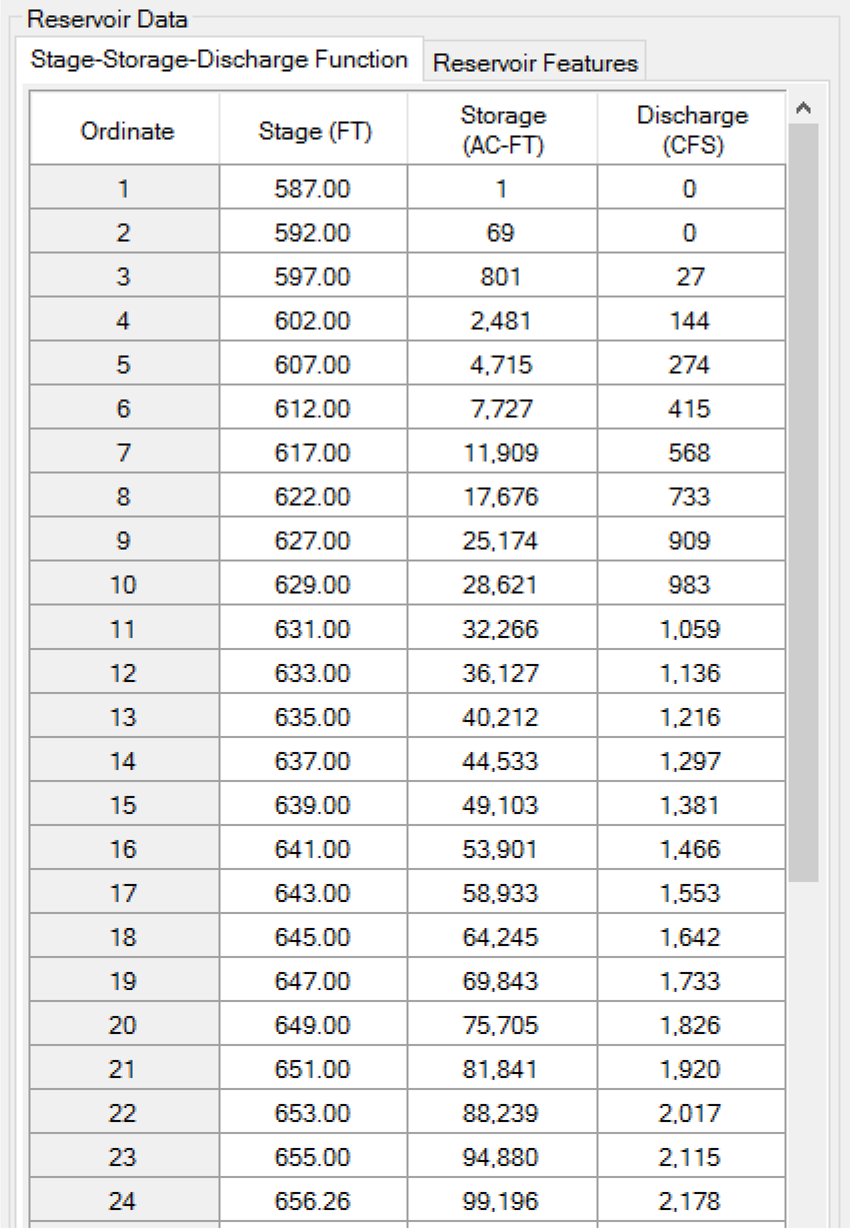
Figure 87: RMC-RFA Starting Stage Duration Curves

Reservoir Model

Reservoir routing in RMC-RFA is based on a “hydrologic method”, which is concentrated on the concept of storage for the flood water and does not directly include effects of resistance to the flow. The reservoir model development was shown in the Reservoir Model Development chapter.

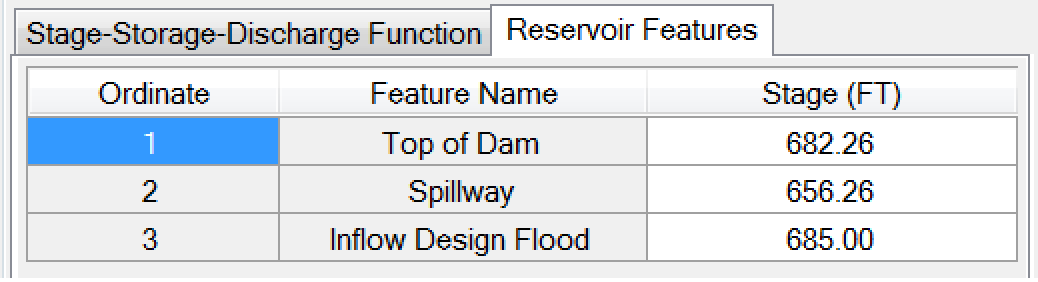
RMC-RFA requires a stage-storage-discharge function and elevations for select reservoir features, specifically the top of dam, spillway, and inflow design flood elevations as shown in Figure 88 and Figure 89. These reservoir features are used as reference points to aid with interpretation of simulation results.

It is important that the stage-storage-discharge function is extended beyond the top of dam to include overtopping discharge information. Extreme overtopping flood events will likely be sampled in the stochastic simulation. Therefore, reservoir stage-overtopping discharge relationships need to be developed to ensure that the model is capable of routing the extreme flood events. Extending the stage-storage-discharge function to five feet above the top of dam will likely be adequate for the purposes of an SQRA.



Ordinate	Stage (FT)	Storage (AC-FT)	Discharge (CFS)
1	587.00	1	0
2	592.00	69	0
3	597.00	801	27
4	602.00	2,481	144
5	607.00	4,715	274
6	612.00	7,727	415
7	617.00	11,909	568
8	622.00	17,676	733
9	627.00	25,174	909
10	629.00	28,621	983
11	631.00	32,266	1,059
12	633.00	36,127	1,136
13	635.00	40,212	1,216
14	637.00	44,533	1,297
15	639.00	49,103	1,381
16	641.00	53,901	1,466
17	643.00	58,933	1,553
18	645.00	64,245	1,642
19	647.00	69,843	1,733
20	649.00	75,705	1,826
21	651.00	81,841	1,920
22	653.00	88,239	2,017
23	655.00	94,880	2,115
24	656.26	99,196	2,178

Figure 88: Reservoir Data Table for Foster Joseph Sayers Dam



Ordinate	Feature Name	Stage (FT)
1	Top of Dam	682.26
2	Spillway	656.26
3	Inflow Design Flood	685.00

Figure 89: Reservoir Features for Foster Joseph Sayers Dam

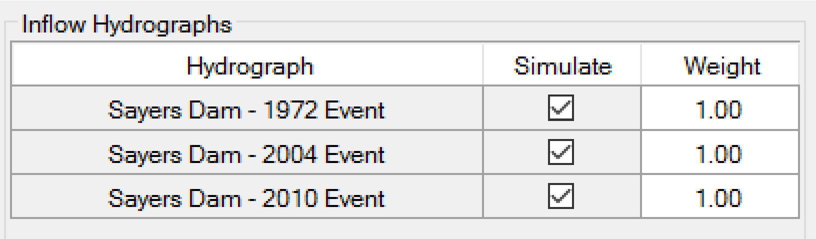
Inflow Hydrograph Shapes

Inflow hydrographs for major historical events, large events, or synthetic events should be entered. The shape of the hydrograph is a reflection of the response of the watershed to an event. At least one inflow hydrograph shape is required to perform a simulation. Multiple inflow hydrographs can be sampled as part of the simulation. The inflow hydrograph shape is scaled up or down based on the sampled inflow volume in the stochastic simulation.

- *Note*: An observed inflow hydrograph from a major event should be used if at all possible. However, if no such events are available the PMF or IDF hydrograph may be utilized.

- *Note*: RMC-RFA will scale the entire input hydrograph shape to match the sampled inflow volume based on the user-defined critical inflow duration set in the **Volume Frequency Curve** input. For example, if a 3-day duration is selected as the critical duration, RMC-RFA will calculate a 3-day moving average of the input hydrograph. The maximum value from this moving average will then be used to derive a scale ratio for the sampled volume from the Monte Carlo procedure.

For this example, the 1972, 2004, and 2010 events described in the Critical Inflow Duration Analysis section were used in the RMC-RFA simulation. The three hydrograph shapes used in this example were given equal probability of occurrence since there is limited hydrograph data available for large events in the watershed to suggest a different weighting scheme.

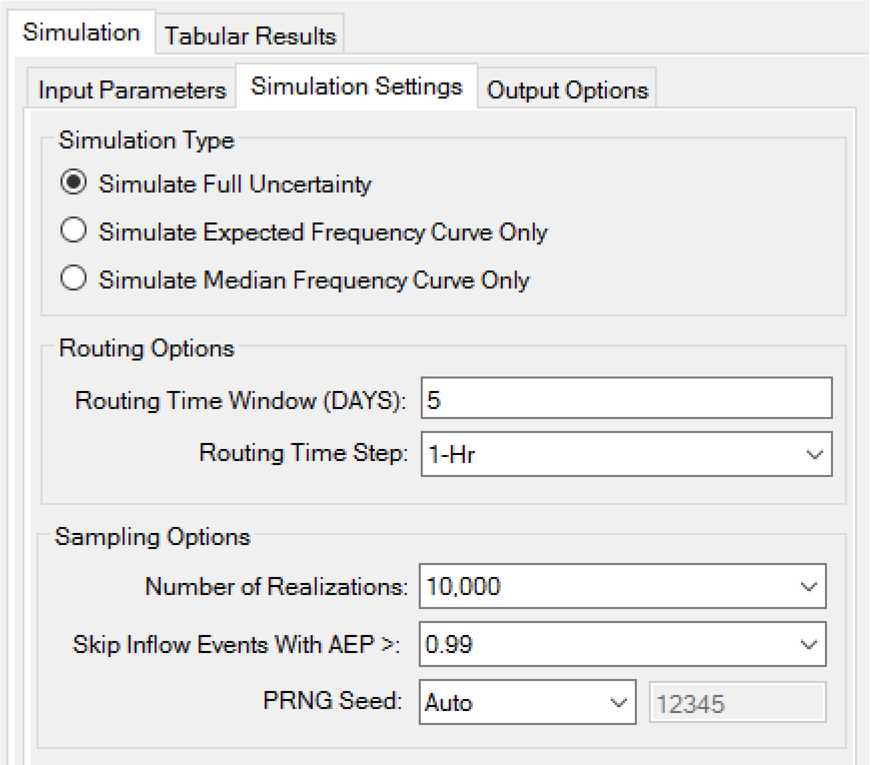


Hydrograph	Simulate	Weight
Sayers Dam - 1972 Event	☑	1.00
Sayers Dam - 2004 Event	☑	1.00
Sayers Dam - 2010 Event	☑	1.00

Figure 90: Inflow Hydrograph Weights

RMC-RFA Simulation Settings

When you have finished inputting the pertinent data, navigate to the **Simulation Settings** tab as shown below in Figure 91. The RMC-RFA User's Manaul provides a detailed description of each element in the simulations settings. This section will only discuss the most critical simulation settings required for a SQRA.



Simulation Type

● Simulate Full Uncertainty

○ Simulate Expected Frequency Curve Only

○ Simulate Median Frequency Curve Only

Routing Options

Routing Time Window (DAYS): 5

Routing Time Step: 1-Hr

Sampling Options

Number of Realizations: 10,000

Skip Inflow Events With AEP >: 0.99

PRNG Seed: Auto 12345

Figure 91: RMC-RFA Simulation Settings

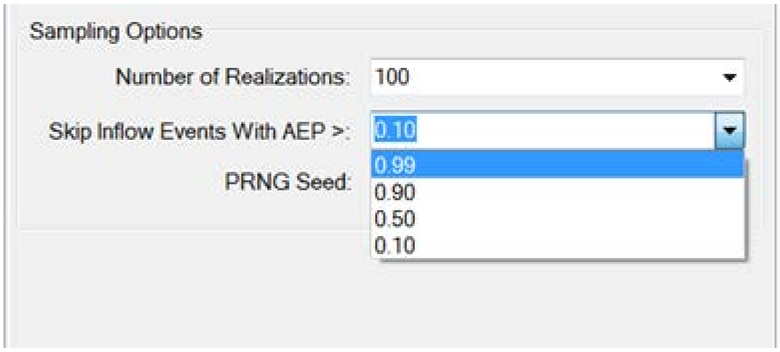
Three options are available for simulation type:

- Simulate Full Uncertainty
- Simulate Expected Frequency Curve Only
- Simulate Median Frequency Curve Only

For rapid sensitivity analysis, the user should select either **Simulate Expected Frequency Curve Only** or **Simulate Median Frequency Curve Only** as run times are much shorter. **Simulate Full Uncertainty** will have the longest run time, as it calculates the Median Curve, Expected Curve, and Uncertainty Bounds. For an SQRA, make sure to simulate **10,000 Realizations** to ensure precision in the resulting uncertainty bounds.

The routing option labeled **Routing Time Window (DAYS)** indicates the number of days to route the simulation. This value should be at least as long as the critical inflow duration defined by the Volume Frequency Curve input. The routing time window needs to be long enough to ensure the reservoir stage has had enough time to crest in order to capture peak stage values.

The **Skip Inflow Events With AEP >** option allows the user to skip inflow events with an annual exceedance probability greater than the value selected in the drop down menu, which is shown in the figure below. For an SQRA, make sure to run the full frequency curve by selecting **0.99**.



Number of Realizations: 100
Skip Inflow Events With AEP >: 0.10
PRNG Seed:

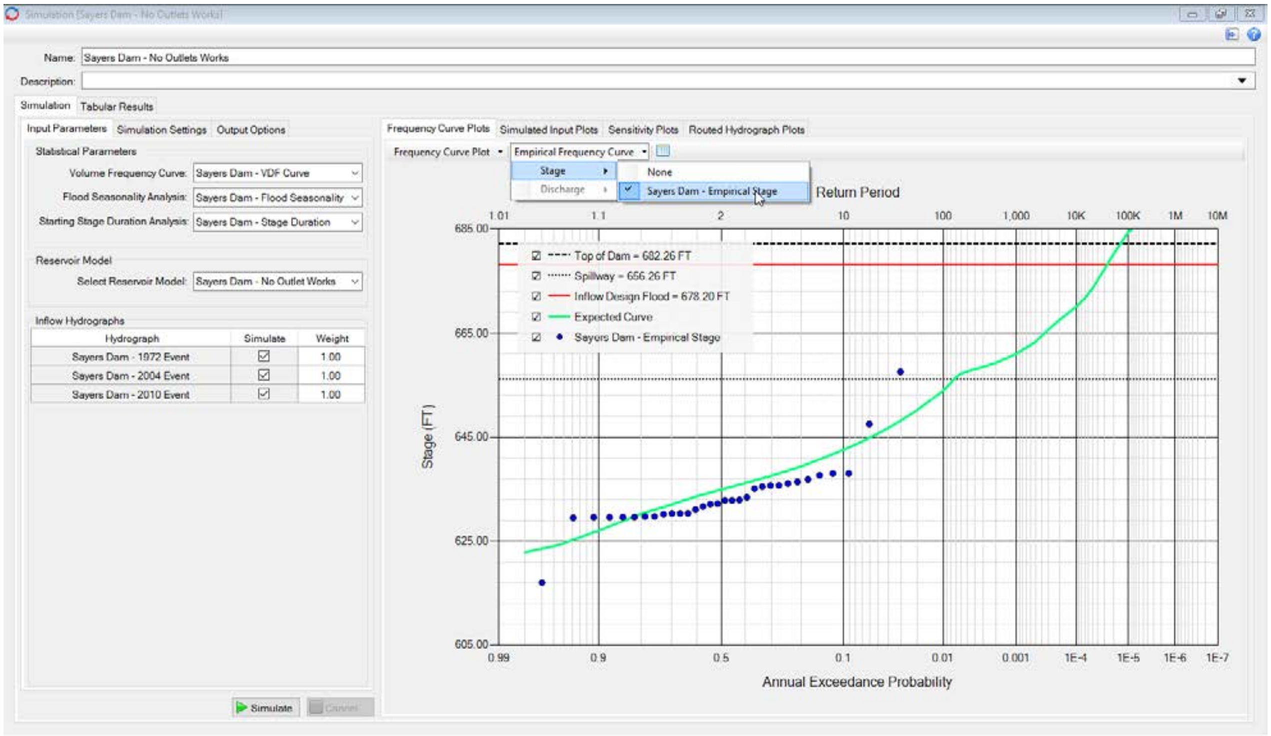
Figure 92: RMC-RFA Skip Inflow Events Option

After you have selected the input parameters and selected the proper simulation settings, click the **Simulate** button. Runtimes for the **Simulate Full Uncertainty** could exceed 30 minutes up to a few hours in duration depending on the inputs and the properties of the computer. The **Simulate Expected (and Median) Frequency Curve Only** options will only take seconds to compute. It is recommended that the **Expected Only** option is used for preliminary calibration runs. However, final results should be based off of the **Full Uncertainty** results.

Stage-Frequency Calibration

Before running the **Full Uncertainty** simulation, it is important to run a few preliminary calibration runs using the **Expected Only** option. The purpose of the calibration runs is to ensure the simulated stage-frequency curve fits well with the empirical stage-frequency curve derived previously in the Empirical Stage-Frequency Analysis section. If the simulated stage-frequency curve plots well compared to the observed data, then we will have more confidence in the estimated exceedance probabilities for much rarer flood events, such as those that would cause overtopping.

1. First, create a stage-storage-discharge function that assumes zero releases from the outlet works. Then, run an RMC-RFA expected only simulation. After the RMC-RFA simulation has completed, the empirical stage-frequency curve data can be displayed on the same plot as shown below in Figure 93. The simulated expected stage-frequency curve assuming zero outlet work discharges is shown in Figure 94.



Name: Sayers Dam - No Outlets Works
Description:

Volume Frequency Curve: Sayers Dam - VDF Curve
Flood Seasonality Analysis: Sayers Dam - Flood Seasonality
Starting Stage Duration Analysis: Sayers Dam - Stage Duration
Select Reservoir Model: Sayers Dam - No Outlet Works

Hydrograph	Simulate	Weight
Sayers Dam - 1972 Event	☑	1.00
Sayers Dam - 2004 Event	☑	1.00
Sayers Dam - 2010 Event	☑	1.00

Frequency Curve Plot: Empirical Frequency Curve
Stage: ✓ Sayers Dam - Empirical Stage

Figure 93: Stage-Frequency Curve with Empirical Frequency Curve Displayed in RMC-RFA

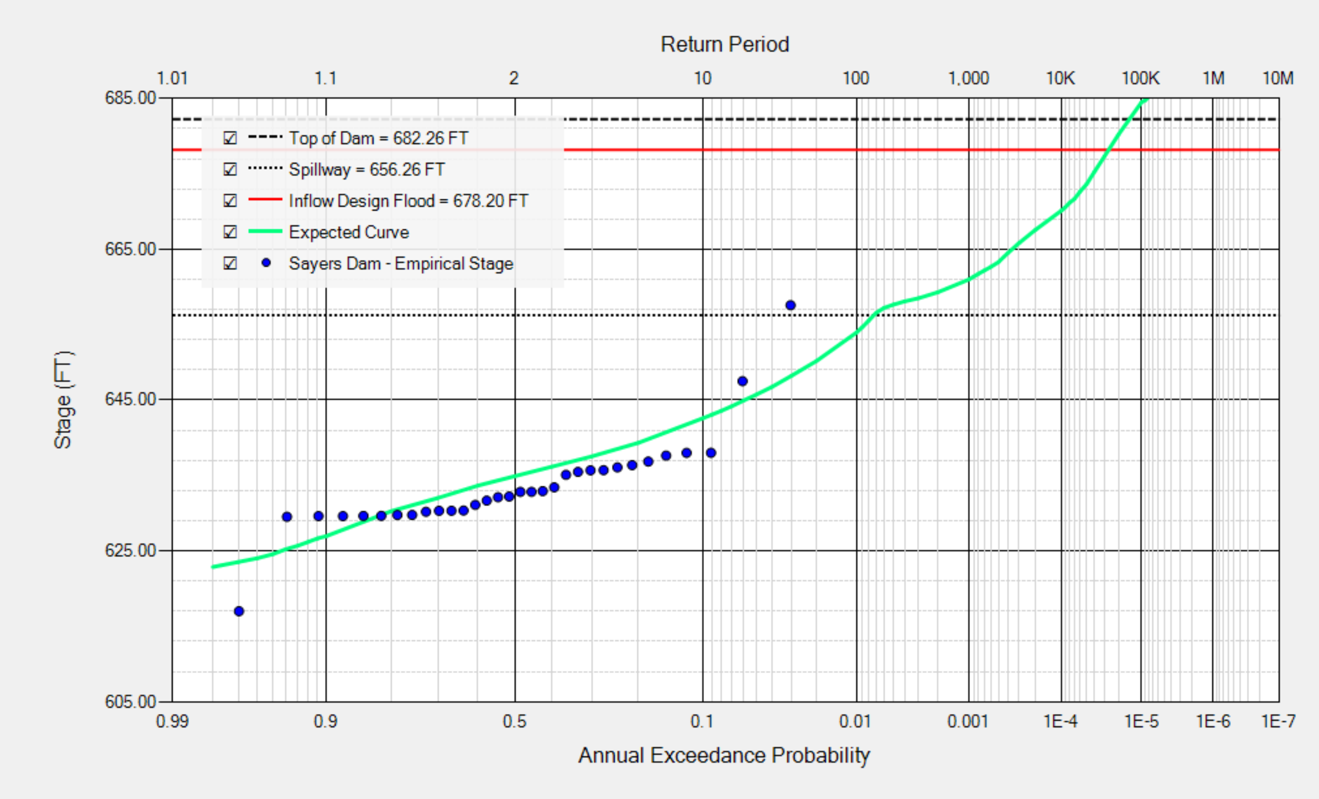


Figure 94: Expected Stage-Frequency Curve Assuming Zero Outlet Work Discharges

2. As you can see, the simulated stage-frequency curve fits the empirical data relatively well. Assuming zero outlet works releases results in simulated stages that are slightly higher than the observed data for frequent events in the 0.5 AEP range. Conversely, the simulated curve produces lower stages as compared to less frequent events in the 0.1 to 0.01 AEP range. However, it is important to remember that the empirical frequency curve is based on a very limited data set. It is likely that these high events are plotting more frequently than they should be. A longer period of record might reveal that these high events will actually plot further to the right and closer to the simulated curve, but the actual plotting position is unknown. Because these events are most likely outliers, we will focus our calibration on the more frequent events.

