FERC Engineering Guidelines
Risk-Informed Decision Making

Chapter R19

Probabilistic Flood Hazard Analysis

Table of Contents

Chapter R19 Probabilistic Flood Hazard Analysis

R19.1 Introduction and Purpose

Historically, dam design and analysis methods have focused on selecting a level of protection based on spillway evaluation flood loadings. Traditionally, the protection level is based on the Probable Maximum Flood (PMF) (Cudworth, 1989; FEMA, 1998). Chapter 8 of the FERC Deterministic Engineering Guidelines (EGs) discusses methods for calculating a PMF.

As discussed in Chapter R1, the FERC is developing risk informed decision-making (RIDM) EGs. This RIDM EG chapter discusses risk-informed procedures for evaluating the hazards from floods. Using RIDM necessitates changes in analysis techniques and in decision-making for dams and spillways.

Risk analysis, from a hydrologic perspective, requires an evaluation of a full range (frequency of occurrence) of hydrologic loading conditions and possible dam failure mechanisms tied to consequences of a failure. This risk approach is in contrast to the traditional approach of using a single upper bound. In the context of probabilistic hydrologic loadings, a deterministic maximum event such as the PMF is just one flood outcome amongst a nearly infinite collection of flood peaks, volumes and hydrograph shapes.

The flood loading inputs to a dam safety risk analysis take the form of hydrologic hazard curve that are developed from a Probabilistic Flood Hazard Analysis (PFHA). The most commonly used hydrologic hazard curves (HHCs) are peak flow and volume probability relationships. These hazard curves are presented as graphs and tables of peak flow and volume (for specified durations) versus Annual Exceedance Probability (AEP) (Figure 19-1). The range of AEPs that is displayed on these graphs is intended to be sufficient to support the decision making needs of the organization. Hydrologic Hazard Curves can also be developed for flood characteristics such as: depth of dam overtopping; and depth and/or duration of flooding above specified elevations in the reservoir or spillways. These HHCs would be used in the hydrologic risk analysis to evaluate specific failure modes. Much of the information below is taken from the U.S. Department of Interior, Bureau of Reclamation’s (Reclamation) guidance documents.

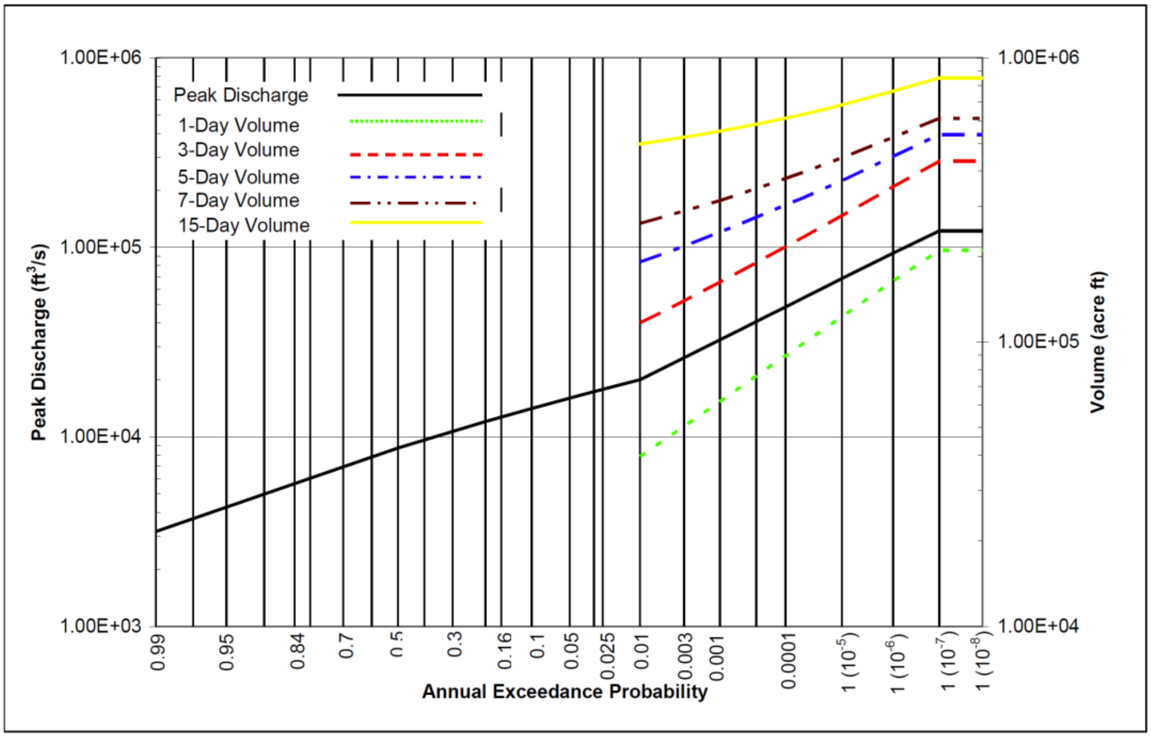


Figure 19-1 – Example hydrologic hazard curves showing peak flow and volume probability relationships (taken from Reclamation Risk Best Practices, Chapter 3, Figure 3.1, April 10, 2010).

In this example, the relationships flatten at $1x10^{-7}$ AEP as they are limited by the PMF. The hydrologic hazard curves can be used to assess potential hydrologic-related failure modes, such as overtopping, seepage/piping at high reservoir levels, erosion in earth spillways, and overstressing structural components, and risks that are associated with these failure modes.

Guidance on how to develop HHCs is provided in this chapter. In addition, the , Bureau of Reclamation has developed guidelines on methods to develop HHCs (Swain et al., 2006), Reclamation Risk Best Practices, Chapter 3, April 10, 2010, and Reclamation and the U.S. Army Corps of Engineers (USACE) Risk Best Practice, Chapter 7, November 26, 2012 (RBP, Chapter 7). This latter reference can be found at the following website: http://www.usbr.gov/ssle/damsafety/Risk/methodology.html.

For basic definitions, see Appendix A. For expanded definitions, additional information to be published as Supplemental Information for Hydrologic Hazard. A section titled PFHA Applied Probability and Statistics gives more information about making probabilistic estimates.

R19.2 Decision-Making – Upper Bounds of HHCs

The FERC is not going to truncate the HHC at the PMF. The primary reason is that using a non-frequency based extreme-flood estimate is inconsistent with a risk-informed process. Because calculation of the PMF does not provide an Annual Exceedance Probability (AEP) or uncertainty calculations, it is insufficient for use in a probabilistic analysis. As part of the risk informed decision, the PMF should however be compared with the proposed probabilistic design flood.

The frequencies of all potential floods need to be considered in a risk assessment. An extreme flood is less likely to occur but could be more likely to fail a dam. However, this same flood may cause extensive flooding in the downstream areas resulting in evacuations and therefore a lower population at risk. The combination of factors may indicate that an extreme storm poses less risk than a smaller storm that in conjunction with an operational failure (such as a gate not operating) that could cause a dam failure with relatively less time to reduce the potential consequences through evacuation. In other cases, the highest risk flood may be larger than the PMF.

Therefore no hard upper bound is going to be used. The risk analysis process will help define the AEP ranges needed for the analysis. The risk assessment will consider all available information including the credibility of the PMF and Hydrologic Hazard Curve(s) and associated uncertainties.