3. Next, run an RMC-RFA expected only simulation using the reservoir model developed in the Reservoir Model Development chapter. In that chapter, we created an outlet works stage-discharge trendline equation derived using observed discharges averaged over five foot stage bands. The simulated expected stage-frequency curve using the outlet works stage-discharge function defined by trendline equation is shown in Figure 95.

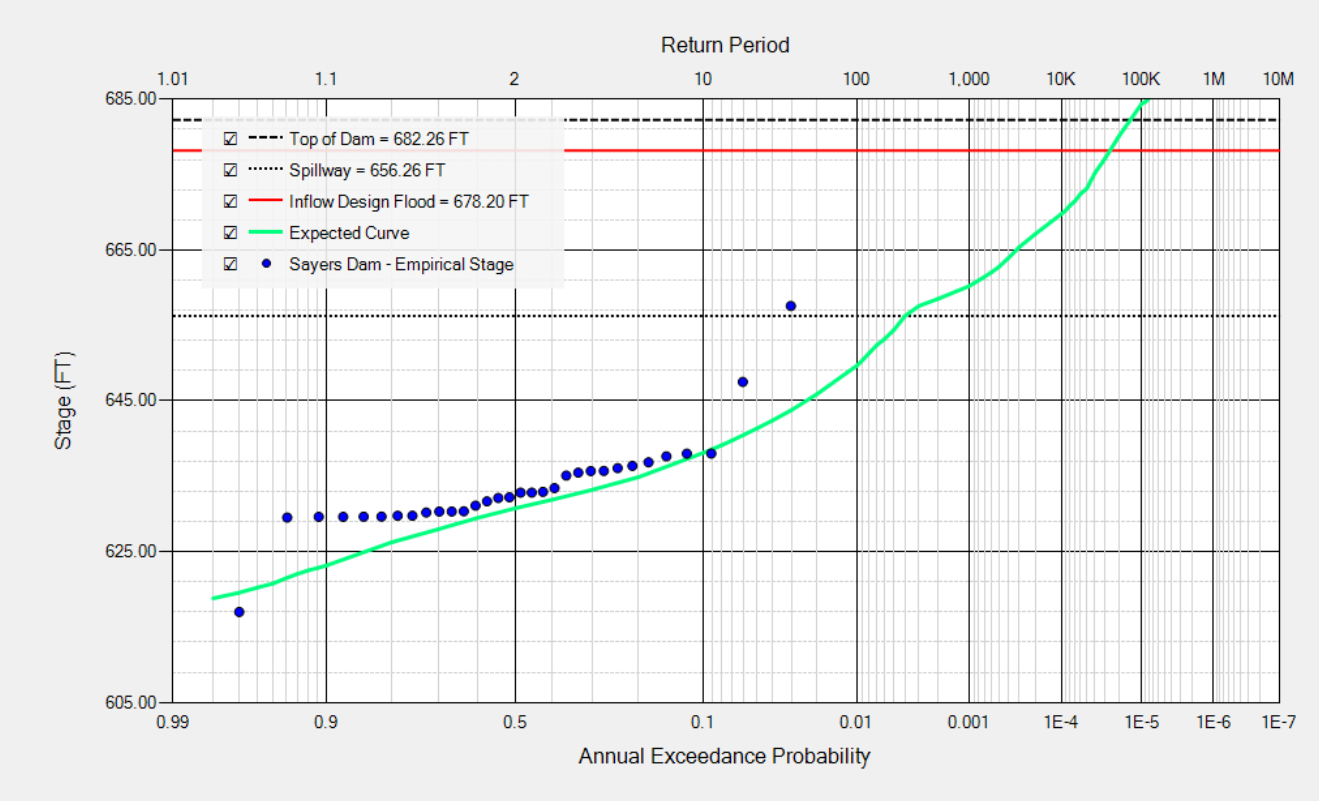


Figure 95: Expected Stage-Frequency Curve Using Outlet Works Stage-Discharge Function Defined by Trendline Equation

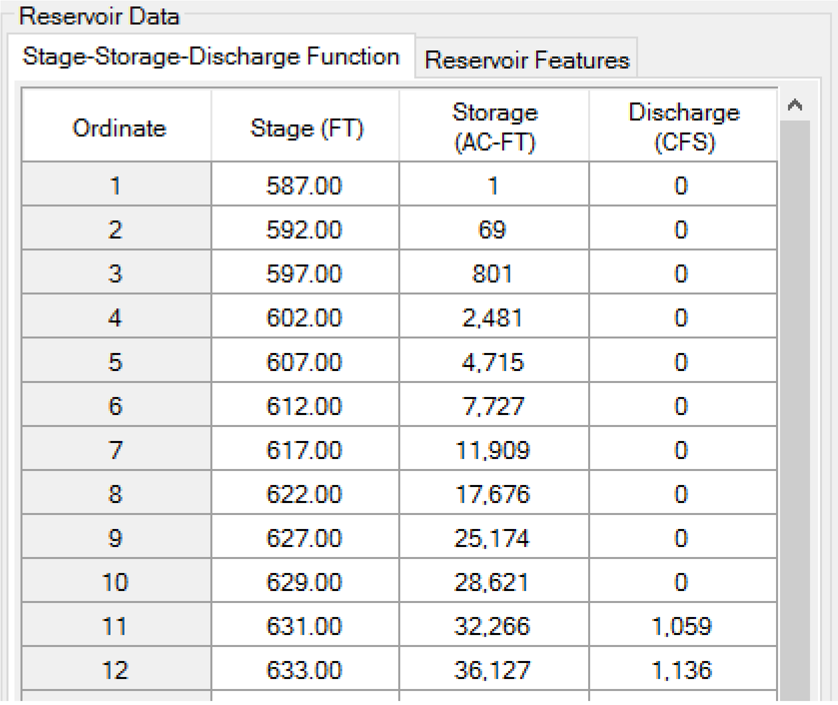
4. As you can see, this stage-frequency curve also fits relatively well with the historic data. However, the simulated stages are slightly lower than the observed data for frequent events in the 0.9 to 0.1 AEP range. The outlet works rating curve needs to be adjusted again in order to improve the fit.

5. The reservoir elevation guide curve for Foster Joseph Sayers Dam is shown on Plate 7-01 of the water control manual (U.S. Army Corps of Engineers, 1996) and is shown in Figure 59 of the Reservoir Starting Pool Duration Analysis chapter. As you can see from the guide curve, the priority is to keep the pool at 630 feet for the majority of the year. Releases under this condition would be limited to merely passing inflow. It is likely that for most years, releases would be minimal or near zero.

6. Next, using the outlet works stage-discharge trendline equation derived using observed discharges averaged over five foot stage bands, set all discharges to zero for stages less than 630 feet as shown in Figure 96. The simulated expected stage-frequency curve, using the adjusted outlet works stage-discharge function, is shown in Figure 97.

7. As you can see from Figure 97, the simulated stage-frequency curve has very strong agreement with the empirical frequency curve for events in the 0.9 to 0.1 AEP range. Now that the stage-storage-discharge function has been calibrated, the **Full Uncertainty** simulation should be performed.

    - *Note*: When deriving a stage-discharge function, it is necessary to consult the project Water Control Manual for additional operational rules and seasonal guide curves to ensure that you are capturing all the project requirements and limitations. Regardless of how the stage-discharge function is ultimately derived and calibrated, do not forget to check that the stage-discharge relationship complies with the operational guide lines provided in the Water Control Manual.



Ordinate	Stage (FT)	Storage (AC-FT)	Discharge (CFS)
1	587.00	1	0
2	592.00	69	0
3	597.00	801	0
4	602.00	2,481	0
5	607.00	4,715	0
6	612.00	7,727	0
7	617.00	11,909	0
8	622.00	17,676	0
9	627.00	25,174	0
10	629.00	28,621	0
11	631.00	32,266	1,059
12	633.00	36,127	1,136

Figure 96: Calibrated Reservoir Data Table for Foster Joseph Sayers Dam

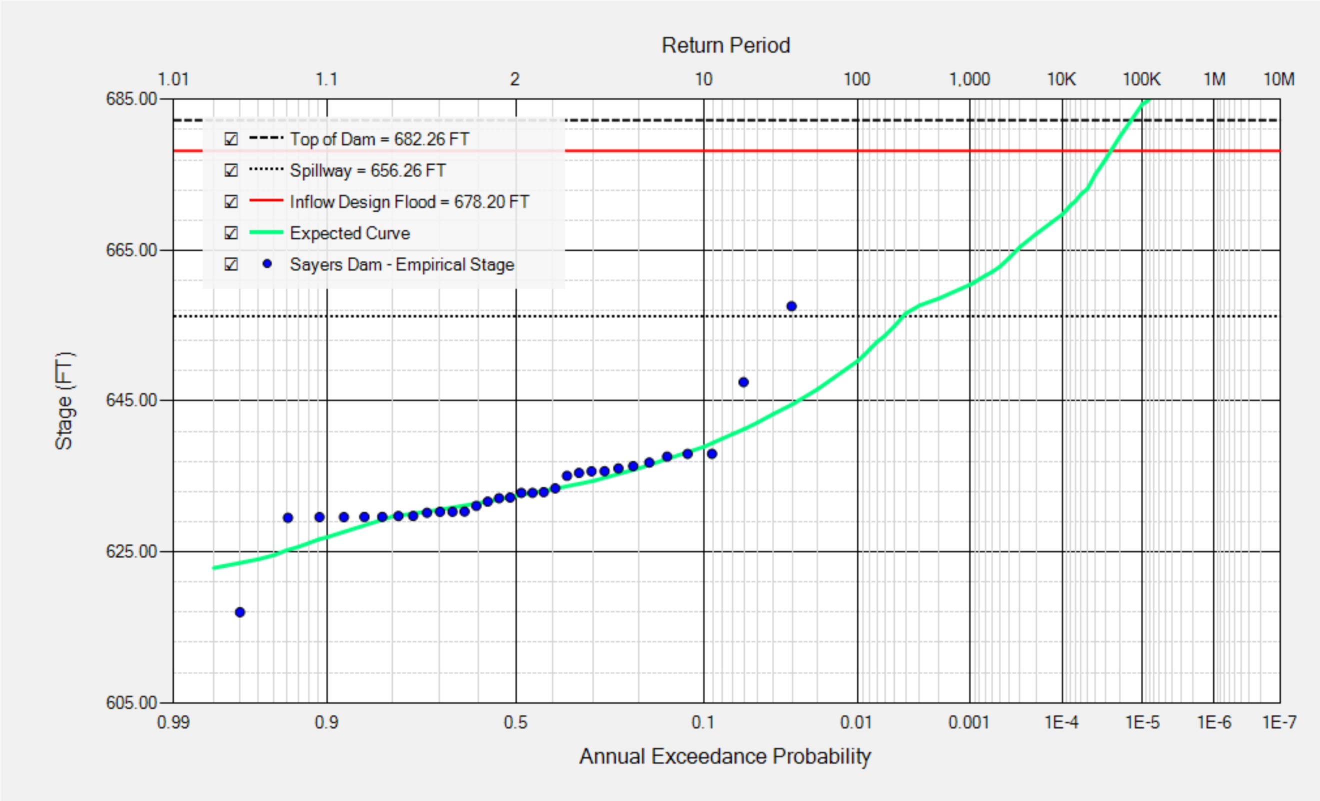


Figure 97: Expected Stage-Frequency Curve Using Calibrated Outlet Works Stage-Discharge Function

Stage-Frequency Results

When RMC-RFA finishes computing, it will automatically create the **Stage-Frequency Curve** plot as shown in Figure 98. The ***median curve*** represents the uncertainty in stage-frequency due to natural variability, the ***90% uncertainty bounds*** represent the uncertainty in stage-frequency due to knowledge uncertainty, whereas the ***expected curve*** represents the combined uncertainty due to both natural variability and knowledge uncertainty.

There is a high degree of knowledge uncertainty due to the short record length of the inflow volume-frequency curve, which was 48 years. As a result, the median curve does not adequately represent the long tail of the probability distribution. Therefore, instead of using the median to represent the "best-estimate" probability of exceedance, the mean is used for this analysis. The **expected curve** is considered the **best-estimate** because it reflects the relative likelihood of all probabilities of a stage exceeding a certain predefined stage, rather than the point where 50% of the exceedance probabilities lie either above or below the median curve. The expected curve implies that on average the estimated exceedance probability for a given reservoir stage is correct (U.S. Geological Survey, 1982).

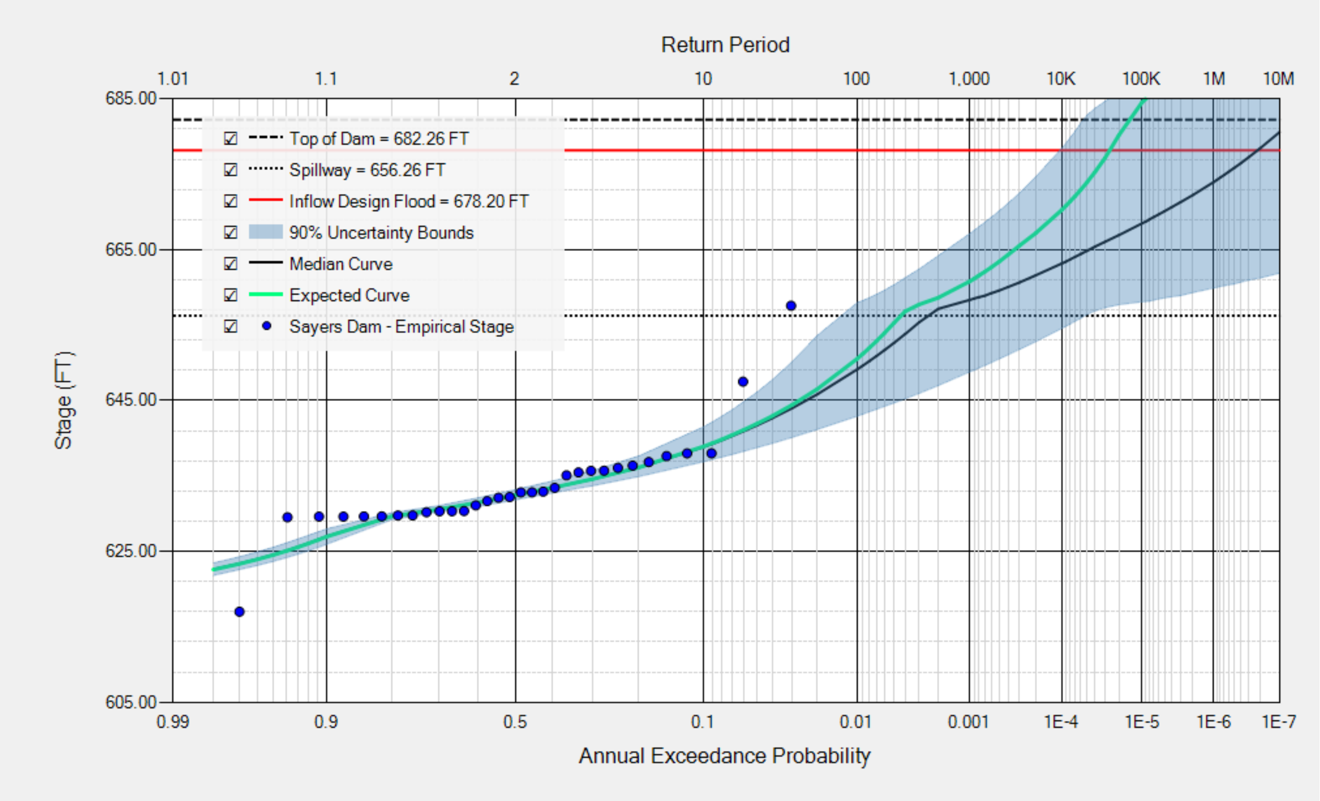


Figure 98: Stage-Frequency Chart Results

Recall, in the Empirical Stage-Frequency Analysis section, the last two points in the empirical stage-frequency curve (black dots) are actually more infrequent than there plotting positions would indicate as shown below in Figure 99. Using the Hirsch-Stedinger plotting position formula would improve the fit of the empirical frequency curve.

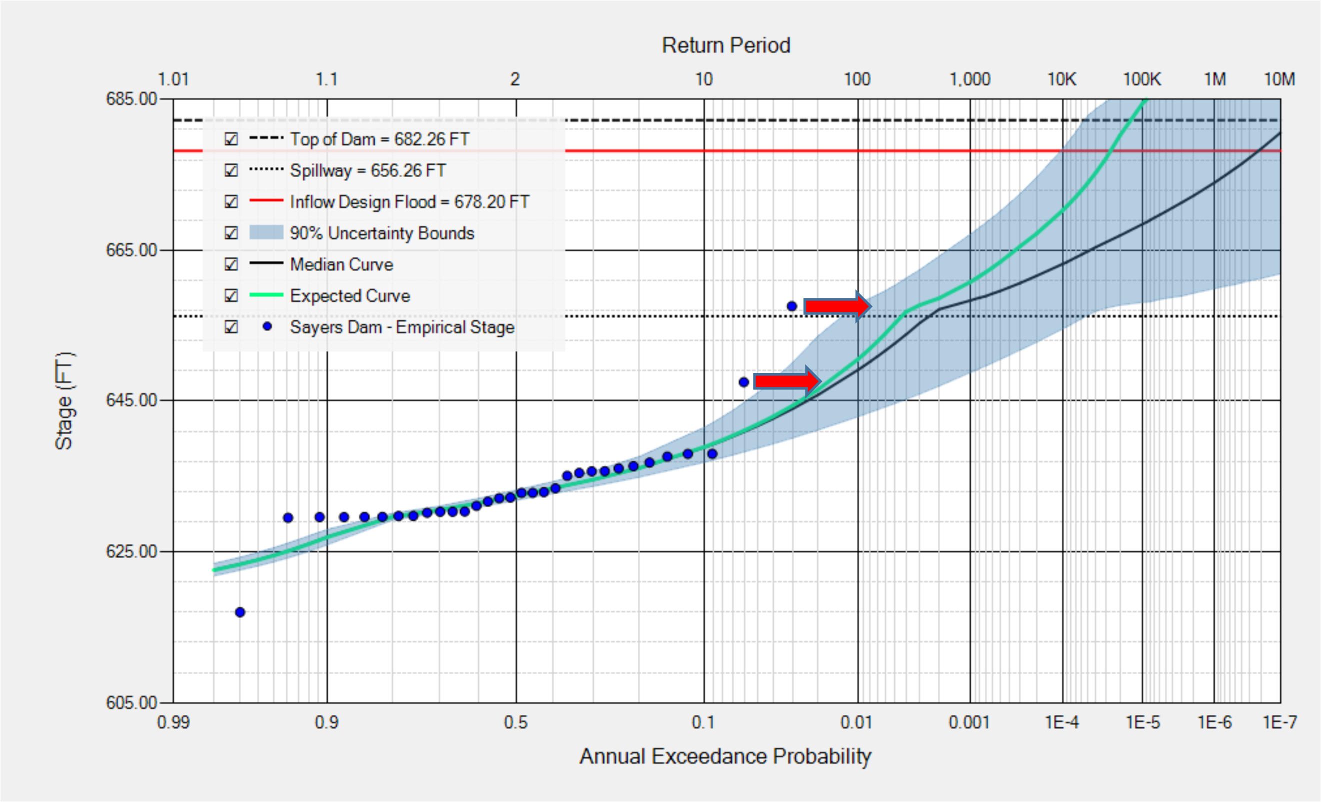
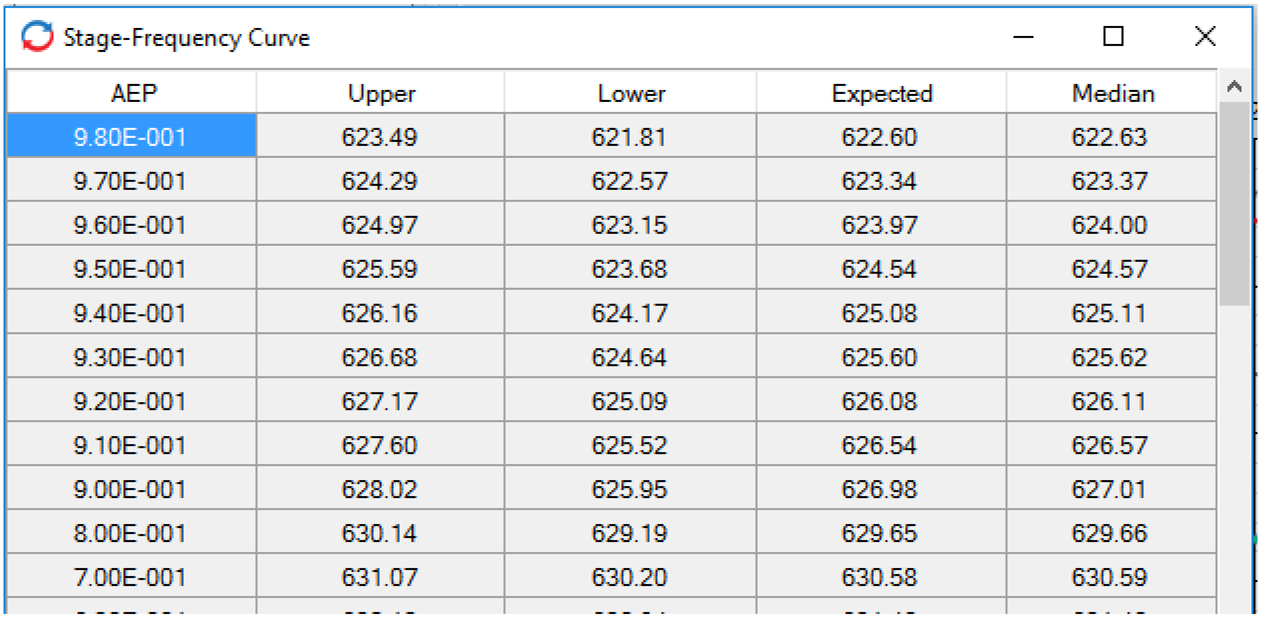


Figure 99: Stage-Frequency Chart, Showing Hypothetically Adjusted Historical Points

The stage-frequency curves results can be tabulated and exported by clicking the **Get Tabular Output** button ▦. The results are tabulated as shown in Figure 100.