At FERC regulated dams, decision-making is primarily by the dam owner with the concurrence of the FERC and requires more discussion during the risk analysis process. This chapter is to be used to analyze the hydrologic hazard, i.e., develop an HHC. Chapter 27, Risk Assessment is the RIDM chapter that discusses how to evaluate this risk estimate and assess the risk.

R19.3 Hydrologic Analysis

As discussed in Chapter R24, prior to starting a risk analysis, a scoping meeting is to be held. During that meeting, the purpose of the risk analysis and level of analysis will be defined. This scope will determine the type and level of hydrologic analysis that will be made including the level of uncertainty analysis.

Hydrologic hazard curves (Figure 19-2) should be developed by a specialist (hydraulic engineer or hydrologist) in flood hydrology. The curves are then used to estimate the hydrologic risks for particular failure modes. For example, reservoir elevation frequency curves (Figure 19-3) can be used to assess an overtopping failure mode. The duration information from hydrographs (Figure 19-4) can be used as a critical factor in estimating overtopping fragility curves for embankment dams or levees. Typically, the flood specialist provides an overview of the hydrologic hazard results at an initial risk workshop. If there is a hydrologic-related failure mode, the flood specialist typically needs to be included as a risk analysis team member. The flood specialist can then help interpret and apply the HHC for the particular site of interest.

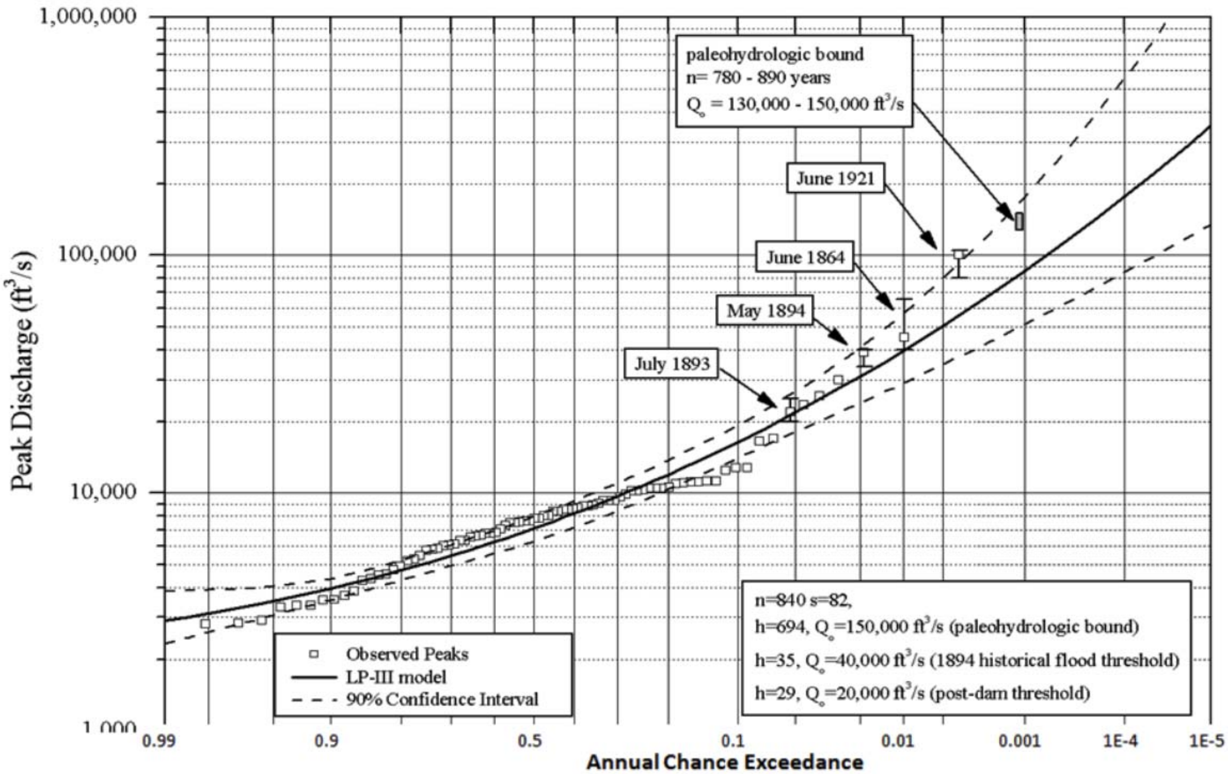


Figure 19-2 – Example peak flow hydrologic hazard curves showing recorded events, historical estimates and paleoflood data, and includes uncertainty (90% confidence interval) (RBP, Chapter 7) Note that Annual Chance Exceedance is equivalent to Annual Exceedance Probability

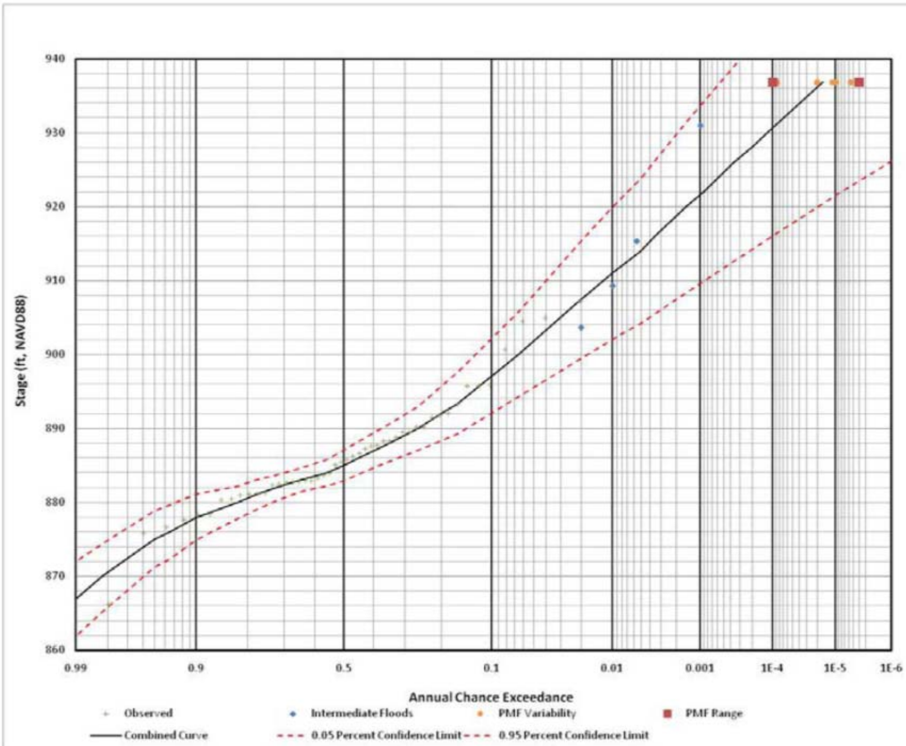


Figure 19-3 – Example (hypothetical) reservoir elevation frequency curve with uncertainty (RBP, Chapter 7)