- *Note*: RMC-RFA provides a full suite of plots for analyzing stage frequency results. Each of the simulated inputs can be plotted to ensure results look as expected. RMC-RFA provides sensitivity plots to demonstrate which input parameter has the greatest effect on peak stage. Finally, the routed hydrographs from each stochastic event can be plotted and tabulated for export. This feature is particularly useful for troubleshooting errors in results as well as outputting outflow hydrographs for evaluating potential spillway erosion failure modes. An example of routed stochastic event that results in a peak stage that overtops the dam is provided in Figure 101.



AEP	Upper	Lower	Expected	Median
9.80E-001	623.49	621.81	622.60	622.63
9.70E-001	624.29	622.57	623.34	623.37
9.60E-001	624.97	623.15	623.97	624.00
9.50E-001	625.59	623.68	624.54	624.57
9.40E-001	626.16	624.17	625.08	625.11
9.30E-001	626.68	624.64	625.60	625.62
9.20E-001	627.17	625.09	626.08	626.11
9.10E-001	627.60	625.52	626.54	626.57
9.00E-001	628.02	625.95	626.98	627.01
8.00E-001	630.14	629.19	629.65	629.66
7.00E-001	631.07	630.20	630.58	630.59

Figure 100: Stage-Frequency Tabular Output

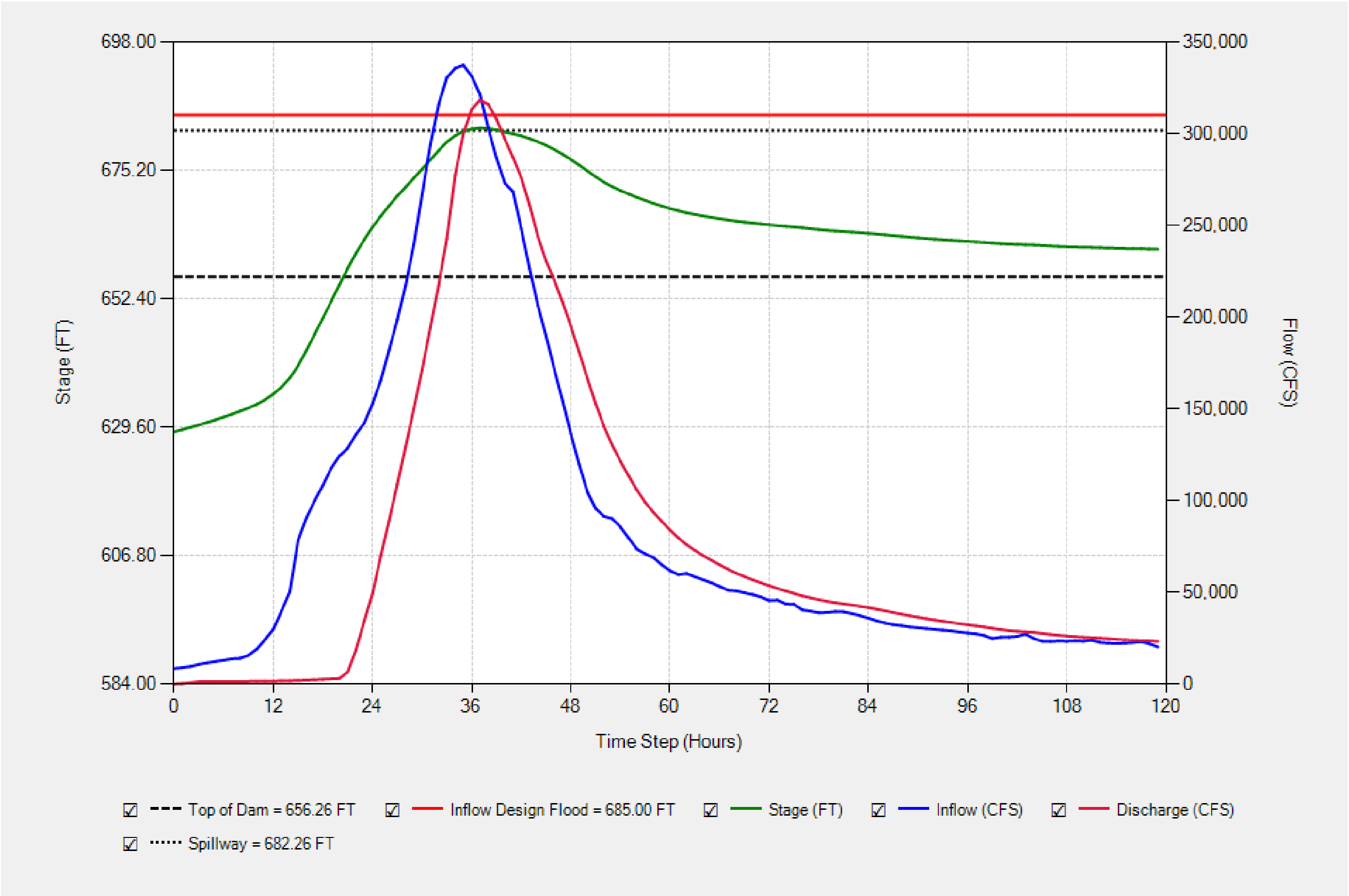


Figure 101: Routed Hydrographs Plot

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Appendix A: Balanced Hydrograph Analysis

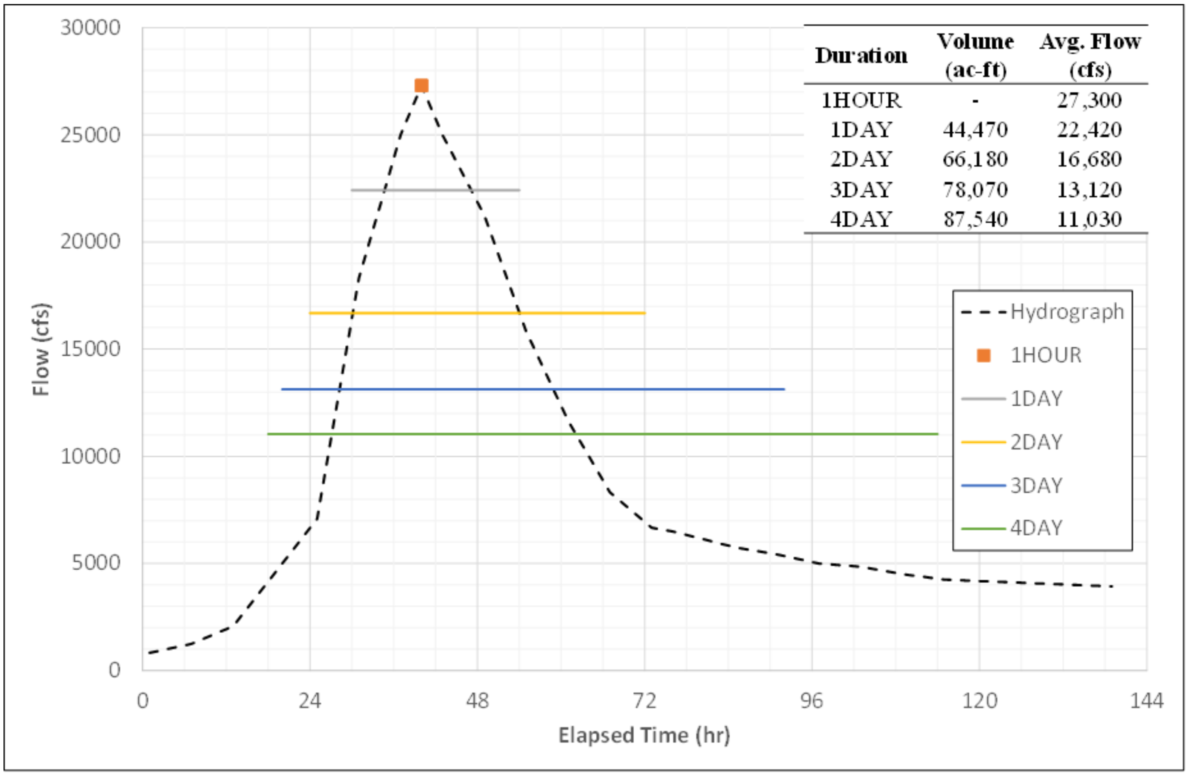
In some extreme cases, the reservoir operations included in RMC-RFA are not adequate to accurately assess the hydrologic hazard for an SQRA. For example, a reservoir could have complex operations that include multipurpose guide curves, gated spillways, and multiple downstream controls. If the driving failure modes occur in the elevation ranges near or below the spillway, a more complex reservoir modeling software, such as HEC-ResSim could be more appropriate. In these situations, routing discrete, “balanced hydrographs” through a reservoir model can be used as a means to inform reservoir stage-frequency curves. In addition, balanced hydrographs can be used to inform inundation, arrival time, and other hydraulic and consequence information when routed through a hydraulic model such as HEC-RAS.

Balanced hydrographs are hydrograph shapes that are based on observed or synthetic flood hydrographs and have been modified to contain specific exceedance flow rates/volumes across one or more durations. Application of balanced hydrographs is mentioned in chapter 18 of (Engineer Manual 1110-2-1417, Flood-Runoff Analysis, 1994); however, the detail for developing a balanced hydrograph is not included. The following description goes into detail for developing balanced hydrographs. A balanced hydrographs implies that the maximum flow/volume for duration X has the same annual exceedance probability (AEP) 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 AEP as other durations. This is due to the complex meteorological conditions that caused the event making each event unique.

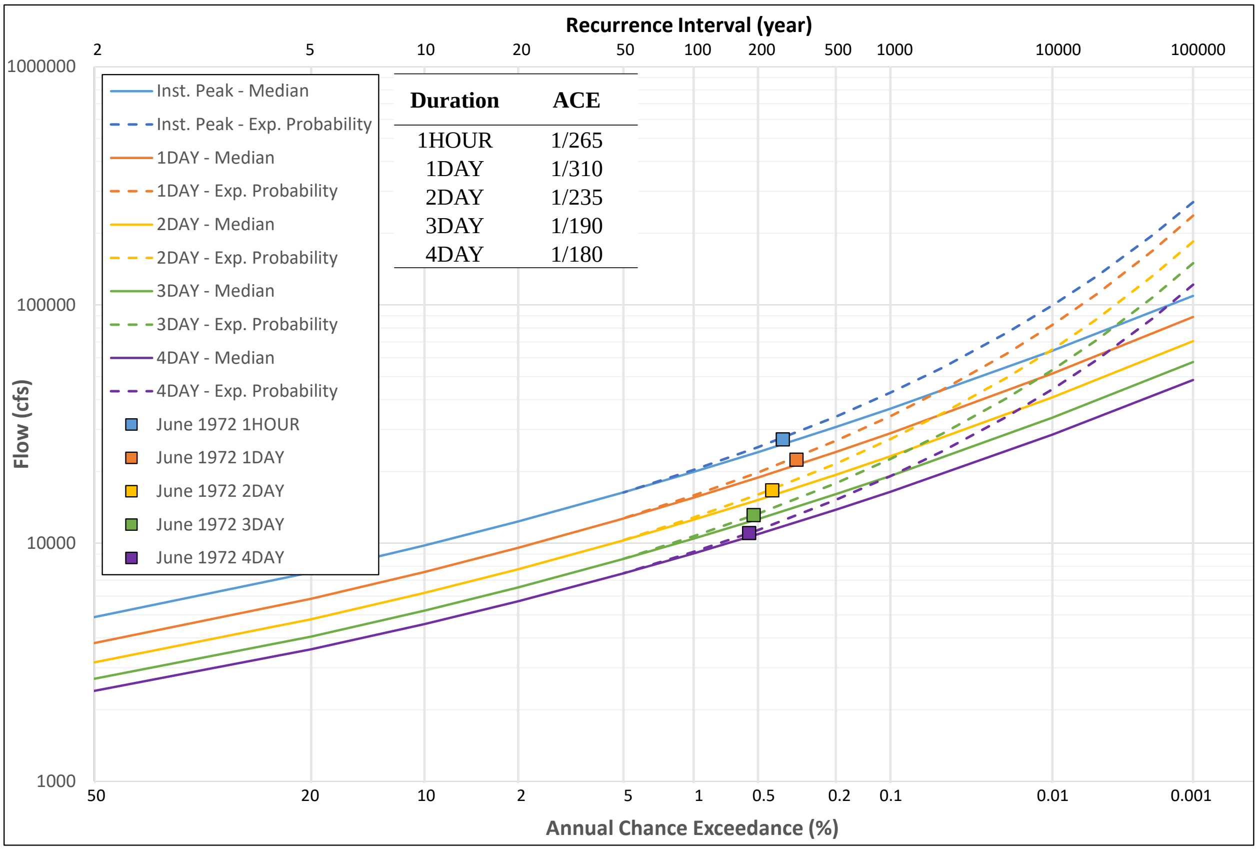
For instance, the June 1972 event (remnants of Tropical Storm Agnes) inflow hydrograph to Foster Joseph Sayers Dam in Pennsylvania can be decomposed into flows/volumes for defined durations. Using the calculated inflow hydrograph, the maximum flow/volume for the 1HOUR, 1DAY, 2DAY, 3DAY, and 4DAY durations were extracted. The inflow hydrograph, volumes, and average flow rates for each duration are presented in Figure 102.

These flows/volumes were then compared against flow- and volume-frequency median and expected probability curves and an AEP was estimated for each duration. As is shown in Figure 103, the June 1972 event was comprised of flows/volumes that ranged between AEP values of approximately 1/180 to 1/310, depending upon the duration.



Duration	Volume (ac-ft)	Avg. Flow (cfs)
1HOUR	-	27,300
1DAY	44,470	22,420
2DAY	66,180	16,680
3DAY	78,070	13,120
4DAY	87,540	11,030

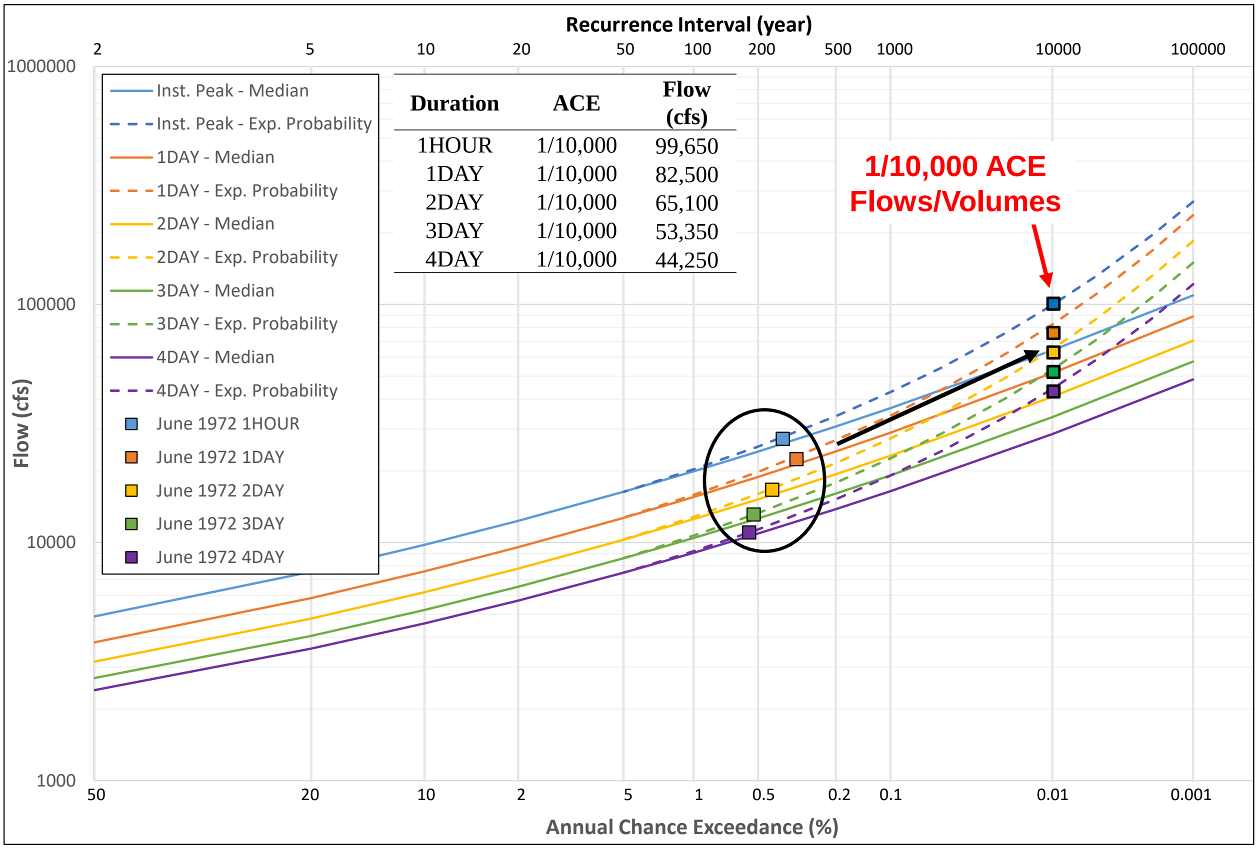
Figure 102: June 1972 Event Inflow to Sayers Dam



Duration	ACE
1HOUR	1/265
1DAY	1/310
2DAY	1/235
3DAY	1/190
4DAY	1/180

Figure 103: June 1972 Event Compared Against Flow- and Volume-Frequency Curves

Balanced hydrographs attempt to fit a specific AEP to one or more durations with a defined hydrograph shape. An example of the conceptual basis for the construction of 1/10,000 ACE balanced hydrographs using the previously shown example data set is shown in Figure 104. The resulting 1/10,000 AEP balanced hydrograph is shown in Figure 105. The following section will describe use of HEC-SSP for developing balanced hydrographs. The balanced hydrograph analysis in HEC-SSP allows for input of peak flow and volume frequency curves and will automatically adjust hydrograph ordinates to reproduce multiple volumes for specific exceedance probabilities. For example, HEC-SSP will create a balanced 0.01 AEP hydrograph that includes the 1-hour, 1 day, 3 day, and 7 day volumes. The HEC-SSP user interface allows the user to select the volumes of interest.



Duration	ACE	Flow (cfs)
1HOUR	1/10,000	99,650
1DAY	1/10,000	82,500
2DAY	1/10,000	65,100
3DAY	1/10,000	53,350
4DAY	1/10,000	44,250

Figure 104: Conceptual Basis for Balanced Hydrographs

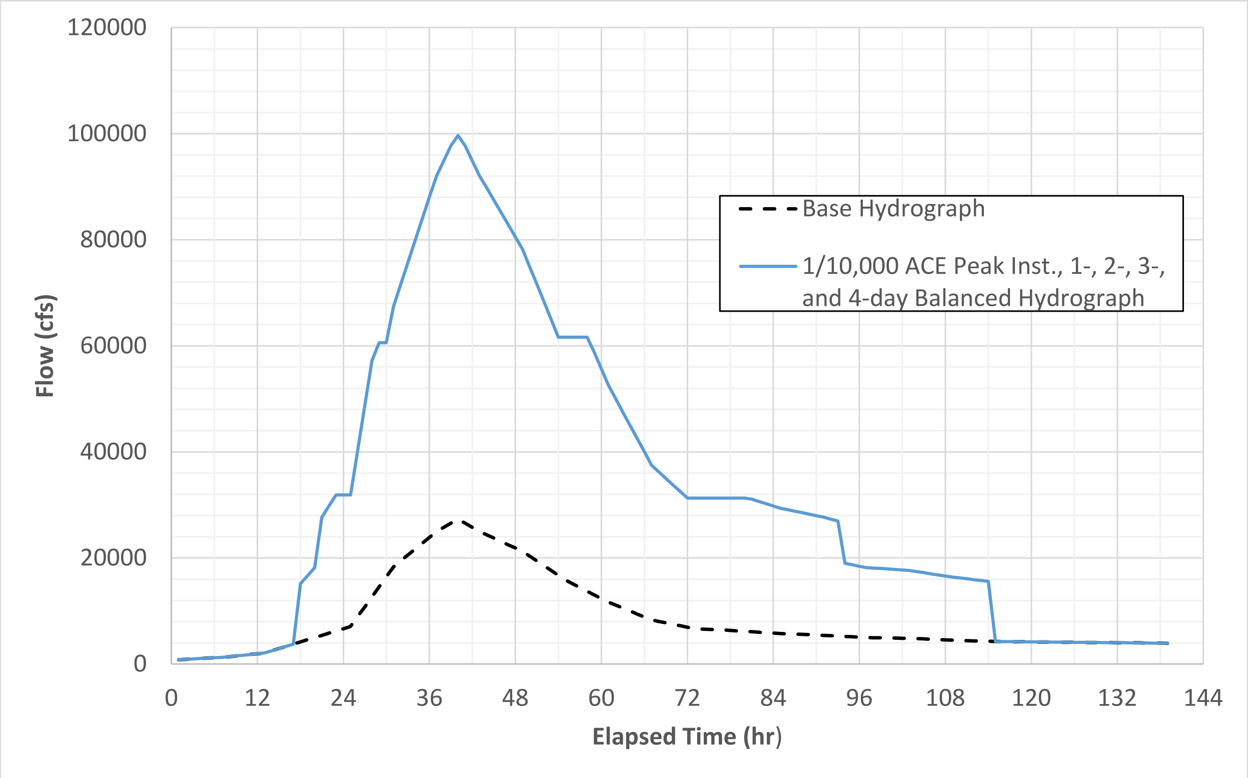


Figure 105: 1/10,000 ACE Balanced Hydrograph

Developing Balanced Hydrographs

The following steps illustrate the procedure for creating balanced hydrographs using the Bald Eagle Creek watershed.