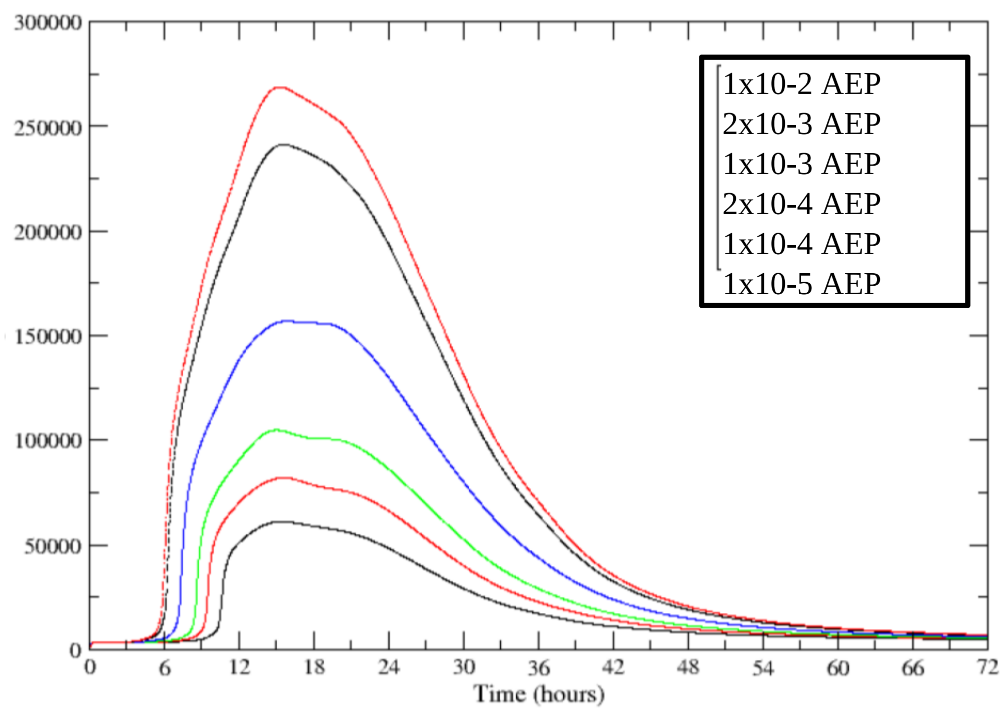


Figure 19-4 – Example patterned hydrographs showing range of hydrologic loading for reservoir routing (RBP, Chapter 7)

R19.4 Development of Hydrologic Hazard Curves (HHCs)

When evaluating hydrologic hazards, a systematic means of developing flood hazard relationships is needed for risk-based assessments to determine hydrologic adequacy for FERC projects. The nature of the potential failure mode and characteristics of the dam and reservoir dictate the type of hydrologic information needed. For some sites, only a peak- discharge frequency analysis may be required, while at other sites, flood volumes and hydrographs may be required. The goal of any hydrologic analysis is to provide the hydrologic information needed to make risk-informed dam safety decisions.

The type of data and the record length used in the analysis form the primary basis for establishing a range on credible extrapolation of flood estimates. The objective of flood frequency analysis and extrapolation is to provide reliable flood estimates for a full range of hydrologic events necessary for dam safety decision-making. In order to develop reliable flood estimates, flood frequency relationships should include an estimate of the uncertainty around the median values. The data used in the analysis provide the only basis for verification of the analysis or modeling results, and as such, extensions beyond the data cannot be verified. The greatest gains to be made in providing credible estimates of extreme floods can be achieved by combining regional data from multiple sources. Thus, analysis approaches that pool data and information from regional precipitation, regional streamflow, and regional paleoflood sources should provide the highest assurance of credible characterization of low AEP floods.

For dam safety risk assessments, flood estimates are needed for AEPs of $1x10^{-4}$ and possibly ranging down several orders of magnitude. Developing reasonably credible estimates at these low AEPs generally requires combining data from multiple sources and a regional approach.

According to the “Australian Rainfall and Runoff: A Guide to Flood Estimation” (Nathan and Weinmann, 2001), floods can be categorized as large, rare, and extreme. These flood categories are shown in Figure 19-5.

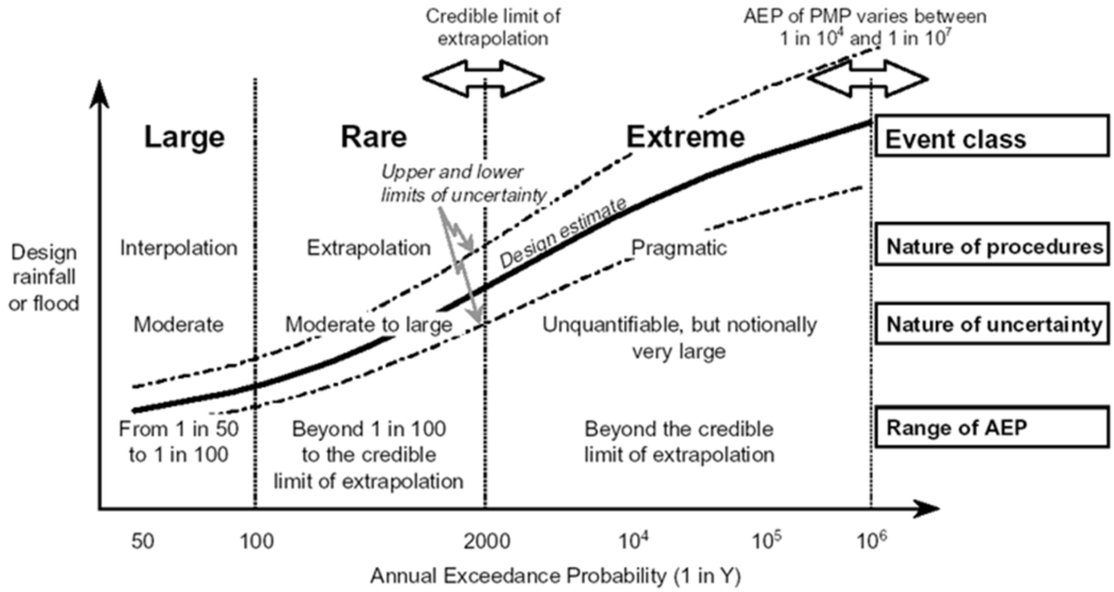


Figure 19-5 – General Characteristics of Hypothetical Floods as a Function of Annual Exceedance Probability (Nathan and Weinmann 2001)

Large floods generally encompass events for which direct observations and measurements are available. Rare floods represent events located in the region between direct observations and the credible range of extrapolation from the data. Extreme floods generally have very small annual exceedance probabilities (AEPs), which are beyond the credible range of extrapolation but are still needed for dam safety risk assessments.

Extreme floods border on the unknowable. Uncertainty is very large and can be very difficult to quantify. Since existing data cannot support flood estimates in this AEP range, hydrologists and engineers must rely on knowledge and understanding of hydrologic processes to estimate extreme floods. Often, these floods result from unforeseen and unusual combinations of hydrologic parameters generally not represented in the flood history at a particular location.

Issues with data extrapolation, use of paleohydrology, and multiple methods is further described below in Section R19.6.

There are two primary methods to estimate extreme flood magnitudes and probabilities for dam safety that are depicted as HHCs. These methods can be broadly classified into streamflow-based statistical approaches, and watershed modeling-based approaches. Current hydrologic hazard curve methods are summarized in Table 19-1, and are generally ranked according to the level of effort involved. Improvements to these current methods and other tools and approaches may be added as project needs and experience dictates.