1. The first piece of information necessary for the development of balanced hydrographs are suitable hydrograph shapes.

    - *Note*: Hydrograph shapes can consist of either historical events or purely hypothetical shapes. There are benefits and drawbacks to the use of both. Historical events are comprised of observed (or calculated) streamflow from events that actually occurred. The use of historical events allows for a more representative sample of site-specific conditions, which includes the time pattern of the event and volume distribution. However, it is more difficult to balance a complicated historical event hydrograph to multiple durations while maintaining the actual hydrograph shape.

    - Purely hypothetical shapes can be used in lieu of historical events. Balancing a hypothetical shaped hydrograph can be easier than balancing a historical event shape. However, the variability within naturally occurring runoff hydrographs can be lost when using these shapes, which can potentially result in inappropriate results. An example of the differences between an historical event shape and a hypothetical shape hydrograph is shown in Figure 106.

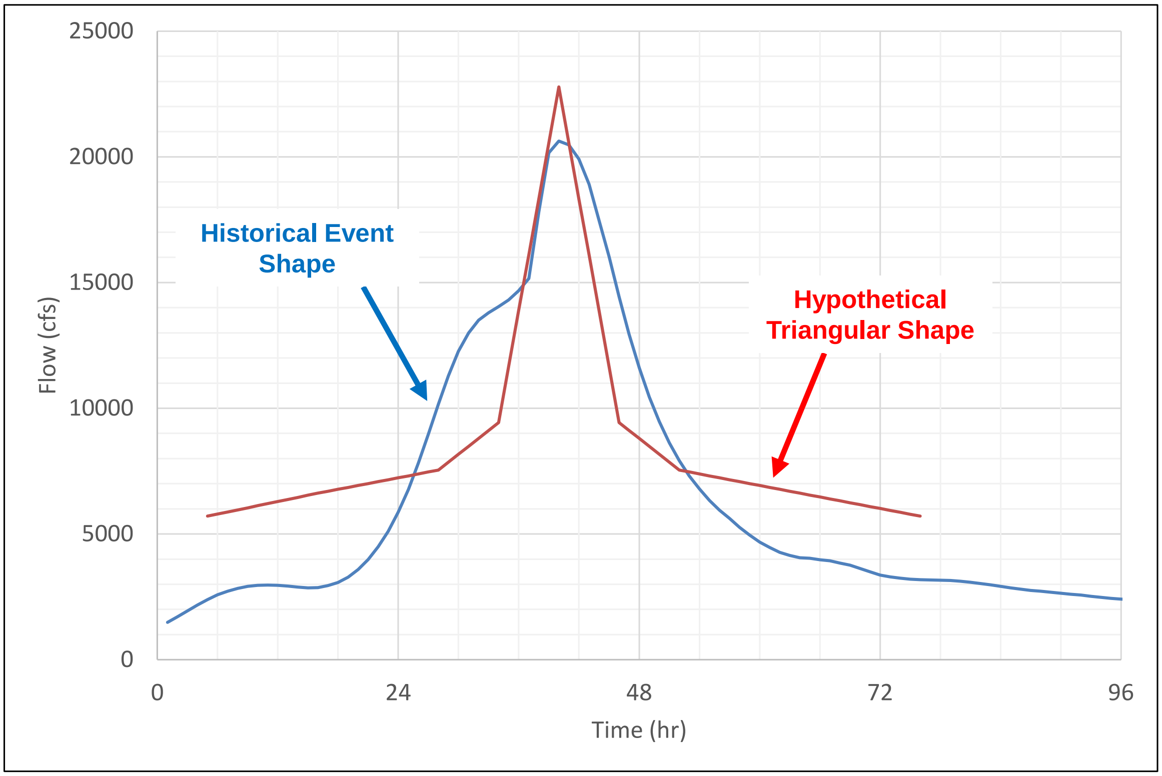


Figure 106: Historical Event Shape vs. Hypothetical Triangular Shape

2. The second piece of information needed to construct a balanced hydrograph is peak flow- and volume-frequency relationship for the duration(s) of interest. Flow- and volume-frequency curves are commonly derived by fitting the Log Pearson Type III (LPIII) analytical distribution to an annual maximum series (AMS) of unregulated instantaneous peaks and/or duration-specific volumes.

    - *Note*: These curves should reflect the expected probability of exceedance, not just the median estimate. The expected probability of exceedance provides a more accurate representation of the actual river or reservoir stage-frequency curve than the median estimate when routing balanced hydrographs in a deterministic manner.

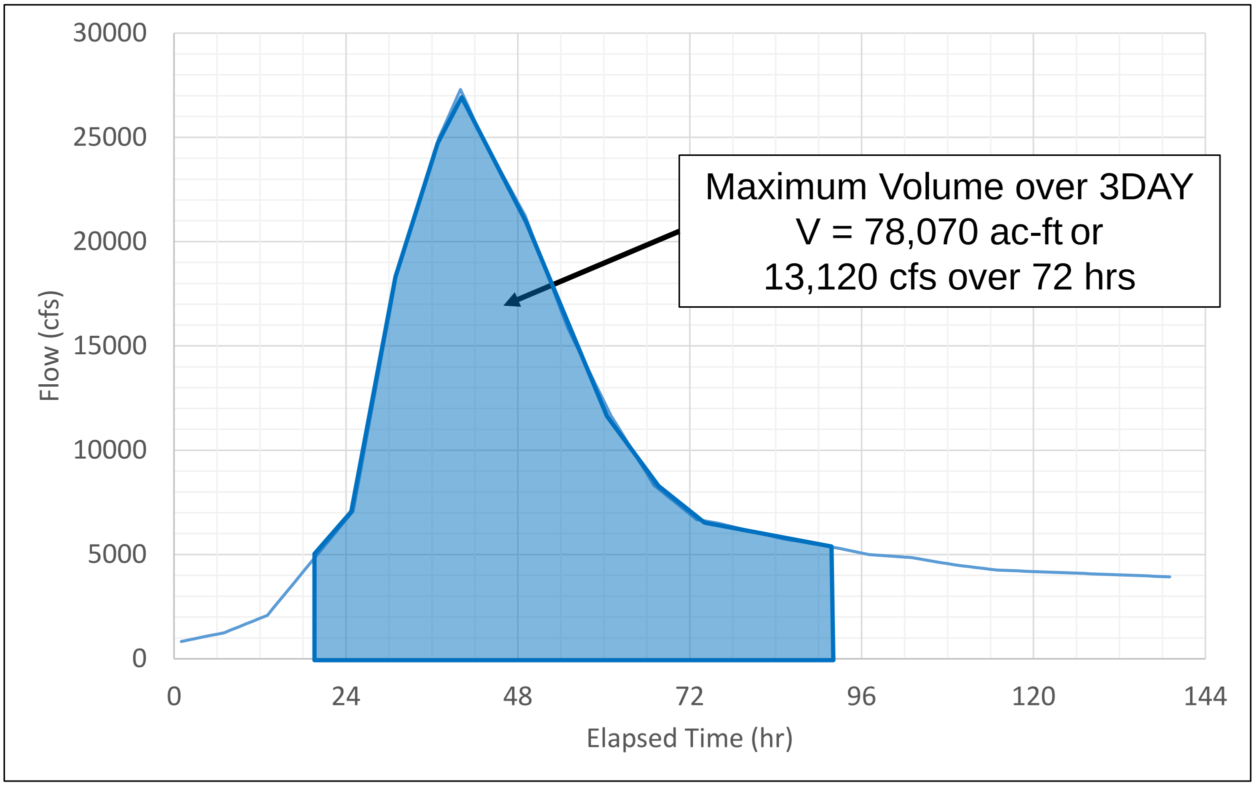
- HEC-SSP can be used to fit the LPIII distribution to an input AMS. The Bulletin 17C methodology should be used when developing flow- and volume-frequency curves within all dam and levee safety analyses, as described in the Inflow Volume-Frequency section.
- However, the STATS_LPIII_ExpectedProbability_v2.0 spreadsheet tool should be used to compute the expected probability adjustment given the three LPIII distribution parameters (i.e. mean, standard deviation, and skew).

3. Balanced hydrographs should be computed with the aid of computer software (i.e. HEC-SSP).
    - *Note*: Examples of the manual calculations necessary to compute balanced hydrographs for both a single and multiple durations will be detailed. Following the description of the manual computations, the approach to compute the balanced hydrographs will be shown in HEC-SSP. The algorithm used in both approaches is the same.
    - The balancing only modifies ordinates of the hydrographs which comprise the maximum average flow rate for the desired duration(s). For example, if the template hydrograph shape spans 10 days and balancing over a 3-day duration is desired, the remaining 7 days should not be affected by the balancing operations for that specific duration. In order to modify the entire 10-day hydrograph, balancing across the 10-day duration is necessary.

Manual Computations for Single Duration

It is relatively easy and straightforward to manually calculate a balanced hydrograph using a single duration. HEC-SSP contains a balanced hydrograph analysis that creates repeatable and documented balanced hydrographs. The following example shows the general steps for manually developing balanced hydrographs. For this example, a 1/500 AEP 3-day duration balanced hydrograph is desired using the June 1972 event (Tropical Storm Agnes) inflow hydrograph to Foster Joseph Sayers Dam.

1. Determine the maximum average flow rate for the desired duration in the base (template) hydrograph shape.
    - *Note*: For this example, the maximum 3-day duration volume is approximately 78,070 ac-ft which equates to an average flow rate of approximately 13,120 cfs over 72-hours, as shown in Figure 107. A moving-average over three days, or 72-hours, was applied to the hourly flow data in order to find the maximum 3-day volume.
2. Determine a desired flow rate from the flow- or volume-frequency curves.
    - *Note*: For this example, the 1/500 AEP 3-day duration has an average flow rate of approximately 17,850 cfs (106,200 ac-ft over 72-hours), as shown in Figure 108.



Maximum Volume over 3DAY
V = 78,070 ac-ft or
13,120 cfs over 72 hrs

Time (hr)	Flow (cfs)	Time (hr)	Flow (cfs)	Time (hr)	Flow (cfs)	Time (hr)	Flow (cfs)	Time (hr)	Flow (cfs)	Time (hr)	Flow (cfs)
1	830	25	7080	49	21250	73	6670	97	5000	121	4170
2	900	26	8955	50	20347	74	6613	98	4975	122	4157
3	970	27	10830	51	19443	75	6557	99	4950	123	4143
4	1040	28	12705	52	18540	76	6500	100	4925	124	4130
5	1110	29	14580	53	17637	77	6417	101	4900	125	4117
6	1180	30	16455	54	16733	78	6333	102	4875	126	4103
7	1250	31	18330	55	15830	79	6250	103	4850	127	4090
8	1388	32	19442	56	15137	80	6167	104	4792	128	4077
9	1527	33	20553	57	14443	81	6083	105	4733	129	4063
10	1665	34	21665	58	13750	82	6000	106	4675	130	4050
11	1803	35	22777	59	13057	83	5917	107	4617	131	4037
12	1942	36	23888	60	12363	84	5833	108	4558	132	4023
13	2080	37	25000	61	11670	85	5750	109	4500	133	4010
14	2497	38	25767	62	11113	86	5695	110	4458	134	3997
15	2913	39	26533	63	10557	87	5640	111	4417	135	3983
16	3330	40	27300	64	10000	88	5585	112	4375	136	3970
17	3747	41	26533	65	9443	89	5530	113	4333	137	3957
18	4163	42	25767	66	8887	90	5475	114	4292	138	3943
19	4580	43	25000	67	8330	91	5420	115	4250	139	3930
20	4997	44	24375	68	8053	92	5350	116	4237		
21	5413	45	23750	69	7777	93	5280	117	4223		
22	5830	46	23125	70	7500	94	5210	118	4210		
23	6247	47	22500	71	7223	95	5140	119	4197		
24	6663	48	21875	72	6947	96	5070	120	4183		

Figure 107: Maximum 3-day Volume / Average Flow Rate for Template Hydrograph

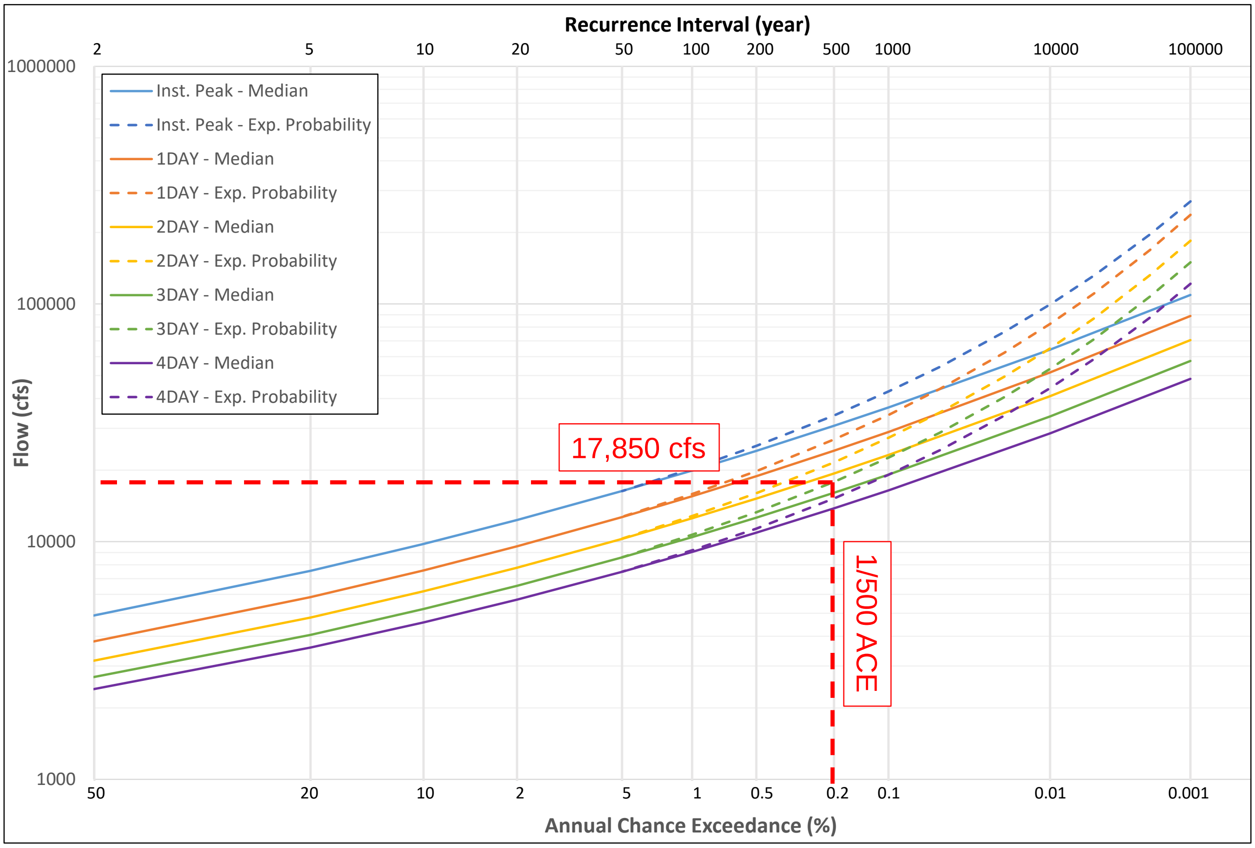


Figure 108: 1/500 ACE 3-day Average Flow Rate

3. Determine a desired flow rate / base flow rate ratio.

    - *Note*: For this example, the calculation is:

      Desired/Base Ratio = 17,850 cfs / 13,120 cfs = 1.36

4. Multiply the ordinates that comprise the maximum average flow rate for the desired duration by the desired/base ratio.

    - *Note*: For this example, the ordinates from t = 21 hours through t = 93 hours were multiplied by 1.36.

5. Check to see if the balanced hydrograph shape and volume is acceptable.

    - *Note*: The resulting balanced hydrograph is compared against the base hydrograph in Figure 109. The shape of the underlying base hydrograph is adequately maintained. In some cases it might be necessary to smooth the transition between the scaled duration and the unscaled portion of the hydrograph. There is no hard and fast guidance for smoothing the hydrograph shape. If smoothing is applied, clearly document and show that the added volume does not result in unreasonable exceedance probabilities for the longer duration volumes. HEC-SSP will automatically modify the hydrograph shape as it iteratively adjusts hydrograph ordinates to balance multiple volumes.

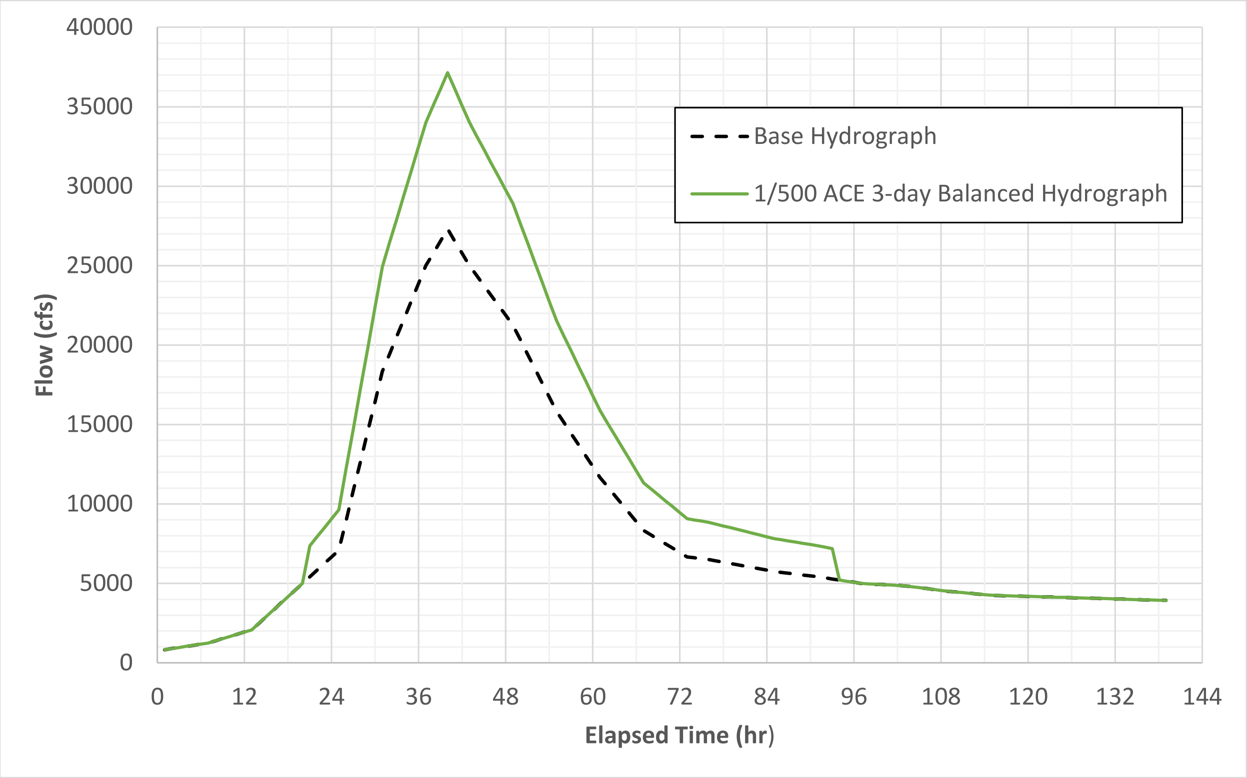


Figure 109: 1/500 ACE 3-day Balanced Hydrograph

Manual Computations for Multiple Durations

It can be much more difficult to manually calculate a balanced hydrograph using multiple durations, which is due to the overlapping modifications that are necessary. This usually requires multiple iterations to achieve acceptable volumes and hydrograph shapes. For this example, a 1/500 AEP balanced hydrograph is desired using instantaneous peak, 1-day, and 2-day duration information as well as the June 1972 event (Tropical Storm Agnes) inflow hydrograph to Foster Joseph Sayers Dam.

1. Determine the average flow rate for the desired durations in the base (template) hydrograph shape. Just like the example above, a moving time window is applied to find the hydrographs ordinates that are responsible for the maximum volumes.

   Also, it is not expected nor accepted for the balanced hydrograph analysis to be performed in a spreadsheet. Instead, the balanced hydrograph tool in HEC-SSP will be applied as the algorithm produces reproducible results that adequately match flow volumes specified by the user.

   - *Note*: For this example, the instantaneous peak flow rate is 27,300 cfs, the 1-day duration average flow rate is 22,420 cfs, and the 2-day duration average flow rate is 16,680 cfs, as shown in Figure 110.