CLASS	METHOD OF ANALYSIS AND MODELING	DATA SOURCES	LEVEL OF EFFORT	RISK* ANALYSIS LEVEL
Streamflow-based Statistics	Peak-flow frequency analysis with historical data – Bulletin 17B	At-site streamflow data	Low	1-2
Streamflow-based Statistics	Peak-flow frequency analysis with historical/paleoflood data – Graphical or EMA method	At-site streamflow and reconnaissance paleoflood data	Moderate	2
Streamflow-based Statistics	Peak-flow frequency analysis with historical/paleoflood data –FLDFRQ3 (RECLAMATION)	Regional streamflow and detailed paleoflood data	Moderate to High	2-3
Watershed Modeling Based	Pseudo-Stochastic Watershed Modeling (AEP Neutral Hydrometeorological Inputs)	Simplified Precipitation-Frequency Relationship for Watershed. Limited analyses of hydrometeorological inputs and greater judgment in selection of hydrometeorological inputs and model parameters	Moderate	2-3
Watershed Modeling Based	Stochastic Watershed Modeling (Simplified Assessment of Hydrometeorological Inputs)	Regional Precipitation-Frequency Analysis and Use of Areal Reduction Factors for Precipitation-Frequency Relationship for Watershed Analyses of selected hydrometeorological inputs and judgment in selection of some hydrometeorological inputs and model parameters	Moderate to High	3
Watershed Modeling Based	Stochastic Watershed Modeling (Detailed Assessment of Hydrometeorological Inputs)	Detailed analysis for Precipitation-Frequency Relationship for Watershed Detailed analyses of hydrometeorological inputs and model parameters	High	3-4

Table 19-1 – Summary of current HHC methods

*Risk Analysis Level is further discussed below in Section 19.8.

R19.5 Hydrologic Hazard Curves – Methods Based On Streamflow Modeling

Developing HHCs for risk assessment from streamflow uses the length of record and type of data to determine the extrapolation limits for flood frequency analysis. Extrapolation beyond the range of the historic data is often necessary to provide information needed for dam safety risk assessments. The sources of information used for streamflow-based flood hazard analyses include gage data, including volume and stage, historic streamflow measurements and paleoflood data.

Streamflow records consist of data collected at established gauging stations and indirect measurements of streamflow at other sites. Streamflow data can include estimates of peak discharge as well as average or mean discharge for various time periods. Most streamflow measurements on U.S. streams began after 1900, with only a few records dating back that far. Most often, streamflow records at a single site range in length from 20 to 60 years. In some cases, these records can be extended to about 150 years using historical information, which includes historic observations at nearby sites and recordings prior to the development of systematic streamflow measurement.

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. The paleoflood investigator studies geomorphic and stratigraphic records 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 depending on the location it may be possible to develop records that are 10 to 100 times longer than conventional or historical records from other data sources. Paleoflood data generally includes records of the largest floods, or commonly, the limits on the stages of the largest floods over long time periods.

R19.5.1 Applicability of Streamflow Models

Streamflow-based hydrologic work usually begins with a flood frequency analysis developed for peak flows and volumes. In some cases where the risk estimate is relatively insensitive to the extreme peak flow or volume, this type of information may be sufficient to address hydrologic issues and make dam safety decisions. The need for flood volume in addition to peak discharge is most important for dams with a significant impoundment. Preliminary methods that have generally been used for developing frequency curves for annual peak flow data have often applied to volume data for the computation of volume-duration frequency curves (1-day, 2-day, 3-day, 7-day, etc.)

Local stream flow can be used to credibly extrapolate annual exceedance probabilities to 1:100 with 1:200 as an upper limit under optimum conditions, i.e., the station has a consistent record over many years (e.g., 100 years) including no changes in river basin or regulation from dams, etc.. Through the use of regional streamflow data, the optimal range of credible extrapolation is established at up to 1:1000 depending on the number of stations in the region, lengths of record, and degree of independence of these data. For paleoflood data, only in the Holocene epoch (or the past 10,000 years) is our climate judged to be sufficiently like that of the present climate for these types of records to have meaning in estimating extreme floods for dam safety risk assessment. This climatic constraint indicates that an optimal range for extrapolation from paleoflood data, when combined with at-site gaged data, for a single stream could be up to about $1x10^{-4}$.

A basic premise of any analysis of past events to predict future probabilities is that the statistical distribution exhibited by historic events will be the same for future events. (i.e. - stationarity assumption) Historically, engineers have generally assumed that the economic life of the typical water resource project (50-100 years) is short enough to ignore the potential impact of changes to local runoff patterns. Recently, there has been considerable debate regarding the potential effect of climate change on the frequency and severity of floods. Although there is an increasing consensus that the climate is warming, estimates of future warming and its effect on the hydrologic cycle cover a broad range. In addition to the uncertainty over the effects of climate change, future changes to land cover, urbanization and operation of upstream water management facilities such as dams, irrigation works and diversions can have an even greater short term effect. These factors point out the need for the engineer to be fully aware of the potential effect of these influences, to remain current with the latest analyses intended to quantify these effects and to include them where appropriate in the overall risk assessment for a given project.

R19.5.2 Data Sources for Streamflow Models

Streamflow data requirements for performing a frequency curve analysis are peak annual flow data (for a peak flow frequency curve), daily flow data (for developing a preliminary volume-duration frequency curve, such as a one-day or three-day frequency curve), and any historic flood information that could be used to improve the frequency estimates. Annual peak-flow data fall into two classes: systematic and historic. The systematic record includes all annual peaks observed in the course of one or more systematic gauging programs at the site. Historical flood information consists of estimated high flows for floods that are not part of the gaged record.

Where the record of at-site systematic streamflow measurements is sufficiently long (i.e. it captures the variability within the climate) and is well located in terms of the dam site (or easily transferred to the dam site), a single gage record may be sufficient. Unfortunately, the data record at a single site is often inadequate to capture the more extreme flow events to support meaningful extrapolation. In these cases and to provide the longest possible record, data from nearby sites with similar hydrologic settings can be used together with simultaneous data for the initial site to develop correlations between observed discharge measurements. These correlations can then be used to develop a longer record at the initial gage site.

Where more detailed information is required such as flood hydrographs for historic floods, daily, hourly and instantaneous records for many gages are available on-line. In some cases, original copies of archived records need to be located to provide data for the longest possible period and to obtain actual hydrographs for historic storms. In cases where no upstream stream gages are available, a reasonable record of reservoir inflows can sometimes be developed through using a reverse routing procedure, which determines average reservoir inflow from combining outflow with the change in reservoir storage over a specific period. When using this procedure, it is essential to have an understanding of the operating procedures for any gates and a history of any physical changes to the outlet works over the period of available data.

It is important to note that due to geomorphological and other changes to a river (e.g. channel improvement, dams, bridges, etc.), stream gages may have been moved and recalibrated many times during the historic record. It is also possible that land use and groundcover changes (e.g. deforestation or urbanization) may have effected significant changes to the watershed's hydrologic response during the period of record. It is therefore important for the engineer to ensure all data for a given gage represents the same drainage area and upstream catchment characteristics. Where significant changes to the upstream catchment or gage location have occurred, adjustment to a portion of the record may be necessary to ensure that statistical differences between portions of the record are eliminated to the extent possible. These adjustments are intended to ensure that extrapolations derived from past events best represent the future hydrologic response of the watershed. Another adjustment that might be needed is for the effect of reservoir storage on outflows. These issues are further discussed in Chapter R18, Determining Reservoir Level Exceedance Curves.

R19.5.3 Method of Analysis for Streamflow Models

There are four main techniques currently in use in PFHA to develop a peak-flow frequency curve and integrate streamflow (gage) data, historical data, and paleoflood data. The first is a traditional flood frequency approach using Bulletin 17B. The second is a mixed-population graphical approach (England et al., 2001). The two other techniques are statistical models that use gage, historical, and paleoflood data. The Expected Moments Algorithm (EMA) uses moments to estimate the parameters of a log-Pearson Type III (LP3) distribution and is consistent with Bulletin 17B. A Bayesian maximum likelihood approach is used by FLDFRQ3 to estimate a peak-flow frequency curve with historical and paleoflood data and uncertainties. All four techniques have been used for estimating flood peaks at various Reclamation dams.

R19.5.3.1 Traditional Flood Frequency Approaches – Bulletin 17B

In the United States, the Log-Pearson Type III (LP3) Distribution has been the standard technique used by the various Federal Agencies and is generally recommended for flood frequency analysis. The LP3 Distribution is a statistical technique for fitting frequency distribution data to predict the design flood for a river at some site. Once the statistical information is calculated for the river site, a frequency distribution can be constructed.

For this reason, it is customary to perform the flood frequency analysis using the annual maximum instantaneous peak discharge data. However, the LP3 Distribution can also be constructed using the maximum values for mean daily or multiple day discharge data. By considering multiple-day average discharge values, the probabilities of floods of various volumes can be determined. The advantage of this particular technique is that extrapolation can be made of the values for events with AEPs well beyond the observed flood events.

A full description of this method as well as its application is described in Bulletin 17B from the Interagency Advisory Committee on Water Data. Bulletin 17B provides regional generalized skew coefficients based on analysis of multiple stream gage records within a given area. The generalized skew together with the station skew developed from the at-site data are used to form a weighted average skew for use in the computations. The use of the generalized skew is intended to help prevent anomalies in the data for a single station from unrealistically influencing the computed recurrence intervals for extreme events and ensure that the distribution accurately represents the river's long term flood characteristics. Bulletin 17B also outlines methodologies for handling an array of situations that may arise with observed data, including a non-continuous record; an incomplete record; zero flow years; mixed populations of data (rainfall events versus rain on snow, etc.); high and low outliers; and the use of historic information which is not part of the continuous record to improve frequency estimates. The 17B guidelines also provide for computing confidence limits where the mean, standard deviation and skew of the sample and final LP3 Distributions are compared to compute upper and lower bounds within which future floods of the stated recurrence interval can be expected to occur.

Although Bulletin 17B and the regional skew map have not been updated since 1976, recent analyses have concluded that the LP3 Distribution continues to be a very reasonable and flexible model of flood risk within the range of parameter values consistent with U.S flood series. Nevertheless, for events whose AEPs are greater than the number of years of record in the observed data, the Bulletin 17B methodology is not considered to be highly accurate. Accordingly, the suggested credible limit to using the Bulletin 17B methodology for frequency curve extrapolation is about twice the length of the observed data record. For frequencies beyond the AEP of the observed data, the LP3 result should be weighted together with the other suggested methods to obtain a curve that goes all the way to the desired flood magnitude or exceedance probability. Confidence limits should always be computed, as they are a way of measuring the uncertainty (Either for the exceedance probability of a selected discharge or for the discharge corresponding to a given exceedance probability).

Although it is possible to develop frequency curves using hand calculation and graphical methods, use of one of the available computer programs is highly recommended. The Bulletin 17B methodology has been employed in several computer programs developed by the US Geological Survey (USGS), US Army Corps of Engineers (USACE), and

Reclamation. Currently available programs include PeakFQ from the USGS, HEC-SSP from the USACE's Hydrologic Engineering Center, and FLDFRQ3 from Reclamation. Each of these programs differs slightly in the manner in which the Bulletin 17B guidelines are applied particularly regarding the inclusion of historic and paleoflood data, mixed populations of data (rainfall events versus rain on snow etc.) and computation of confidence limits. Differing methodologies include the expected moments algorithm (EMA) and Bayesian maximum likelihood procedure.

R19.5.3.2 Mixed-Population Graphical Approach

A mixed-population graphical peak-discharge frequency approach has been developed by Reclamation (England et al., 2001). The graphical approach is an at-site frequency method and the frequency curve is constructed in two distinct parts: (1) standard hydrologic statistical methods are used to define a frequency curve for AEPs less than and including the $1x10^{-2}$ AEP and (2) graphical methods are used for estimates greater than the $1x10^{-2}$ AEP. Peak discharge estimates from gaging stations are used to define the first part of the curve and at-site paleoflood data are used to define the second part of the curve. The first part is estimated assuming an LP3 distribution. Historical information is included in the at-site frequency analysis when it is available. The second portion of the frequency curve is estimated assuming a 2-parameter log-Normal (LN-2) distribution. It is defined between the $1x10^{-2}$ and the available paleoflood data AEPs, and extrapolated beyond the paleoflood data using this LN-2 distribution. Two points are typically used to estimate this portion of the flood-frequency curve: (1) the LP3 model $1x10^{-2}$ AEP peak discharge estimate and (2) the midpoint in time and discharge of the paleoflood data. Logarithms (base 10) of the peak flows and standard Normal variants of AEPs are used to estimate the LN-2 parameters using least squares. The LN-2 distribution was found to reasonably represent daily standardized precipitation in the western United States (Lane, 1997).

An example peak-flow frequency curve using the graphical approach is shown in Figure 19-6.

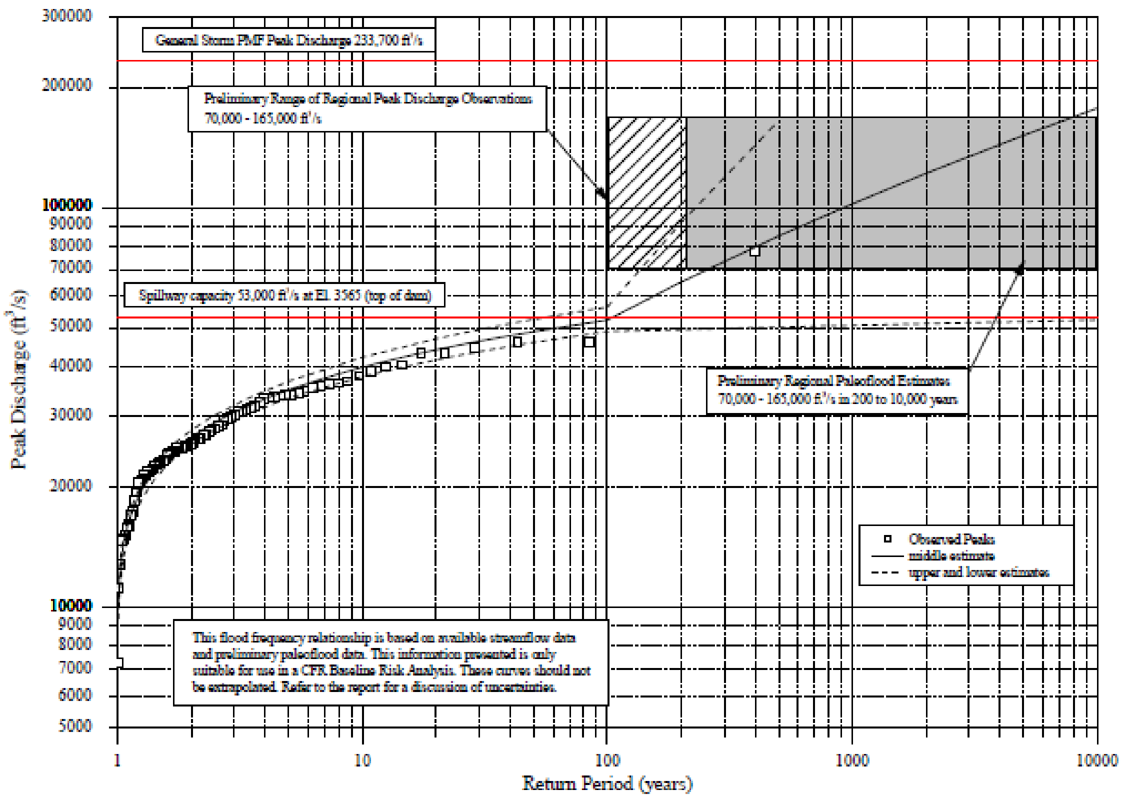


Figure 19-6 – Example application of mixed-population graphical flood frequency curve using peak discharges on the South Fork Flathead River near Hungry Horse, Montana.