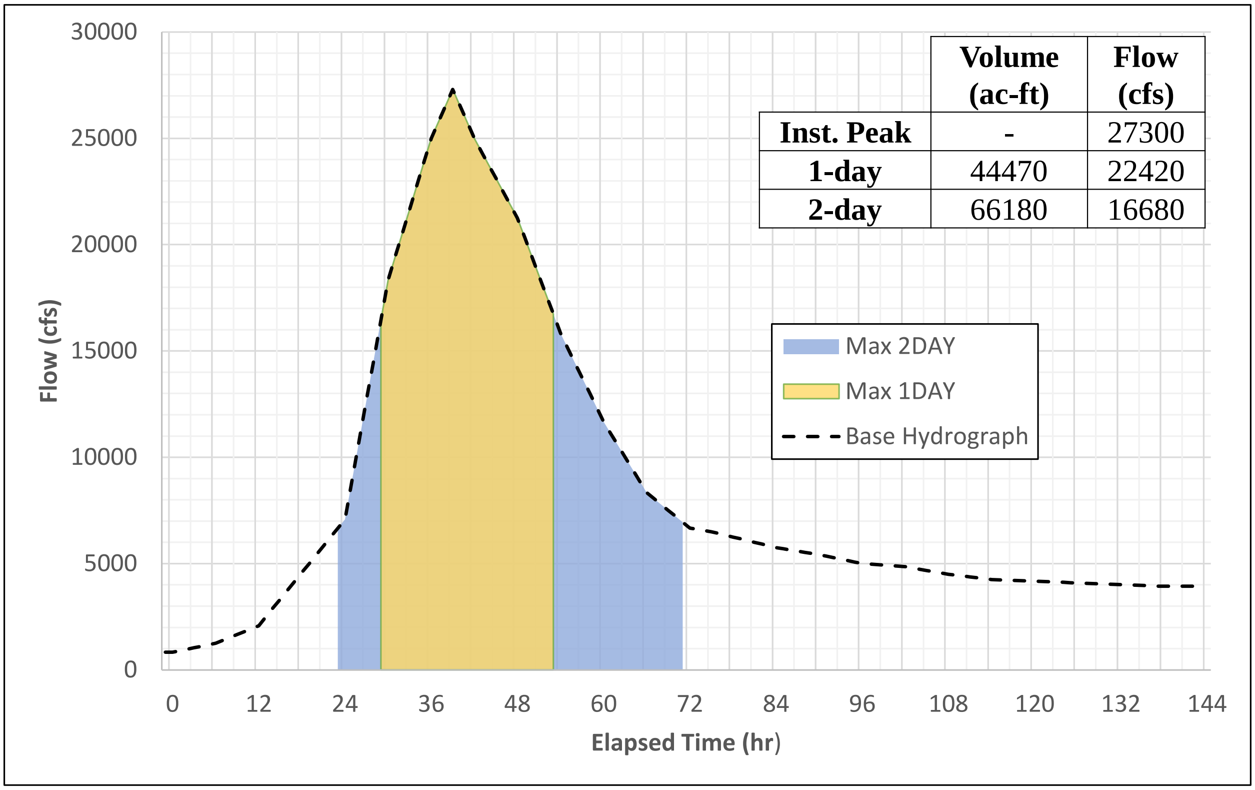


Figure 110: 1/500 ACE Inst. Peak, 1-, and 2-day Average Flow Rate

2. Determine a desired flow rate for all durations from the flow- or volume-frequency curves.
   - For this example, the 1/500 AEP instantaneous peak, 1-day, and 2-day duration has a flow rate of approximately 33,965 cfs, 26,905 cfs, and 21,540 cfs, respectively, as shown in Figure 111.
3. Determine a desired flow rate / base flow rate ratio for all durations.
   - *Note*: For this example, the calculation is:

Inst. Peak Desired/Base Ratio = 33,965 cfs / 27,300 cfs = 1.244

1-Day Desired/Base Ratio = 26,905 cfs / 22,420 cfs = 1.2

2-Day Desired/Base Ratio = 21,540 cfs / 16,680 cfs = 1.291

4. Multiply the ordinates that comprise the maximum average flow for the 1st (shortest instantaneous peak) duration by the desired/base ratio for that duration.
   - *Note*: For this example, the single ordinate at t = 40 hours was multiplied by 1.244.
5. Multiply the ordinates that comprise the maximum average flow for the 2nd (second shortest; 1-day) duration by the desired/base ratio for that duration.
   - *Note*: For this example, the ordinates from t = 30 hours to t = 39 hours and t = 41 hours to t = 54 hours were multiplied by 1.2. Notice that the single ordinate at t = 40 hours was excluded from modification since this had already been modified to balance across the instantaneous peak duration.

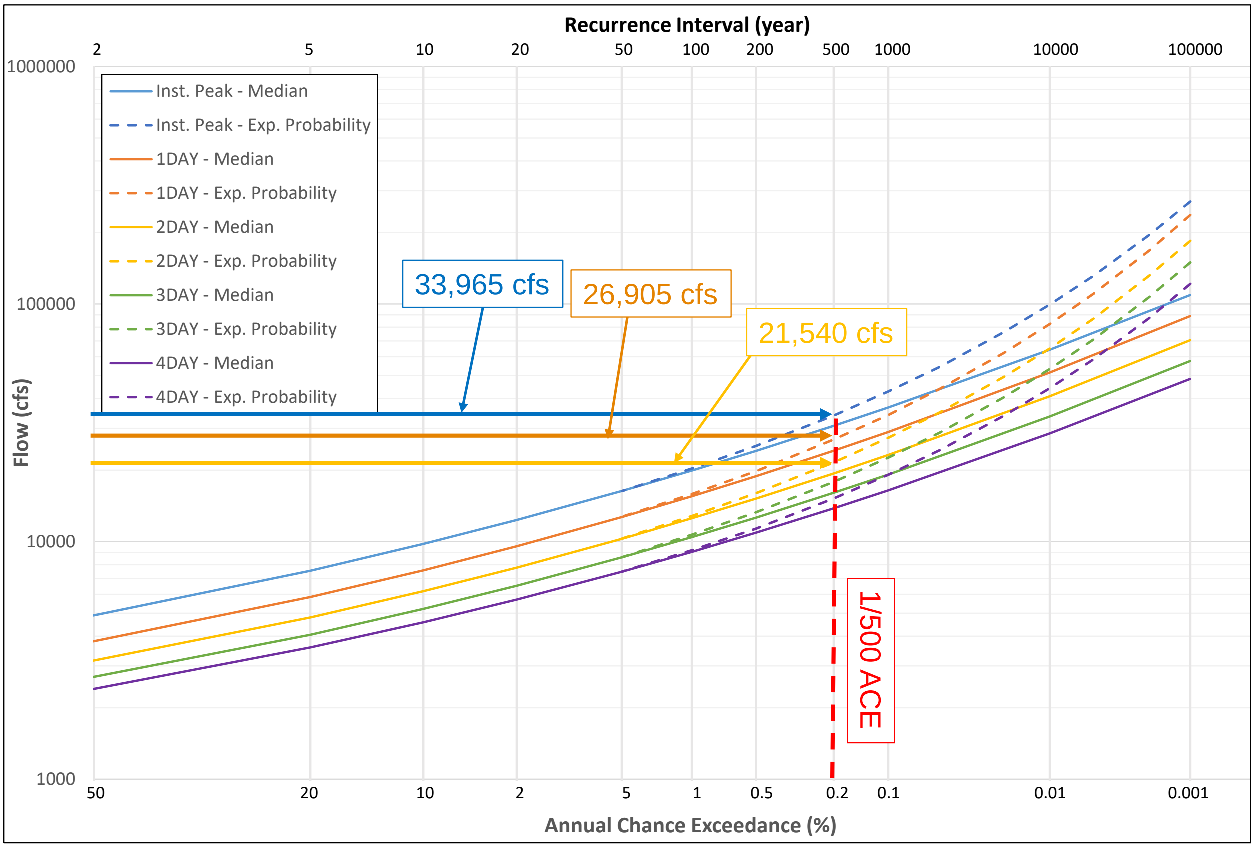


Figure 111: Inst. Peak, 1-, and 2-day Average Flow Rate

6. Check to see if the balanced hydrograph volume and shape is acceptable.

    - *Note*: The 1-day volume / average flow rate for the modified hydrograph was calculated to be 26,956 cfs, which is within an acceptable tolerance of the desired flow/volume. Also, the shape of the underlying base hydrograph is adequately maintained. HEC-SSP will go through a number of iterations to match volumes across multiple durations.

7. Multiply the ordinates that comprise the maximum average flow for the 3rd (third shortest; 2-day) duration by the desired/base ratio for that duration.

    - *Note*: For this example, the ordinates from t = 24 hours to t = 29 hours and t = 55 to t = 72 hours were multiplied by 1.291. Notice that the ordinates from t = 30 hours to t = 54 hours were excluded from modification since they had already been modified to balance across the inst. peak and 1-day durations.

8. Check to see if the balanced hydrograph volume is acceptable.

    - *Note*: The 2-day volume / average flow rate for the modified hydrograph was calculated to be 20,540 cfs which is not within an acceptable tolerance of the desired flow/volume.

    - The use of a larger ratio will increase the volume / average flow rate. However, sharp inflection points begin to be realized at t = 29 hours and t = t = 55 hours, which corresponds to the transition from the 1- to the 2-day durations. This causes the balanced hydrograph shape to deviate from the underlying base hydrograph shape, which shows no sharp inflections at these times.

- To better balance the hydrograph and avoid this inflection point and still maintain the desired flow/volume, the desired / base multiplication factor can be smoothed to produce a “flat” hydrograph shape for several ordinates. Another option is to manually change the base hydrograph shape so there are smooth transition between durations. HEC-SSP includes an algorithm that adjust the ordinates up to the last flow value in the shorter duration, notice the flat spots in Figure 112. The “final” balanced hydrograph shape is shown in Figure 112.

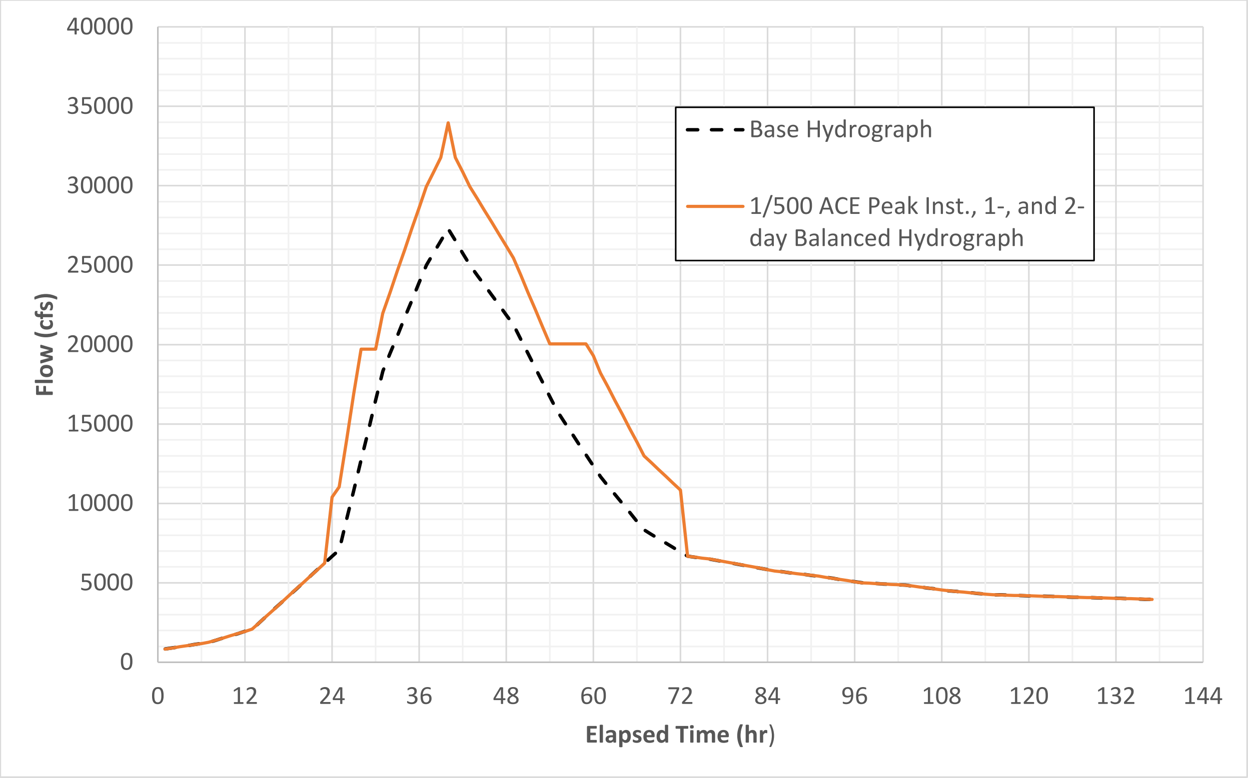


Figure 112: 1/500 ACE Inst. Peak, 1-, and 2-day Balanced Hydrograph

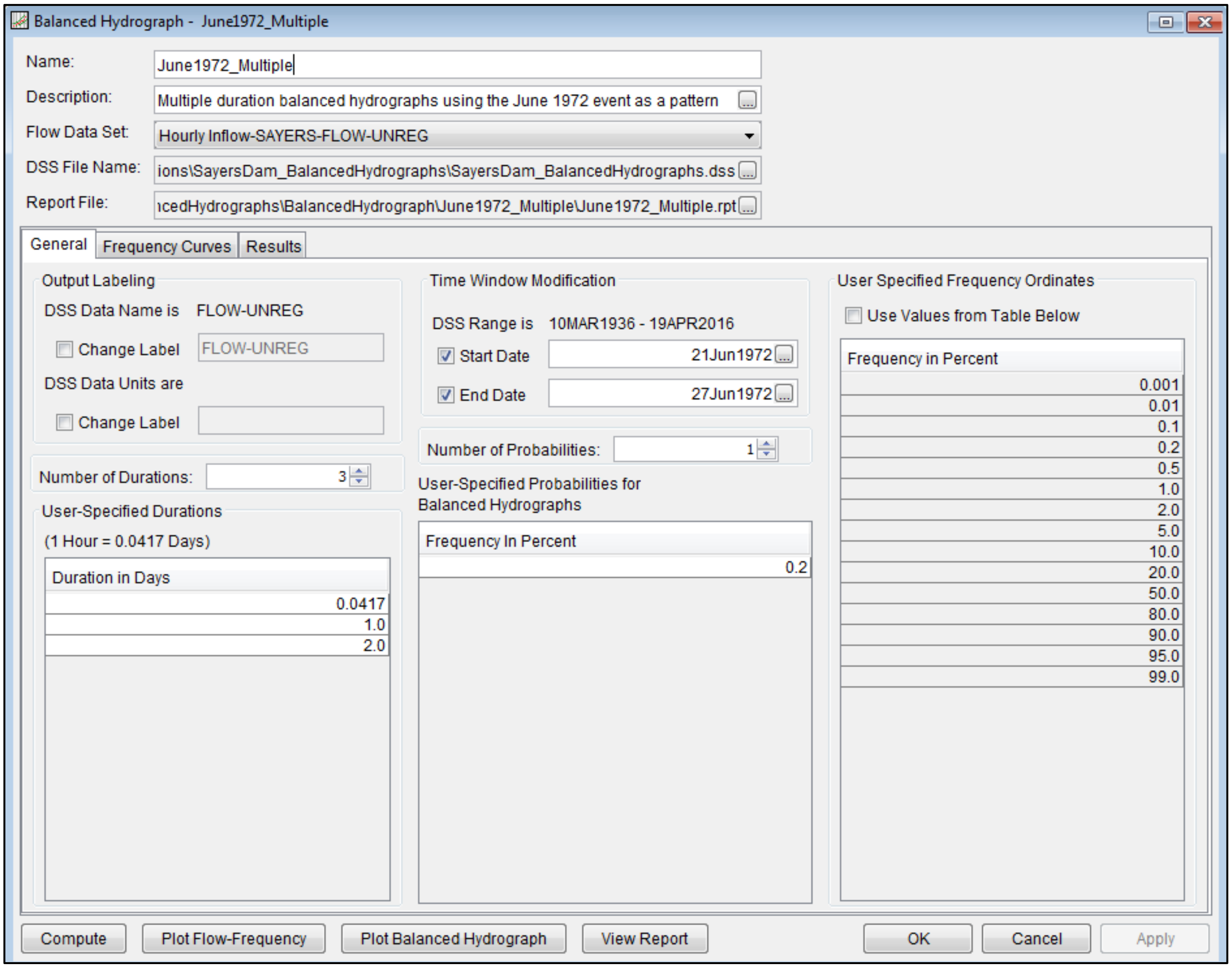
Balanced Hydrograph Creation Using HEC-SSP

Balanced hydrographs can be computed within HEC-SSP using the following steps:

1. Create an HEC-SSP project.

2. Create a data set that contains the desired base template hydrograph shape. Use the June 1972 event hydrograph which was previously shown in Figure 102.

3. Create a **Balanced Hydrograph** analysis. Set the **Number of Durations** to **3**. Enter **0.0417** (i.e. 1-hour), **1**, and **2** days for the durations. Enter a Start and End Date of **20Jun1972** and **27Jun1972**. Set the **Number of Probabilities** to **1**. Enter a frequency of **0.2** percent. The completed **General** tab is shown in Figure 113.



Name: June1972_Multiple

Description: Multiple duration balanced hydrographs using the June 1972 event as a pattern

Flow Data Set: Hourly Inflow-SAYERS-FLOW-UNREG

DSS File Name: ions\SayersDam_BalancedHydrographs\SayersDam_BalancedHydrographs.dss

Report File: ıcedHydrographs\BalancedHydrograph\June1972_Multiple\June1972_Multiple.rpt

DSS Data Name is FLOW-UNREG

☐ Change Label FLOW-UNREG

DSS Data Units are

☐ Change Label

Number of Durations: 3

User-Specified Durations

(1 Hour = 0.0417 Days)

Duration in Days
0.0417
1.0
2.0

DSS Range is 10MAR1936 - 19APR2016

☑ Start Date 21Jun1972

☑ End Date 27Jun1972

Number of Probabilities: 1

User-Specified Probabilities for Balanced Hydrographs

Frequency In Percent
0.2

☐ Use Values from Table Below

Frequency in Percent
0.001
0.01
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
80.0
90.0
95.0
99.0

Figure 113: Balanced Hydrograph Analysis General Tab

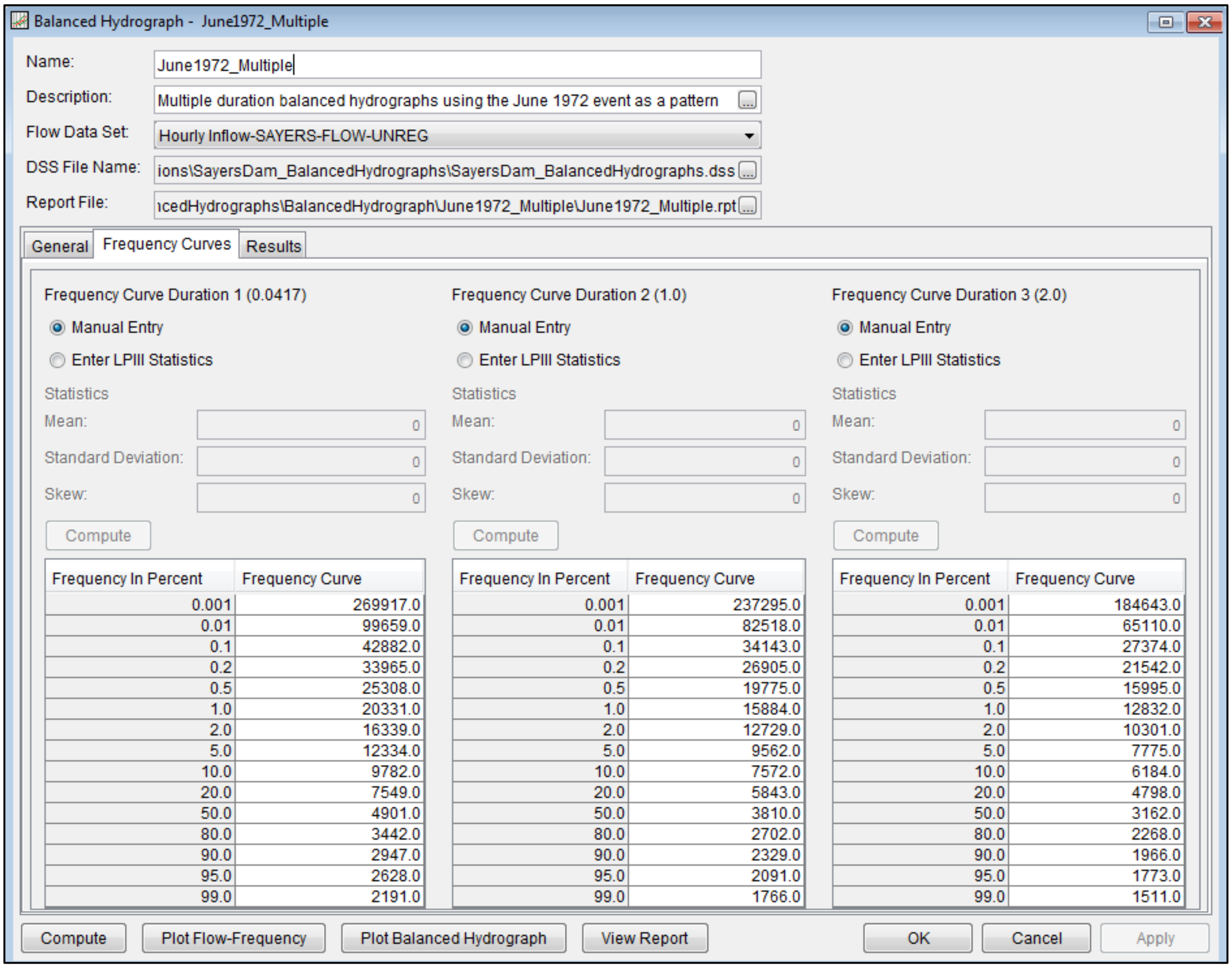
4. On the **Frequency Curves** tab, enter the flow- or volume-frequency information for the three desired durations as shown in Figure 114.

5. Click **Plot Flow-Frequency** and ensure that the flow-frequency curves are appropriate for use.

6. Click **Compute**.

7. On the **Results** tab, you will see the computed and tabulated balanced hydrograph. Additionally, the computed balanced hydrograph will be plotted along with the base template hydrograph on the right side of the screen. The **Results** tab is shown in Figure 115.

8. Click **View Report** to open the report file. Within this window you will find the summary computations of the analysis. The report file is shown in Figure 116.



Balanced Hydrograph - June1972_Multiple

Name: June1972_Multiple

Description: Multiple duration balanced hydrographs using the June 1972 event as a pattern

Flow Data Set: Hourly Inflow-SAYERS-FLOW-UNREG

DSS File Name: ions\SayersDam_BalancedHydrographs\SayersDam_BalancedHydrographs.dss

Report File: cedHydrographs\BalancedHydrograph\June1972_Multiple\June1972_Multiple.rpt

Frequency Curve Duration 1 (0.0417)

● Manual Entry

○ Enter LPIII Statistics

Statistics

Mean: 0

Standard Deviation: 0

Skew: 0

Frequency In Percent	Frequency Curve
0.001	269917.0
0.01	99659.0
0.1	42882.0
0.2	33965.0
0.5	25308.0
1.0	20331.0
2.0	16339.0
5.0	12334.0
10.0	9782.0
20.0	7549.0
50.0	4901.0
80.0	3442.0
90.0	2947.0
95.0	2628.0
99.0	2191.0

Frequency Curve Duration 2 (1.0)

● Manual Entry

○ Enter LPIII Statistics

Statistics

Mean: 0

Standard Deviation: 0

Skew: 0

Frequency In Percent	Frequency Curve
0.001	237295.0
0.01	82518.0
0.1	34143.0
0.2	26905.0
0.5	19775.0
1.0	15884.0
2.0	12729.0
5.0	9562.0
10.0	7572.0
20.0	5843.0
50.0	3810.0
80.0	2702.0
90.0	2329.0
95.0	2091.0
99.0	1766.0

Frequency Curve Duration 3 (2.0)

● Manual Entry

○ Enter LPIII Statistics

Statistics

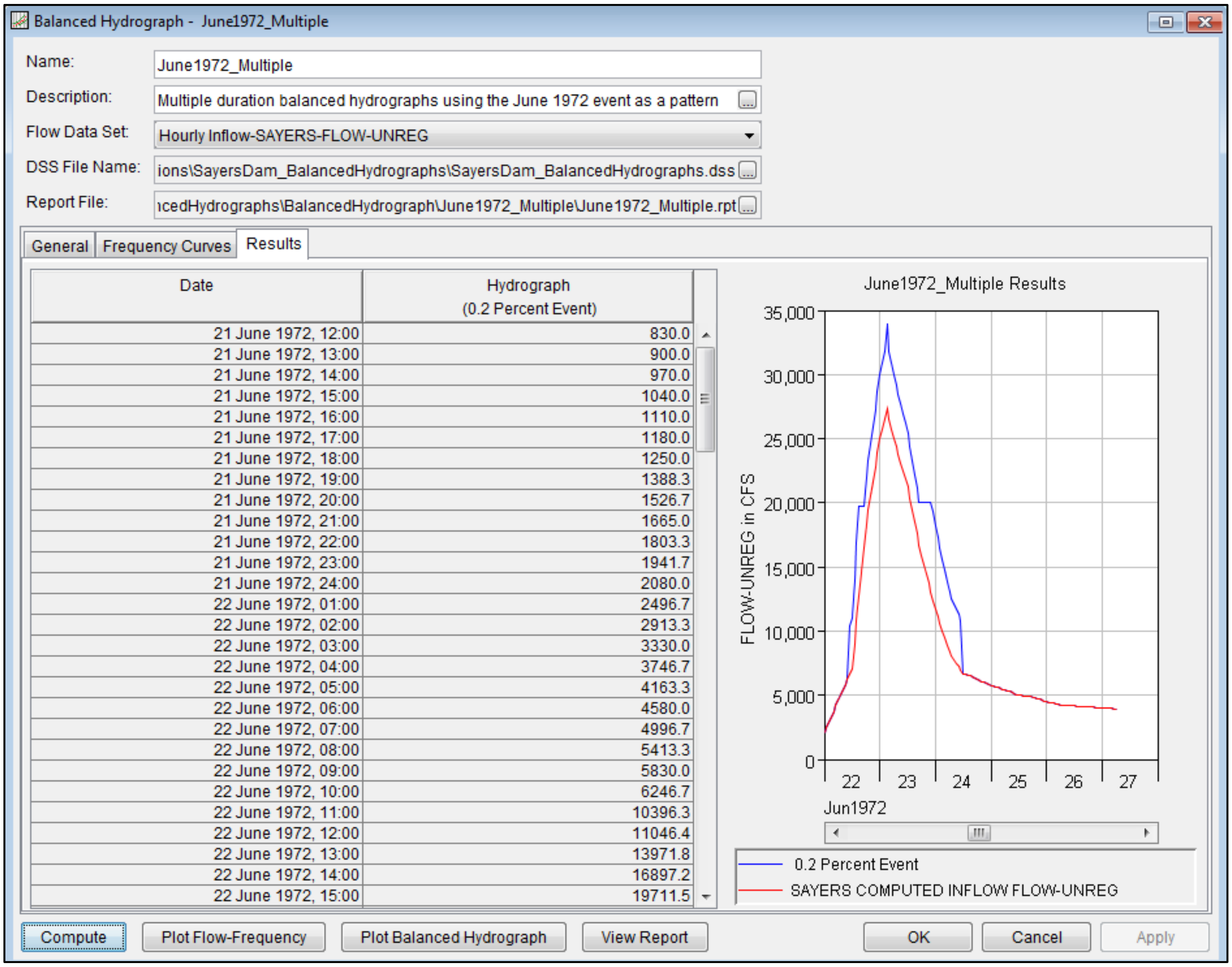
Mean: 0

Standard Deviation: 0

Skew: 0

Frequency In Percent	Frequency Curve
0.001	184643.0
0.01	65110.0
0.1	27374.0
0.2	21542.0
0.5	15995.0
1.0	12832.0
2.0	10301.0
5.0	7775.0
10.0	6184.0
20.0	4798.0
50.0	3162.0
80.0	2268.0
90.0	1966.0
95.0	1773.0
99.0	1511.0

Figure 114: Balanced Hydrograph Analysis Frequency Curves Tab



Balanced Hydrograph - June1972_Multiple

Name: June1972_Multiple

Description: Multiple duration balanced hydrographs using the June 1972 event as a pattern

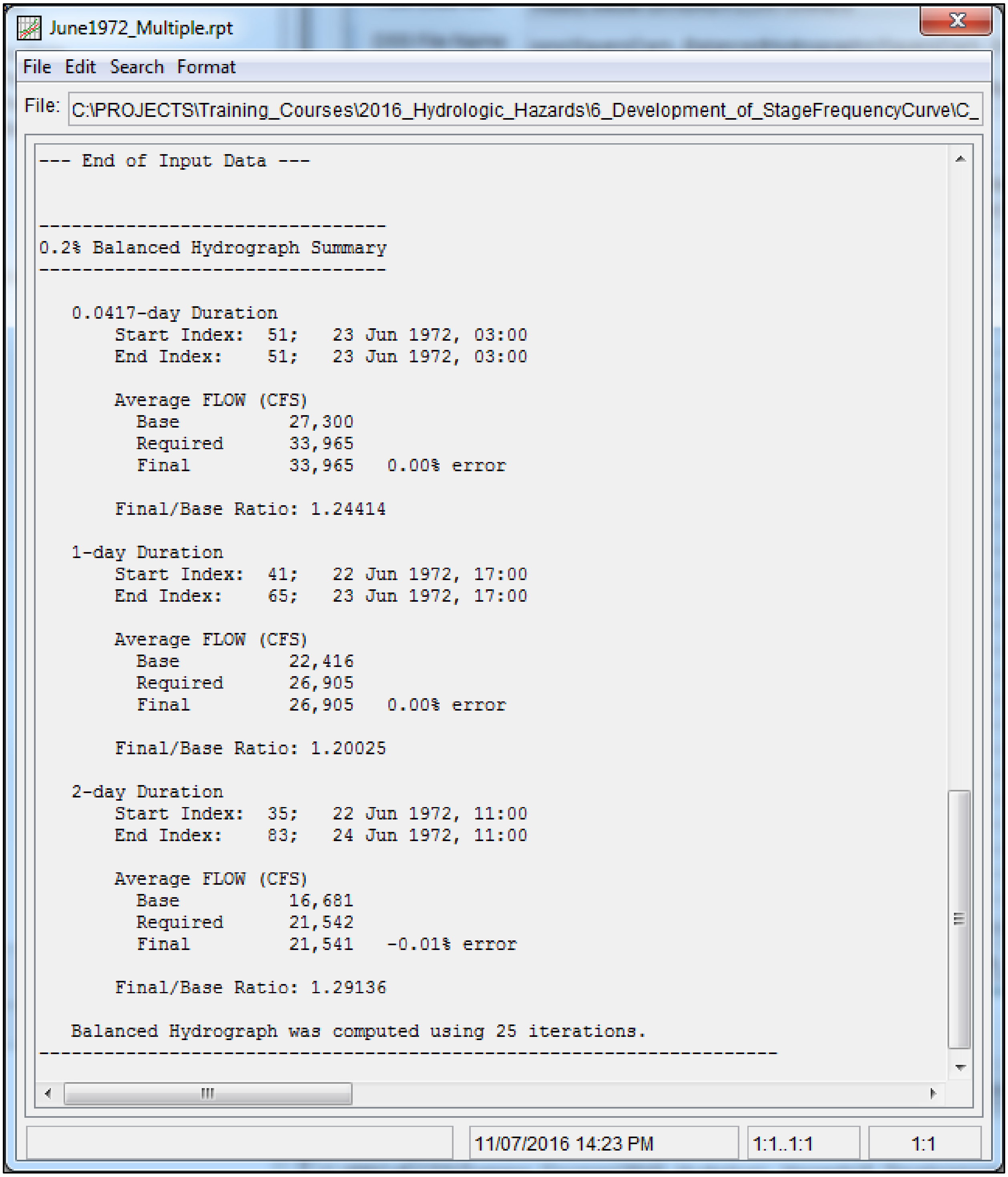
Flow Data Set: Hourly Inflow-SAYERS-FLOW-UNREG

DSS File Name: ions\SayersDam_BalancedHydrographs\SayersDam_BalancedHydrographs.dss

Report File: ıcedHydrographs\BalancedHydrograph\June1972_Multiple\June1972_Multiple.rpt

Date	Hydrograph (0.2 Percent Event)
21 June 1972, 12:00	830.0
21 June 1972, 13:00	900.0
21 June 1972, 14:00	970.0
21 June 1972, 15:00	1040.0
21 June 1972, 16:00	1110.0
21 June 1972, 17:00	1180.0
21 June 1972, 18:00	1250.0
21 June 1972, 19:00	1388.3
21 June 1972, 20:00	1526.7
21 June 1972, 21:00	1665.0
21 June 1972, 22:00	1803.3
21 June 1972, 23:00	1941.7
21 June 1972, 24:00	2080.0
22 June 1972, 01:00	2496.7
22 June 1972, 02:00	2913.3
22 June 1972, 03:00	3330.0
22 June 1972, 04:00	3746.7
22 June 1972, 05:00	4163.3
22 June 1972, 06:00	4580.0
22 June 1972, 07:00	4996.7
22 June 1972, 08:00	5413.3
22 June 1972, 09:00	5830.0
22 June 1972, 10:00	6246.7
22 June 1972, 11:00	10396.3
22 June 1972, 12:00	11046.4
22 June 1972, 13:00	13971.8
22 June 1972, 14:00	16897.2
22 June 1972, 15:00	19711.5

Figure 115: Balanced Hydrograph Analysis Results Tab



```
--- End of Input Data ---


--------------------------------
0.2% Balanced Hydrograph Summary
--------------------------------

   0.0417-day Duration
       Start Index:  51;   23 Jun 1972, 03:00
       End Index:    51;   23 Jun 1972, 03:00

       Average FLOW (CFS)
         Base          27,300
         Required      33,965
         Final         33,965   0.00% error

       Final/Base Ratio: 1.24414

   1-day Duration
       Start Index:  41;   22 Jun 1972, 17:00
       End Index:    65;   23 Jun 1972, 17:00

       Average FLOW (CFS)
         Base          22,416
         Required      26,905
         Final         26,905   0.00% error

       Final/Base Ratio: 1.20025

   2-day Duration
       Start Index:  35;   22 Jun 1972, 11:00
       End Index:    83;   24 Jun 1972, 11:00

       Average FLOW (CFS)
         Base          16,681
         Required      21,542
         Final         21,541   -0.01% error

       Final/Base Ratio: 1.29136

   Balanced Hydrograph was computed using 25 iterations.
--------------------------------------------------------------------
```

Figure 116: Balanced Hydrograph Analysis Results File

Short Note on Balancing Across Multiple Durations

When balancing across multiple durations, it is possible to mix runoff generation mechanisms when the watershed of interest is subject to multiple types of flood events. For instance, flood events within the Bald Eagle Creek watershed can be caused by rainfall, snowmelt, and rain-on-snow processes. In the Bald Eagle Creek watershed, rainfall events generally cause excessive runoff for durations less than or equal to 2-days. Conversely, snowmelt or rain-on-snow events generally cause excess runoff for durations greater than 2-days. This is demonstrated within Figure 117, which contains the maximum average flow/volume for the instantaneous peak, 1-, 2-, 3-, and 4-day durations for the top four flood events at Foster Joseph Sayers Dam. The Dec 2010, Sep 2004, and June 1972 events were all rainfall dominated flood events. The most intense periods of runoff (i.e. smallest AEP) for these events are across shorter durations; the instantaneous peak duration tends to be the most extreme. On the other hand, the March 1936 event was a rain-on-snow flood event. For longer durations, the March 1936 becomes more and more rare (i.e. the AEP of the max 4-day duration flow is smaller than the AEP of the inst. peak).

As such, overly conservative balanced hydrographs can be created by balancing across durations less than and greater than this “inflection” duration when using flow- and volume-frequency curves that are not separated by runoff generation mechanisms. A mixed population analysis is commonly used to create rainfall-specific and rain-on-snow-specific flow- and volume-frequency curves. Therefore, when a watershed is subjected to multiple types of flood events and a mixed population analysis has not been completed, balanced hydrographs should only be created by balancing across durations which share a common runoff generation mechanism.

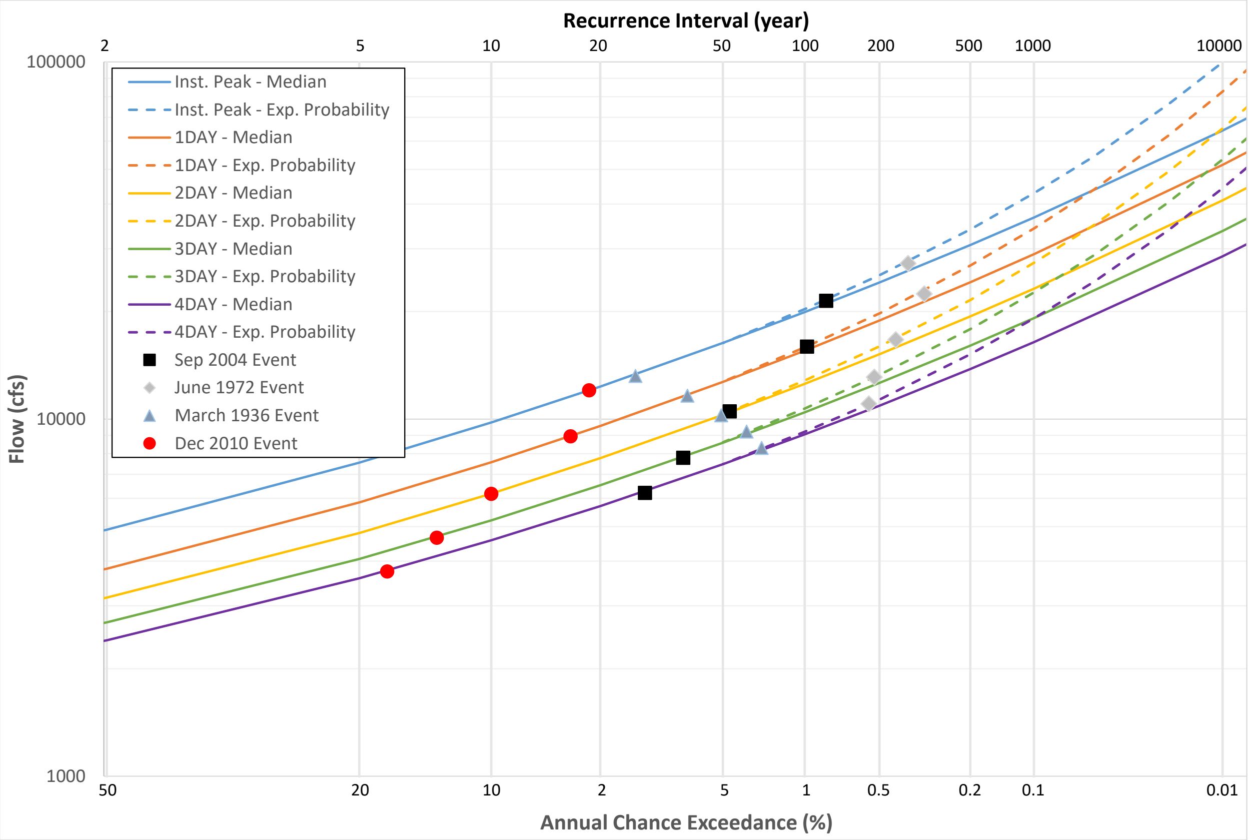


Figure 117: Top Four Runoff Events within the Bald Eagle Creek Watershed Compared Against Flow- and Volume-Frequency Curves

Appendix B: Coincident Frequency Analysis

There are two primary methods for extrapolating the reservoir stage frequency curve: 1) Routing hypothetical flood hydrographs of a known AEP through a reservoir model; or 2) Performing a stochastic simulations using software such as RMC-RFA. This chapter will focus on the first method.

When routing flood hydrographs through a reservoir model, one of the uncertainties is the reservoir stage at the beginning of the simulation. A coincident frequency analysis (CFA) can be used to account for the variability in the starting pool condition. As stated in (Engineer Manual 1110-2-1415, Hydrologic Frequency Analysis, 1993), the objective of CFA is to determine an exceedance-frequency relationship for a variable C, which is a function of both variables, A and B. The variable that has the largest influence on variable C should be designated as Variable A, and the less influential variable should be designated as variable B. For the purpose of the SQRA, variable A is the reservoir inflow volume and variable B is the initial reservoir stage. Variable C is the resulting peak reservoir stage computed by routing balanced hydrographs through a reservoir simulation model.

For all SQRAs, it will be assumed that variables A and B are independent of one another. In the Reservoir Starting Pool Duration Analysis chapter, historical peak stage events were removed from the period of record to derive starting pool duration curves. Removal of the historical peak stage events permits the assumption that there is no dependency between the inflow volume events and the starting reservoir stage. In special cases, variables A and B cannot be assumed independent, in which the CFA analysis described in this section would need to be modified to include conditional variable A frequency curves, as described in (Engineer Manual 1110-2-1413, Hydrologic Analysis of Interior Areas, 1987). However, the level of effort and data requirements for a conditional CFA exceed the time and resources allocated to a SQRA. If the independence assumption is not applicable to a particular dam, this should be noted in the findings and recommendations of the SQRA.

Performing a Coincident Frequency Analysis

The general steps of CFA are as follows. A coincident frequency analysis can be applied to modeling scenarios where HEC-HMS is used to route flow hydrographs where storage and discharge can be modeled using a single elevation-discharge relationship. A coincident frequency analysis can also be applied to modeling scenarios where HEC-ResSim is used to route the flow hydrograph due to complex reservoir operations.

1. Develop a starting pool duration curve, and discretize the duration curve with a set of index points that represent reasonable starting pool values. Select enough index values to represent the shape of the stage duration curve. The reservoir stage duration curve needs to be developed using stage data from observations (measurements) that include current reservoir operations, or from a reservoir simulation model that includes current reservoir operations. The stage duration curve should be developed using stage information from the period where storm events occur. Use the seasonality analysis as described in this document to limit the stage information used in the analysis. For example, if the seasonality analysis shows storm events occur between November and May, then the reservoir stage data should be limited to this time period.

2. Develop the expected probability of exceedance for a peak flow and a family of inflow volume-duration-frequency curves.

3. Develop balanced hydrographs for specific frequencies at the critical duration(s) using observed or synthetic inflow hydrographs.

4. Create a Coincident Frequency Analysis in HEC-SSP.

5. Using a reservoir model, such as HEC-HMS or HEC-ResSim, route multiple AEP balanced hydrographs, each with the different starting pools from step 1, and record the resulting peak stage.

6. For each of the index values from step 1, develop a response curve relating the AEP to the resulting reservoir stage.

7. Run the Coincident Frequency Analysis in HEC-SSP.

8. Repeat using different historical hydrograph shapes.

CFA makes use of the Total Probability Theorem (TPT) shown below. For a specific stage, the exceedance frequency from the balanced hydrograph event, $P(A_n)$, is multiplied by the corresponding proportion of time the initial reservoir pool is exceeded, $P(B_n)$. Then the products are summed to obtain the exceedance-frequency for the specified stage, $P(C)$. The procedures for CFA are described in full in (Engineer Manual 1110-2-1415, Hydrologic Frequency Analysis, 1993). The HEC-SSP analysis will automatically interpolate exceedance frequency values for the user entered stage values and compute the final stage frequency curve using the TPT equation.

$$P(C) = \sum_{i=1}^{n} P(A_i)P(B_i)$$

Equation 7

Using HEC-SSP to Perform Coincident Frequency Analysis

The following steps describe how to set up the CFA in HEC-SSP. A significant portion of the CFA interface is there to help organize the analysis, most of the coincident frequency analysis is performed in other HEC-SSP analyses or outside of HEC-SSP. It is important to note that the CFA in HEC-SSP will not extrapolate the user defined flow frequency curve when “looking up” the exceedance probability for the user defined Variable A, flow, values. The Variable A, flow, frequency curve must be defined for all flow values used in the analysis.