R19.5.3.3 Expected Moments Algorithm (EMA)

The EMA is used by Reclamation and others. It is a moments-based parameter estimation procedure that is designed to incorporate many different types of systematic, historical, and paleoflood data into flood frequency analysis. EMA assumes the LP3 distribution is the true distribution for floods. EMA was designed to handle the four different classes of historical and paleoflood data beyond the applicability of the Bulletin 17B historical weighting procedure. EMA is philosophically consistent with, and is an improvement to, the Bulletin 17B method of moments procedure when one has historical or paleoflood information. EMA is specifically designed to use historical and paleoflood data, in addition to annual peak flows from gaging stations, in a manner similar to Maximum Likelihood Estimators. It is a more logical and efficient way to use historical and paleoflood data than the current Bulletin 17B historical method, and it is a natural extension to the moments-based framework of Bulletin 17B.

EMA has been rigorously peer reviewed in the literature (Cohn et al., 1997, 2001; England et al., 2003a, 2003b) and provides a suitable flood frequency model. EMA has been applied at many sites for peak-flow frequency (England et al., 2003b). The National Research Council applied EMA for 3-day annual maximum mean flood flows on the American River (NRC, 1999). An example peak-flow frequency curve with EMA is shown in Figure 19-7.

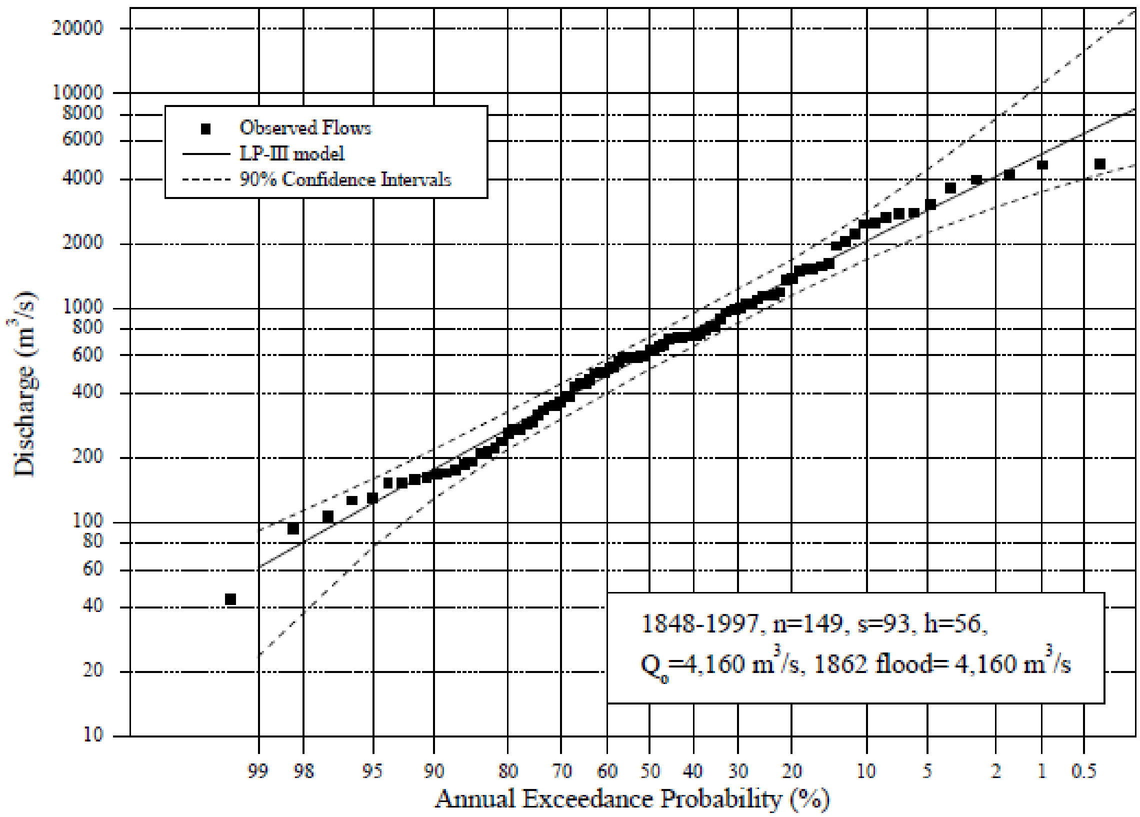


Figure 19-7 – Example application of EMA for American River annual maximum 3-day mean discharge frequency analysis.

Note that the USGS currently has a task force that is developing Bulletin 17C to use the EMA and other methods.

R19.5.3.4 FLDFRQ3 Method

FLDFRQ3 (O'Connell, 1999; O'Connell et al. 2002) uses a Bayesian maximum likelihood procedure to estimate parameters of various distributions. The Bayesian approach includes measurement uncertainty in the parameter estimation procedure. This approach uses a "global" parameter integration grid in order to identify ranges of probability distributions that are consistent with the data (O'Connell, 1999).

There are generally three main steps in running FLDFRQ3 (O’Connell, 1999): input and data check, parameter estimation for a particular distribution, and generating parameter uncertainties for a particular model (e.g., LP3) using grid integration. The data are grouped into two broad classes: data with normal uncertainties, such as peak discharge, and values in a range with potentially variable probability density and skew within the range, such as paleohydrologic bound discharges and ages and discrete paleofloods. After entering and checking data, the parameter estimates are obtained from the data and assumed model. The user then checks the appropriateness of the model and estimated parameters. There can be several steps here to determine the “best models” (there can be more than one) that fit the data and the model parameters. Finally, the user estimates the parameter uncertainty given the chosen model and parameter combination. O’Connell et al. (2002) demonstrate how to combine results of several models and their parameter uncertainties using a likelihood criterion.

FLDFRQ3 has been rigorously peer reviewed in the literature (O’Connell et al., 2002) and contains suitable flood frequency models for all levels of analysis. It has been used at many sites for peak-flow frequency by Reclamation, including Folsom Dam, Seminoe and Glendo Dams and Pathfinder Dam. An example peak discharge frequency curve using FLDFRQ3 is shown in Figure 19-8.

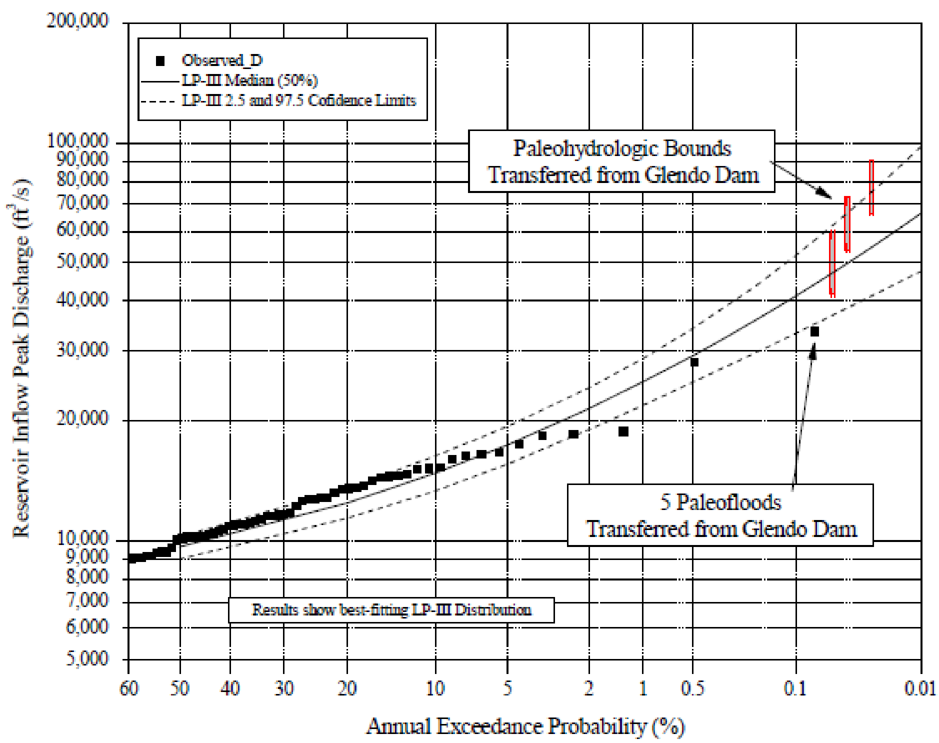


Figure 19-8 – Annual peak-discharge frequency inflows to Pathfinder Dam, Wyoming, from best-fitting LP3 distribution using FLDFRQ3 (England, April 2003).

R19.6 Paleoflood Analyses

Dam Safety decisions are often required for AEPs much greater than $2x10^{-2}$ to $1x10^{-2}$ and therefore extrapolation (an assumption that a curve drawn from 1 to $2x10^{-2}$ to $1x10^{-2}$ may be extended) becomes a necessity. Depending on the hydrologic hazard method being employed (listed above), the sources of information used for the hydrologic hazard analyses may use combinations of streamflow, precipitation, and paleoflood data which are summarized in Table 19-2. Note that the ranges of credible extrapolation listed in Table 19-2 reflect the thinking and evolution of methodologies in 1999 when the Table 19-2 was produced.

Type of data used for hydrologic hazard analysis	**Range of credible extrapolation for Annual Exceedance Probability**	
	Typical	**Optimal**
At-site streamflow data	1×10^{-2}	5×10^{-3}
Regional streamflow data	2×10^{-3}	1×10^{-3}
At-site streamflow and at-site paleoflood data	2.5×10^{-4}	1×10^{-4}
Regional precipitation data	5×10^{-4}	1×10^{-4}
Regional streamflow and regional paleoflood data	6.7×10^{-5}	2.5×10^{-5}
Combinations of regional data sets and extrapolation	2.5×10^{-5}	1×10^{-5}

Table 19-2 – Data types and extrapolation ranges for hydrologic hazard analysis (from Reclamation and USACE Best Practices, 2012)

Reclamation routinely utilizes paleoflood data collected at the site of interest. Gathering paleoflood data is important for development of HHCS at FERC-regulated dams. As discussed below, the statistical methods need physical corroboration which can be obtained using paleoflood hydrological methods. A credible paleoflood estimate for the AEP 1/500 event can improve the quality of the HHC, even for more frequent floods.

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). The paleoflood investigator studies the river geomorphology and soils/stratigraphy adjacent to the river that provides information on 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 gain information about an event 10 to 100 times older than the observational record (e.g., streamgage).

These estimates are made based on the key operational assumption that future flood and hydrologic hazard behavior is similar to the past, and can be estimated from what we have observed. Ongoing climate change research related to floods may eventually provide information on the viability of this routine assumption, and/or potential ways of adjusting methods in Table 19-2 as necessary in light of potential climate change and variability. Further information on data sources is in Swain et al. (2006).

Typically paleoflood data is used to identify a non-exceedance bound (Levish – 2002), i.e., no flood above a certain stage has been exceeded for X numbers of years, for example, no flood exceeding a certain level for at least 10,000 years. The other use is typically to identify the frequency of a flood that has occurred. It should be recognized that just because a flood level has not been shown to be in a particular basin, this does not mean that it can't occur. Rare to extreme storms can occur in basins that have not seen that storm. Judgment is necessary in how to use these results.

R19.7 Hydrologic Hazard Curves – Watershed Models

Hydrographs are the standard output from watershed models and are needed for development of HHCs that describe the frequency of user-specified flood characteristics. A frequency-based approach to watershed modeling requires a greater level of time, effort and analysis than is typically required for deterministic design storm watershed modeling. In addition, the most rigorous watershed modeling requires more specialized skills than deterministic modeling.

Watershed models can generally be considered to be comprised of three major components consisting of: the watershed model structure; the hydrologic processes; and the hydrometeorological inputs. There is wide latitude available in selecting combinations of these three components for constructing simple to very complex watershed models. The sophistication used in describing these three components affects how well the watershed model can reproduce the historical flood behavior of a watershed. A general description of these three components is presented below and will be expanded in the following sections. Table 19-3, below, lists three categories of watershed modeling configurations varying from simple to complex that have been found useful in developing HHCs. The more detailed methods are more likely to be used for HHCs that extend to very low AEPs. Very low AEPs might be required for higher hazard dams because of tolerable risk considerations, dams with potentially very large costs to remediate, or HHCs with large uncertainty.

R19.7.1 Watershed Model Structure

Watershed models may be classified as either continuous or event models. Continuous models generate hydrographs as a continuous time-series of streamflows (HSPF, UBCWM, HEC-HMS), whereas event-based watershed models (HEC-1, HEC-HMS) generate a hydrograph for a user-specified time span. Continuous watershed models require that the hydrometeorological inputs such as precipitation, evapotranspiration, and air temperature be provided on a continuous basis to support continuous computations for the hydrological processes. Event-based models require hydrometeorological inputs only for the time-span when a flood event is generated. There are several considerations for selecting either a continuous or event model that will be discussed in later sections.

Watershed models can also be classified as distributed, lumped or a hybrid system with some hydrometeorological inputs and model parameters distributed and others lumped. Distributed models offer the potential to more accurately characterize the diversity of soils, land-use and spatial variability of hydrometeorological inputs. Distributed models also require greater time and effort in data analysis and assembly of the distributed model structure. This typically involves use of GIS spatial mapping capabilities.

R19.7.2 Hydrological Processes for Watershed Models

A number of hydrologic processes must be modeled for development of HHCs. This would include modeling of: soil moisture conditions; snow-water depth and density; soil infiltration, rainfall-runoff and snowmelt processes and generation of surface runoff and interflow runoff; transforming of runoff to a streamflow hydrograph using some combination of unit hydrographs and linear or non-linear routing methods. Several conceptual and physics-based models are currently available to simulate the hydrological processes, varying from simple to complex. The choices made in selection of the modeling approaches for the hydrological processes will determine the watershed model parameters needed for flood simulations. The choice of modeling approaches will also determine the level of complexity in flood characteristics that can be captured for development of HHCs.