The analyses described in this document are appropriate for those reservoirs that can be modeled using a single reservoir elevation/stage-discharge relationship. For those reservoirs where a single elevation/stage-discharge relationship is not appropriate, then tools like HEC-WAT and HEC-ResSim should be used to model the individual reservoir operation components that add complexity to the overall analysis.

1. The first step is to select index points from the **reservoir stage duration curve** that was developed in the Reservoir Starting Pool Duration Analysis chapter.

    - Index points from the reservoir stage duration curve are used to define starting pool conditions for the CFA and then the incremental probability for each index values is used when computing the TPT equation. As shown in Figure 118, the duration curve was divided into four discrete segments. A stage value was extracted at the mid-point of each segment, and then the incremental probability defined for each segment will be used by the total probability theorem when computing the final frequency curve. For example, the starting pool elevation of 617.5 feet has an incremental probability of 0.2; therefore, 0.2 will be used when weighting the reservoir stage frequency curve that is developed using 617.5 as the starting pool condition.

2. Compute **peak flow** and **volume frequency curves** using historic reservoir inflow information as shown in the Inflow Volume-Frequency Analysis chapter.

    - Peak and volume-frequency curves are needed to develop the balanced hydrographs that are routed through the reservoir model.

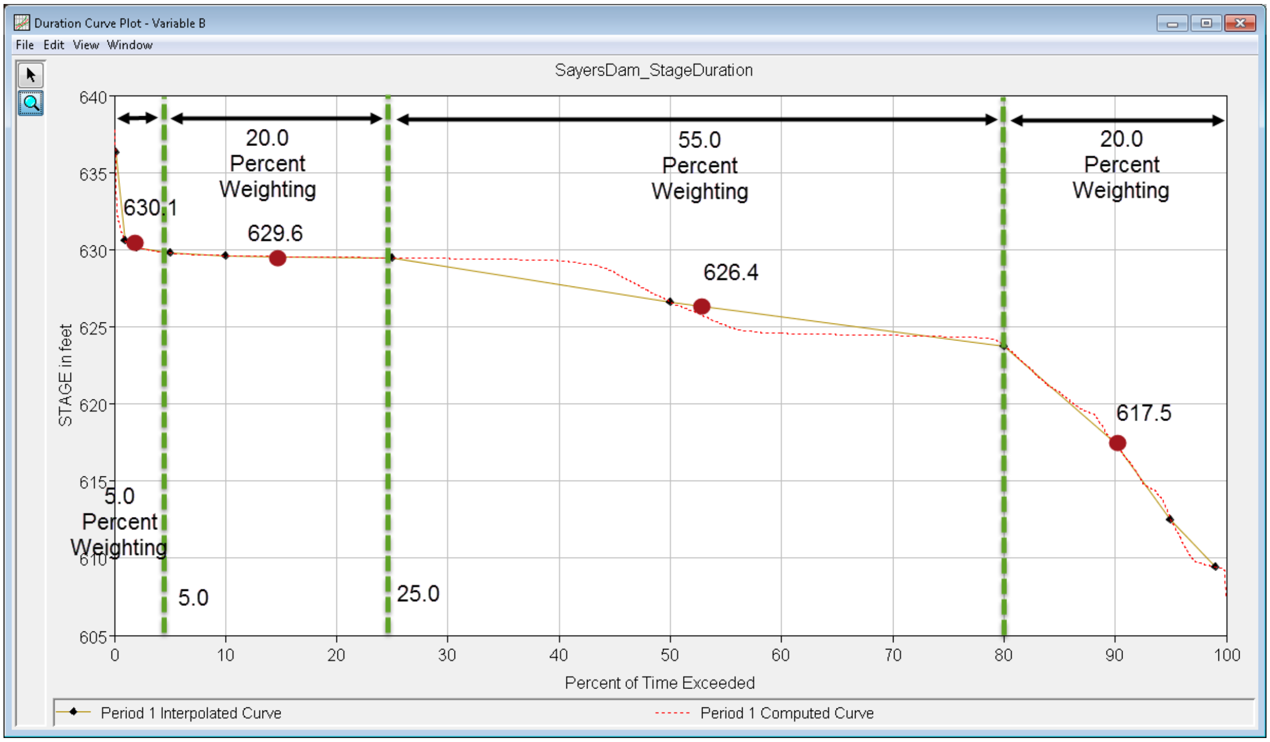


Figure 118: Reservoir Stage Duration Curve Discretized into Four Incremental Probability Ranges with Representative Starting Pool Stages Identified

3. Develop **balanced hydrographs** using historic reservoir inflow hydrographs as shown in Appendix A: Balanced Hydrograph Analysis.

    - It is necessary to extend the balanced hydrographs beyond the AEP events needed to compute the stage frequency curve due to the method used by HEC-SSP to compute the CFA curve. For example, if the study wants to route balanced hydrographs to define the 1, 0.5, 0.2, 0.1, 0.01, and 0.001 percent ACE stage values on the reservoir loading curve, then the analysis will need to include additional ACE events beyond the 1 percent and 0.001 percent ACE events to ensure the frequency curve is computed accurately. In this case, the 2 and 0.0001 percent ACE events should be developed as well. You must use the expected probability curve when developing the balanced hydrographs to be routed within the CFA.

    - At a minimum, two historic hydrograph shapes should be used when developing balanced hydrographs to be used in the CFA. Multiple hydrograph shapes will likely result in different peak stages due timing of the inflow volume and will show uncertainty due to hydrograph shape (or the time pattern of the flood event).

4. Create a **Coincident Frequency Analysis** in **HEC-SSP**. Right click on the Coincident Frequency Analysis folder in the study tree and choose the **New…** menu option. A new coincident frequency analysis editor will open, as shown in Figure 119.

5. Enter a **Name** for the new CFA.

6. On the **General** tab:

    - Select the option “**A and B can be Assumed Independent**”. For an SQRA study, the assumption of independence between inflow magnitude and starting pool will be applied. For this analysis, independence refers to the coincidence of inflow magnitude and pool elevation at the beginning of the large flood event. An independent assumption means that the starting reservoir elevation/storage prior to a flood event is not a function of the magnitude of flood event. The dependent scenario would be where the reservoir starting elevation/storage is typically higher or lower as the magnitude of the flood event increases or decreases. Refer to (Engineer Manual 1110-2-1415, Hydrologic Frequency Analysis, 1993) for a discussion about computing independence or dependence between analysis variables. For all SQRA studies, the analysis will assume independence between reservoir inflow magnitude and reservoir starting stage. Assuming dependence between reservoir inflow and starting stage requires analysis beyond an SQRA level of analysis.

- Select the number of **Variable B Index Values**. Again, variable B is the starting pool condition. As shown in Figure 118, 4 index values were chosen to represent starting pool conditions from the Sayers Dam stage duration curve.

- Enter a data name of “**Stage**” and data units of “**Feet**” for the resulting reservoir stage frequency curve.

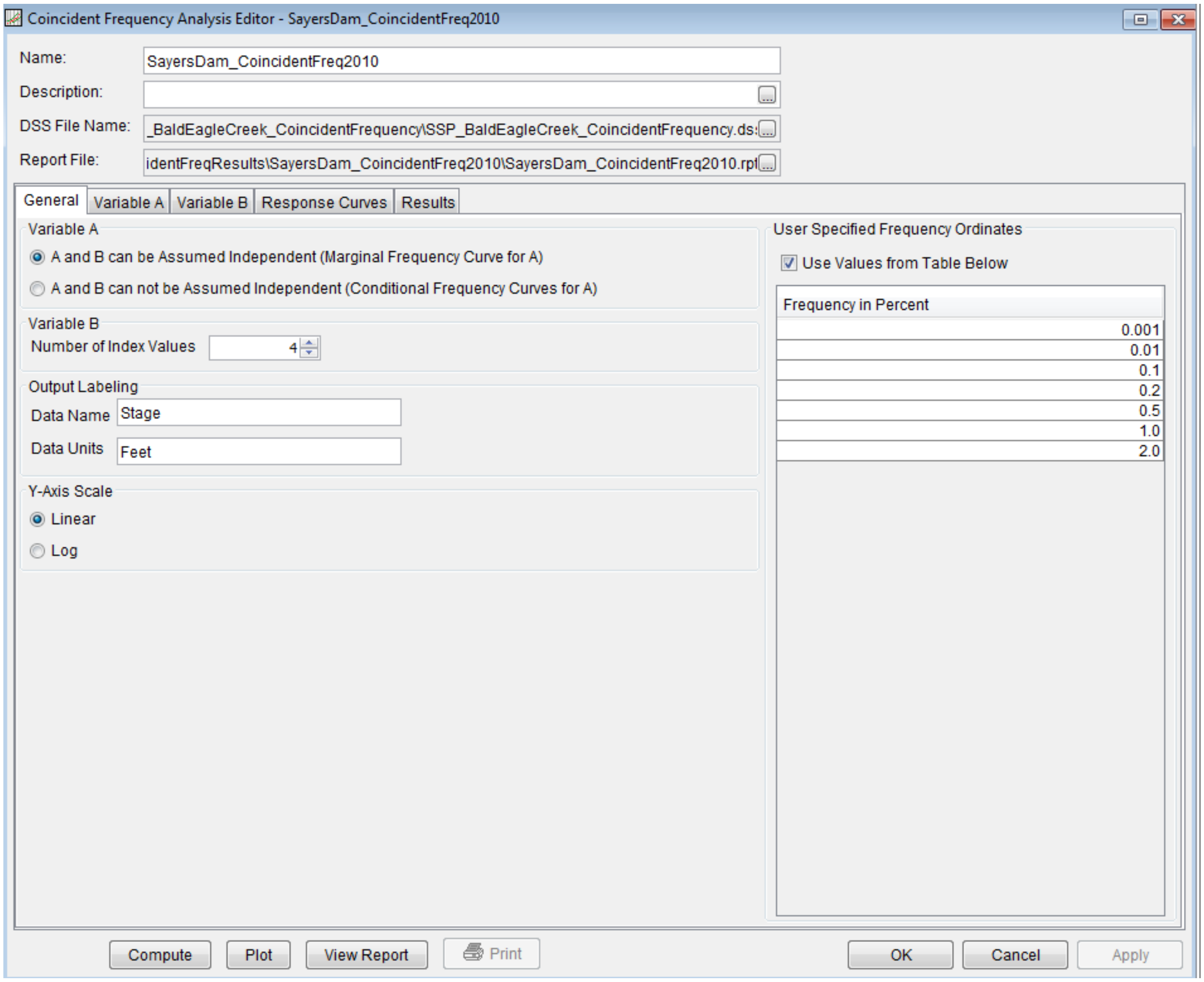
    - *Note*: Stage is one of the five default data types (Options→Results tab), and HEC-SSP will round all values based on the user defined precision. If the user uses an unrecognized data type, then HEC-SSP will assume a rounding precision.

- Set the Y-axis scale to **Linear**, which is a reasonable scale to use when plotting stage/elevation results.

- Edit the **User Specified Frequency Ordinates** for the study. For most studies, probabilities used will range from 2-percent to 0.001-percent. Observed reservoir stage information is typically used to define the reservoir stage frequency curve from 99.9 to 0.2 percent ACE, while the routed balanced hydrographs are used to define the reservoir stage frequency curve from the 2-percent to the 0.001-percent ACE.

- The Variable A frequency curve must be defined on the **Variable A** tab, as shown in Figure 120. The Variable A frequency curve is used to assign a probability to each peak reservoir stage value contained within the table on the Response Curves tab. The Variable C values (peak reservoir stage) are assigned the same probability as the balanced hydrograph. The interval probability obtained from the discretized stage duration curve are used to weight the different conditional reservoir stage frequency curves.

- When defining the Variable A frequency curve, choose the volume frequency curve for the duration representing the critical duration. The critical duration for Sayers Dam is 3-days, therefore, the ordinates for the 3-day frequency curve (expected probability) were used.



Coincident Frequency Analysis Editor - SayersDam_CoincidentFreq2010

Name: SayersDam_CoincidentFreq2010

Description:

DSS File Name: _BaldEagleCreek_CoincidentFrequency\SSP_BaldEagleCreek_CoincidentFrequency.ds

Report File: identFreqResults\SayersDam_CoincidentFreq2010\SayersDam_CoincidentFreq2010.rpt

Variable A

● A and B can be Assumed Independent (Marginal Frequency Curve for A)

○ A and B can not be Assumed Independent (Conditional Frequency Curves for A)

Variable B

Number of Index Values: 4

Output Labeling

Data Name: Stage

Data Units: Feet

Y-Axis Scale

● Linear

○ Log

User Specified Frequency Ordinates

☑ Use Values from Table Below

Frequency in Percent
0.001
0.01
0.1
0.2
0.5
1.0
2.0

Figure 119: Coincident Frequency Analysis Editor, General Tab

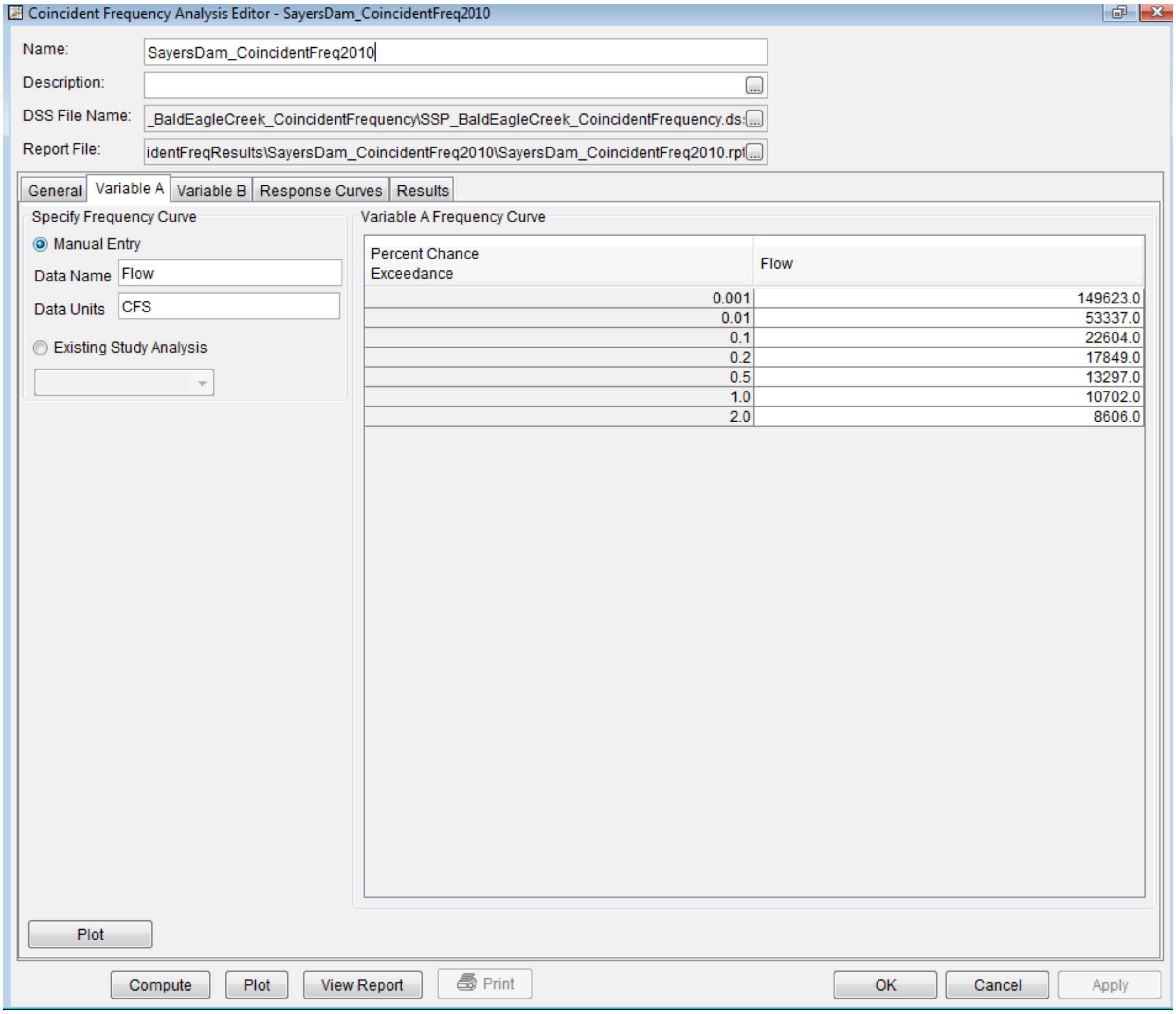
7. On the **Variable A** tab:

    - Choose the **Manual Entry** option and enter a Data Name of “**Flow**” and Data Units of “**CFS**” for the reservoir inflow frequency curve.

    - Enter or paste in the flow frequency curve information into the **Variable A Frequency Curve** table.

8. The **Variable B** tab is used to define the Initial Stage index points (from the reservoir stage duration curve), and the associated probability with each point, as shown in Figure 118.

    - The first step in setting up the **Variable B** tab is to select the stage duration curve analysis already available in the HEC-SSP project, or the stage duration curve can be pasted in to the Duration Curve table.



Name: SayersDam_CoincidentFreq2010

Description:

DSS File Name: _BaldEagleCreek_CoincidentFrequency\SSP_BaldEagleCreek_CoincidentFrequency.ds

Report File: identFreqResults\SayersDam_CoincidentFreq2010\SayersDam_CoincidentFreq2010.rpt

Specify Frequency Curve

● Manual Entry

Data Name: Flow

Data Units: CFS

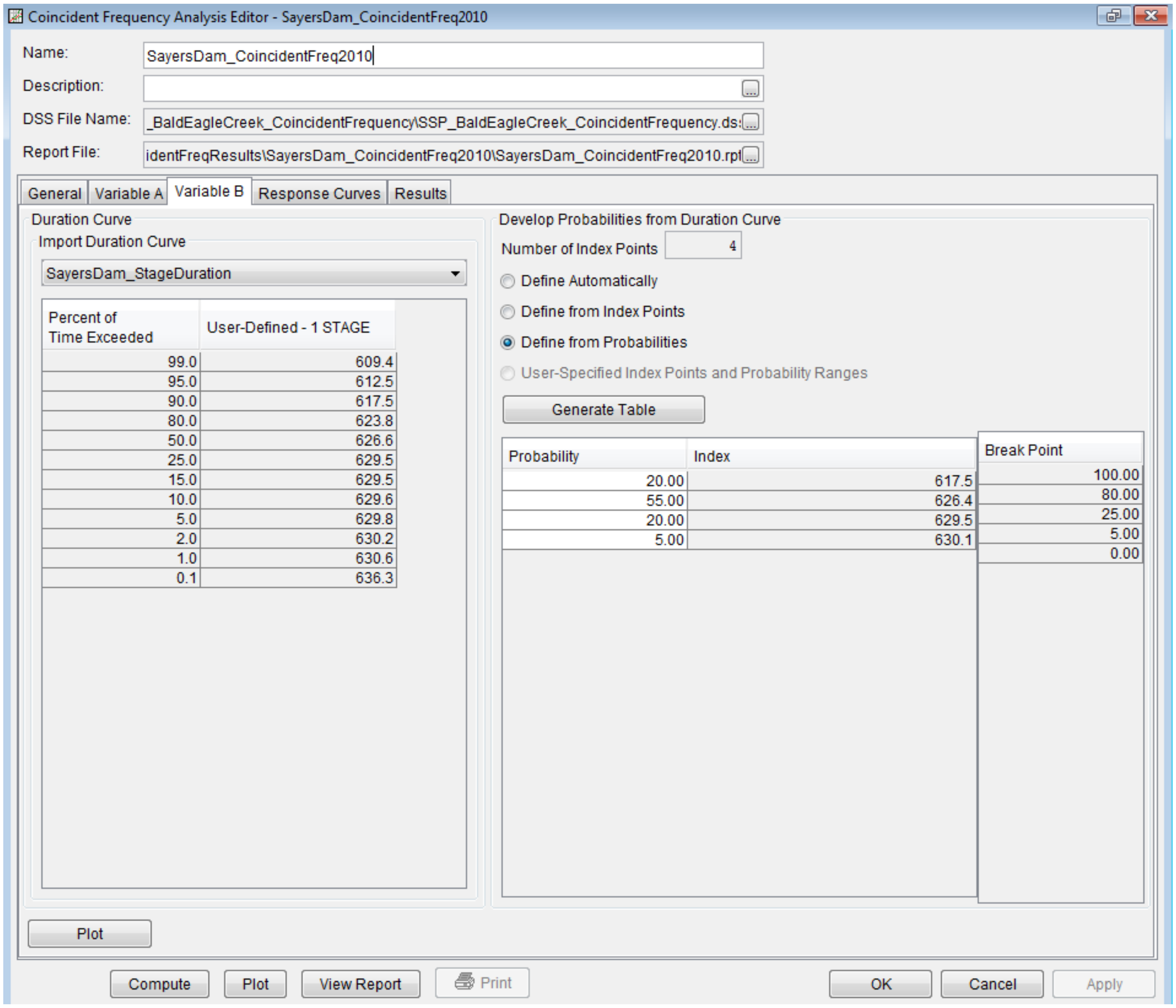
○ Existing Study Analysis

Variable A Frequency Curve

Percent Chance Exceedance	Flow
0.001	149623.0
0.01	53337.0
0.1	22604.0
0.2	17849.0
0.5	13297.0
1.0	10702.0
2.0	8606.0

Figure 120: Coincident Frequency Analysis Editor, Variable A Tab

- Once the Duration Curve has been defined, move to the **Develop Probabilities from Duration Curve** panel and either choose the **Define from Index Points** or **Define from Probabilities** option. If **Define from Index Points** is selected, then enter the stage values for each index point. Once the index values are entered, then press the **Generate Table** button and HEC-SS will compute the values to fill in the **Probability** column. HEC-SSP will start with the first index point and automatically compute the incremental probability (the index values are assumed to be the midpoint of each incremental probability range). If **Define from Probabilities** is selected, then enter the **incremental probability range**, starting from 100 percent of time exceeded in the stage duration curve and moving left to 0 percent of time exceeded. HEC-SSP will compute the index value as the mid-point within the user-defined incremental probability ranges. As shown in Figure 121, incremental probabilities of 20 (from 100 to 80 percent of time exceeded), 55 (from 80 to 25 percent of time exceeded), 20 (from 25 to 5 percent of time exceeded) and 5 percent (from 5 to 0 percent of time exceeded) were defined for the Sayers Dam example. These incremental probabilities resulted in index values of 617.5 ft, 626.4 ft, 629.6 ft, and 630.1 ft. These four reservoir stages were used as the starting elevation in the HEC-HMS model simulations.



Name: SayersDam_CoincidentFreq2010

Description:

DSS File Name: _BaldEagleCreek_CoincidentFrequency\SSP_BaldEagleCreek_CoincidentFrequency.ds

Report File: identFreqResults\SayersDam_CoincidentFreq2010\SayersDam_CoincidentFreq2010.rpt

Duration Curve

Import Duration Curve: SayersDam_StageDuration

Percent of Time Exceeded	User-Defined - 1 STAGE
99.0	609.4
95.0	612.5
90.0	617.5
80.0	623.8
50.0	626.6
25.0	629.5
15.0	629.5
10.0	629.6
5.0	629.8
2.0	630.2
1.0	630.6
0.1	636.3

Develop Probabilities from Duration Curve

Number of Index Points: 4

○ Define Automatically
○ Define from Index Points
● Define from Probabilities
○ User-Specified Index Points and Probability Ranges

Probability	Index
20.00	617.5
55.00	626.4
20.00	629.5
5.00	630.1

Break Point
100.00
80.00
25.00
5.00
0.00

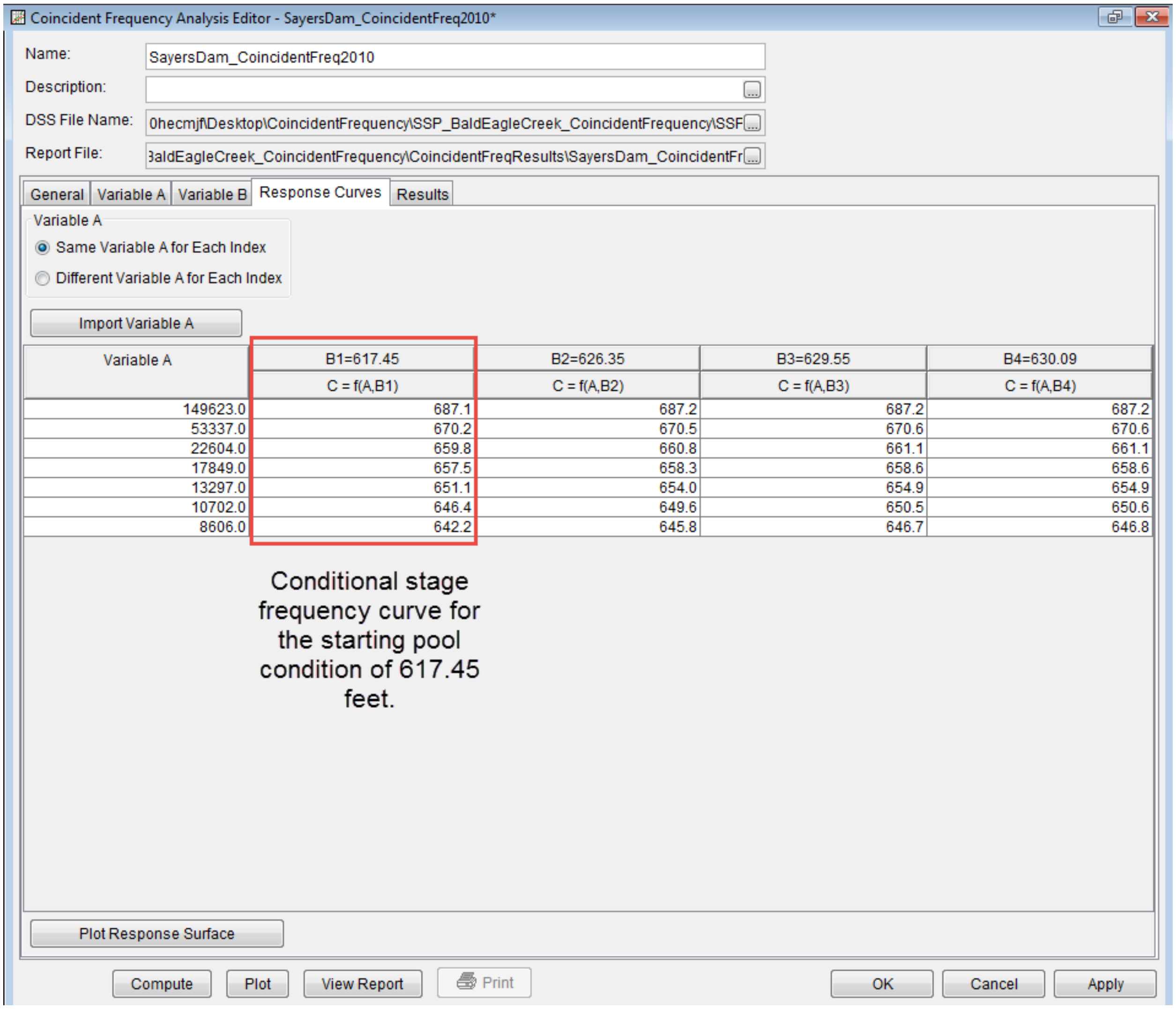
Figure 121: Coincident Frequency Analysis Editor, Variable B Tab

9. Enter results from the HEC-HMS reservoir routing simulations on the **Response Curves** tab.

    - Make sure the "**Same Variable A for Each Index**" option is checked as the same balanced hydrographs will be used for all index points (starting pool values).

    - Click the button to **Import the Variable A** values from the Variable A tab. When this button is pressed, the Variable A column will automatically populate with the flow frequency values on the Variable A tab. If the user enters variable A values that do not match the specific AEP values defined on the Variable A tab, then HEC-SSP will interpolate the exceedance probability (the Variable A values do not have to exactly match the values entered on the Variable A tab).

    - Enter the computed peak stage values into the response curves table. As shown in Figure 122, the column with a starting stage of 617.45 feet is highlighted. This stage frequency curve is conditional on a starting pool of 617.45 feet. The other three stage frequency curves are conditioned on different starting pool values. The incremental probability defined on the Variable B tab will be used to combine (weight) all four conditional frequency curves into one reservoir stage frequency curve.



Name: SayersDam_CoincidentFreq2010

Description:

DSS File Name: 0hecmjf\Desktop\CoincidentFrequency\SSP_BaldEagleCreek_CoincidentFrequency\SSF

Report File: 3aldEagleCreek_CoincidentFrequency\CoincidentFreqResults\SayersDam_CoincidentFr

Variable A

● Same Variable A for Each Index

○ Different Variable A for Each Index

Variable A	B1=617.45	B2=626.35	B3=629.55	B4=630.09
	C = f(A,B1)	C = f(A,B2)	C = f(A,B3)	C = f(A,B4)
149623.0	687.1	687.2	687.2	687.2
53337.0	670.2	670.5	670.6	670.6
22604.0	659.8	660.8	661.1	661.1
17849.0	657.5	658.3	658.6	658.6
13297.0	651.1	654.0	654.9	654.9
10702.0	646.4	649.6	650.5	650.6
8606.0	642.2	645.8	646.7	646.8

Conditional stage frequency curve for the starting pool condition of 617.45 feet.

Figure 122: Coincident Frequency Analysis Editor, Response Curves Tab

- Note: As mentioned above, HEC-SSP will not extrapolate the exceedance probability of the Variable A values defined on the Response Curves tab. The Variable A values defined on the Response Curves tab must be within the defined range on the Variable A tab. HEC-SSP will interpolate the exceedance probability for each variable A value, but it will not extrapolate the exceedance probability beyond the range defined on the Variable A tab.

- After the response curves table has been filled in, as shown in Figure 122, press the **Plot Response Surface** button to visualize the curves. Figure 123 shows the response curves for the Sayers Dam example.

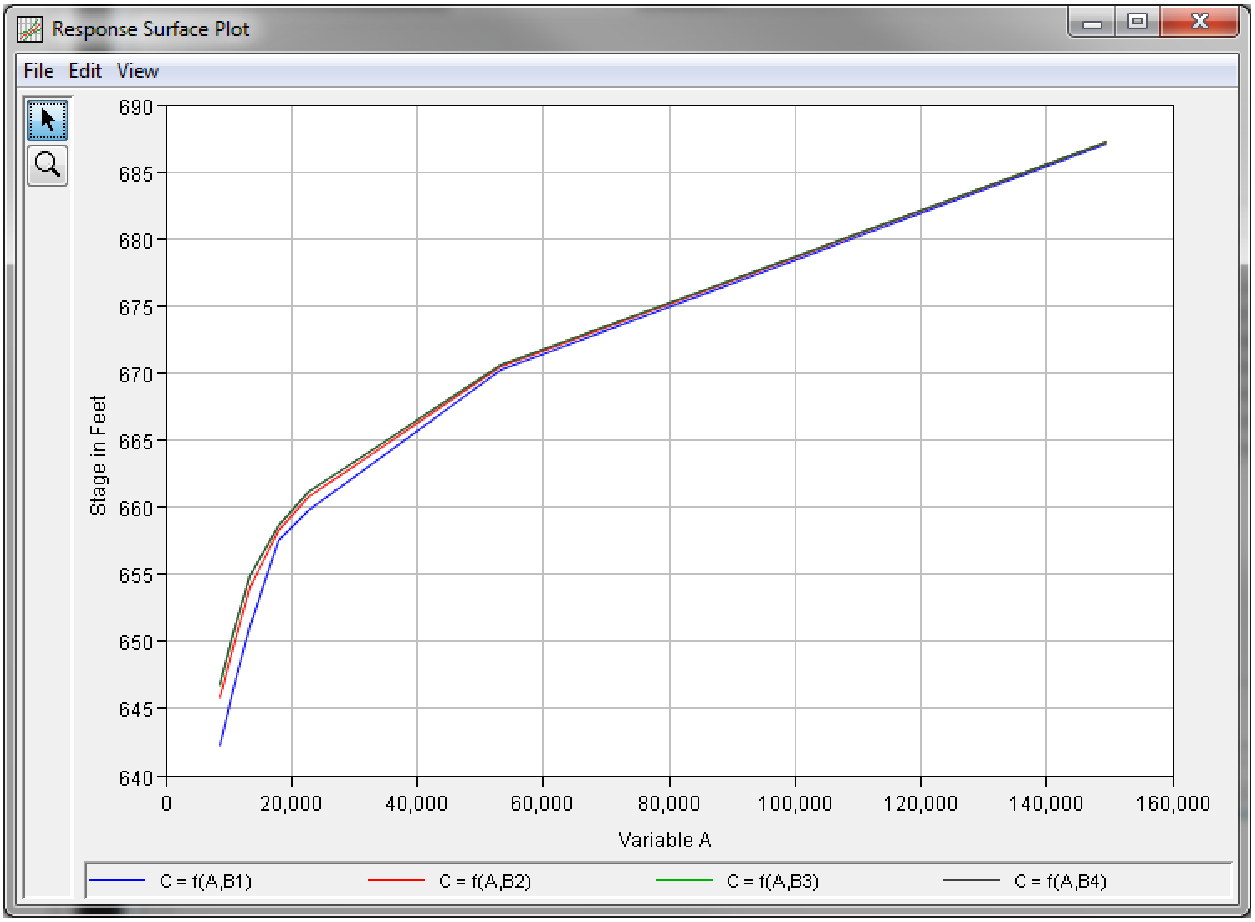
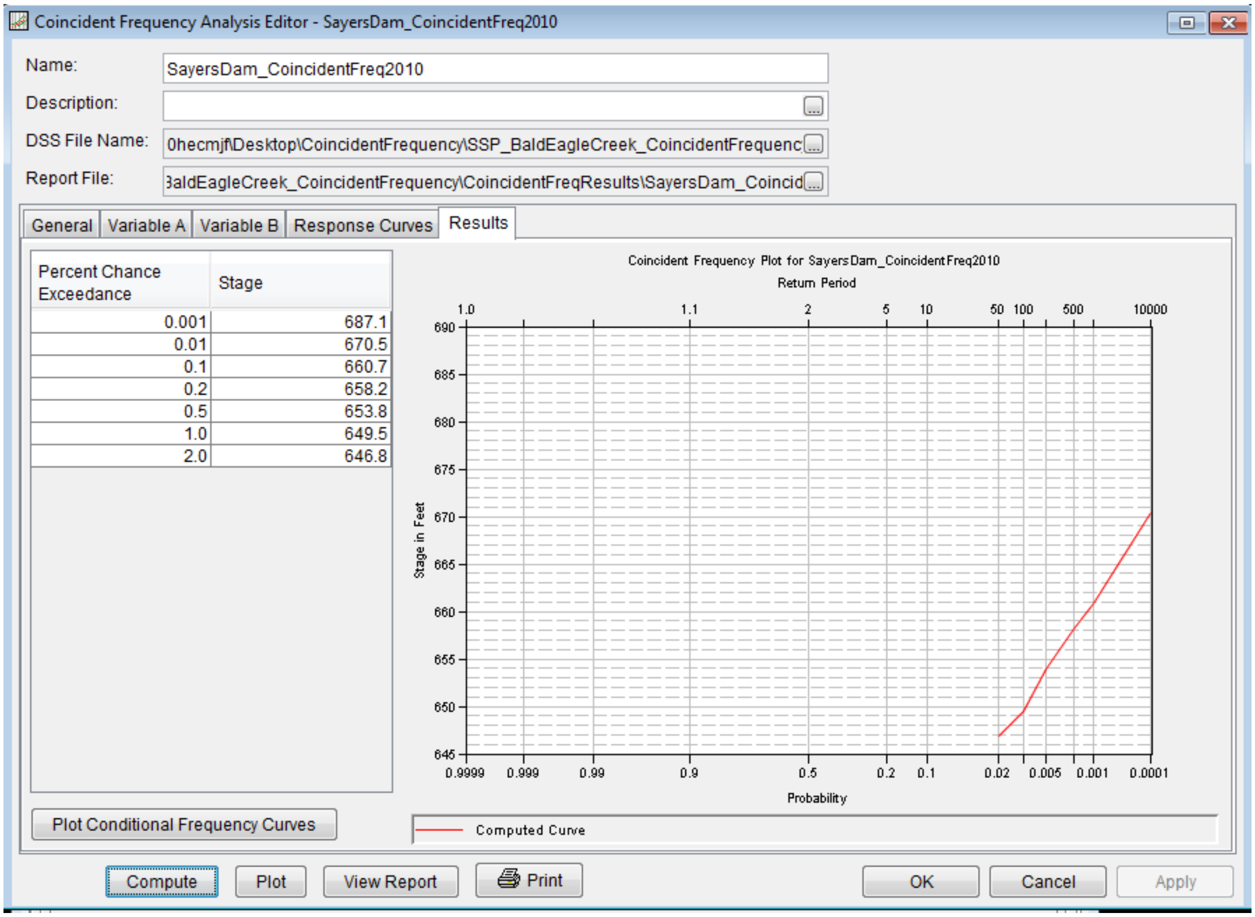


Figure 123: Coincident Frequency Analysis, Response Surface Plot

10. Once the response curves table has been filled in, then the compute button can be pressed.

    - The TPT equation is used compute the final stage frequency curve using the percent of time exceeded associated with each initial stage value from the stage duration curve.
    - The program uses the Variable A frequency curve(s) and the Variable A values in the response curves table to assign a probability to each variable C value in the response curves table.
    - The compute reservoir stage-frequency curve is shown on the **Result**s tab, as shown in Figure 124. The percent exceedance ordinates are the same as those defined on the General tab. The Data Name and Units, defined on the General tab, are used for the y-axis label.



Coincident Frequency Analysis Editor - SayersDam_CoincidentFreq2010

Name: SayersDam_CoincidentFreq2010

Description:

DSS File Name: 0hecmjf\Desktop\CoincidentFrequency\SSP_BaldEagleCreek_CoincidentFrequenc

Report File: 3aldEagleCreek_CoincidentFrequency\CoincidentFreqResults\SayersDam_Coincid

Percent Chance Exceedance	Stage
0.001	687.1
0.01	670.5
0.1	660.7
0.2	658.2
0.5	653.8
1.0	649.5
2.0	646.8

Figure 124: Coincident Frequency Analysis Editor, Results Tab

11. Plot the results with the empirical stage-frequency curve derived in the Empirical Stage-Frequency Analysis section as shown below in Figure 125.

12. Consider creating additional CFA, one for each historic hydrograph shape.

    - The hydrograph shape is a function of the precipitation pattern (time and space) and the hydrologic characteristics in the watershed. Different hydrograph shapes, that contain the same 3-day value, will result in different reservoir peak stage values due to the timing of the hydrograph value and reservoir operations. Running multiple CFA where different balanced hydrograph shapes are used will help define the uncertainty due to the timing of the runoff hydrograph and reservoir operations.

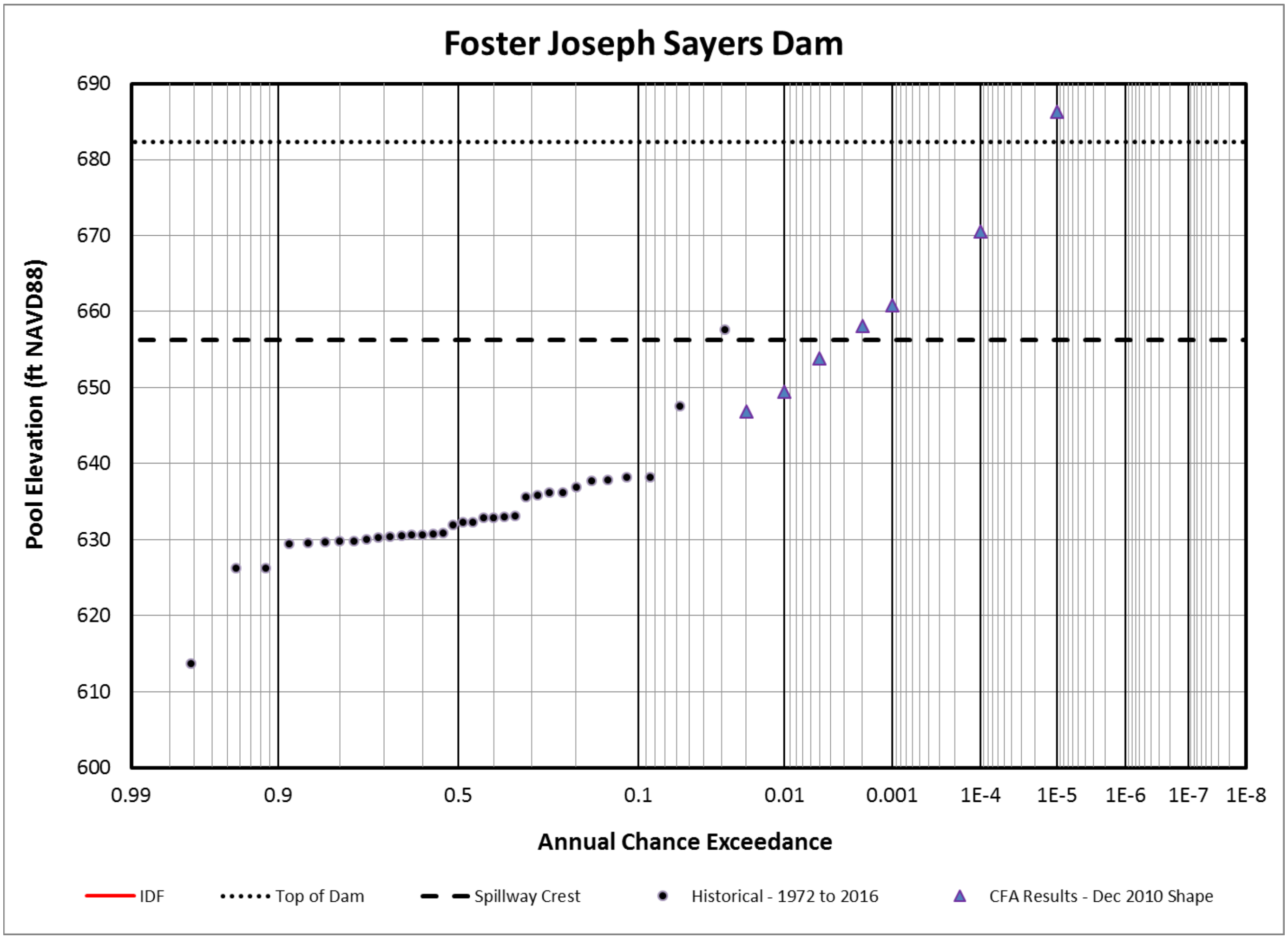


Figure 125: CFA and Empirical Stage-Frequency Curve Results