R19.7.3 Hydrometeorological Inputs

The form of the hydrometeorological inputs is dependent upon the watershed model structure and data needed to support computations for the hydrological processes. Analyses of hydrometeorological data will be needed to support the following products.

- Basin-average precipitation-frequency relationship for the watershed
- Seasonal distribution of storms on the watershed
- Spatial and temporal patterns for storms
- Grouping of soil types based on hydrologic soil properties
- Distribution of daily or monthly precipitation for soil moisture accounting
- Seasonal evapotranspiration for soil moisture accounting
- Seasonal baseflow for setting initial streamflow conditions
- Daily or seasonal reservoir levels for setting initial reservoir level

If snowpack and snowmelt are a consideration, the following products will also be needed.

- Seasonal snowpack snow-water equivalent, depth and density
- Temporal patterns of air temperature for snowmelt computation

If the watershed is located in mountainous terrain, orographic effects must be assessed and many of the hydrometeorological inputs will need to be analyzed to account for variation with elevation. This would include, daily or monthly precipitation, evapotranspiration, snowpack, and air temperatures.

CATEGORY	WATERSHED MODELING HYDROLOGIC METHOD	DATA SOURCES	LEVEL OF EFFORT
1	Pseudo-Stochastic Watershed Modeling AEP Neutral Hydrometeorological Inputs	Simplified Precipitation-Frequency Relationship for Watershed Limited analyses of hydrometeorological inputs and greater judgment in selection of hydrometeorological inputs and model parameters	Moderate
2	Stochastic Watershed Modeling Simplified Assessment Hydrometeorological Inputs	Regional Precipitation-Frequency Analysis and Use of Areal Reduction Factors for Precipitation-Frequency Relationship for Watershed Analyses of selected hydrometeorological inputs and judgment in selection of some hydrometeorological inputs and model parameters	Moderate to High
3	Stochastic Watershed Modeling Detailed Assessment Hydrometeorological Inputs	Detailed analysis for Precipitation-Frequency Relationship for Watershed Detailed analyses of hydrometeorological inputs and model parameters	High

Table 19-3 – Categories of Watershed Modeling Approaches for Developing HHCs

R19.7.4 Applicability of Watershed Models

HHCs can be developed for any flood characteristic that can be obtained from analyses of hydrographs. This would include flood characteristics such as: flood peak discharge; maximum discharge for a specified duration; runoff volume; maximum reservoir level (Figure 19-9); reservoir releases (spillway discharges); depth and duration of flooding above a specified elevation threshold; and the duration of spillway discharges above a specified discharge threshold.

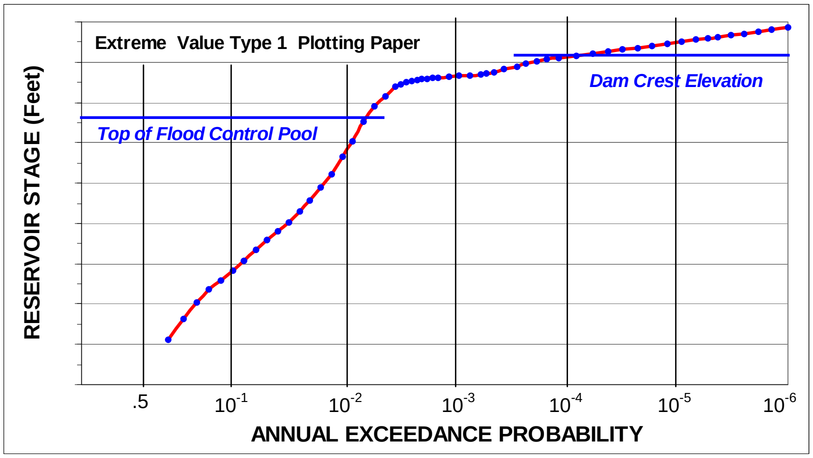


Figure 19-9 – Example of HHC for Maximum Reservoir Level

There are differences in the approaches taken in Category 1, 2 and 3 watershed modeling that make each approach better-suited to certain applications as described below.

R19.7.4.1 Category 1 Watershed Modeling

This is a simplified approach that requires the least amount of effort and is best suited for initial assessments of hydrologic loadings and for portfolio risk assessment. This approach has larger uncertainties in the watershed model outputs and in the HHCs. The hydrologic modeling approach used by the Washington State Dam Safety Program (April 1993) is an example of this type of watershed modeling.

R19.7.4.2 Category 2 Watershed Modeling

This is a mid-level approach with regard to detailed analyses of hydrometeorological inputs and level of effort. It is best-suited to watersheds where there is limited spatial variability in storm temporal patterns or where estimates of hydrologic loadings for very low AEPs are not needed. The level of uncertainties is intermediate between the Category 1 and 3 modeling approaches. The Australian Rainfall-Runoff Model (ARR – 2001) with stochastic inputs is an example of this type of approach.

R19.7.4.3 Category 3 Watershed Modeling

This is the most detailed approach that is best suited for complex or large watersheds where there is spatial variability in storm temporal patterns. The detailed approach is appropriate for risk analyses requiring a rigorous analysis of extreme hydrologic loadings with very low AEPs. This approach has the lowest level of uncertainties of the three modeling approaches. The Stochastic Event Flood Model (SEFM – Jan 2009) is an example of a detailed approach to watershed modeling. (Note that RBP, Chapter 7 also lists TREX as an alternative method).

R19.7.5 Data Sources for Watershed Models

The majority of hydrometeorological data can be obtained from Federal and State agencies that are responsible for data collection and record keeping. Some data are also available from private companies that have a business need for certain data types. Much of the hydrometeorological data are available in electronic formats from sources such as:

- National Climatic Data Center (NCDC)
- National Oceanic and Atmospheric Agency (NOAA)
- National Center for Atmospheric Research (NCAR)
- Western Regional Climate Center (WRCC)
- Remote Automatic Weather Stations (RAWS)
- United States Geological Survey (USGS)
- National Resources Conservation Service (NRCS)

The following sections describe common sources for obtaining specific types of hydrometeorological data.

R19.7.5.1 Storm Related Data for Watershed Model

Precipitation data associated with storm events are used in a number of analyses and for watershed model inputs. This includes data for development of the precipitation-frequency relationship for the watershed, analysis of historical storms for development of spatial and temporal storm patterns and analysis of the seasonality of storm occurrence. Daily and hourly precipitation data for conducting these analyses can be obtained from NCDC, NCAR and WRCC. NEXRAD Radar reflectivity data can also be used in spatial and temporal analyses of storms.

The National Weather Service (NWS) Hydrometeorological Design Studies Center (HDSC) is in the process of completing regional precipitation-frequency analyses for point precipitation for areas throughout the US. The results are being published as part of NOAA Atlas 14. These findings and concurrent NWS studies for areal reduction factors are suitable for developing precipitation-frequency relationships for watersheds for Category 1 watershed modeling (Table 19-3). The datasets of precipitation annual maxima from these studies can be used for conducting more detailed analyses for developing precipitation-frequency relationships for watersheds for Category 2 and 3 watershed modeling.

R19.7.5.2 Data for Soil Moisture Accounting

Daily and monthly precipitation for soil moisture accounting and for setting initial watershed conditions can be obtained from NCDC, NCAR, and WRCC. Evapotranspiration data can also be obtained from these organizations, from State

Agricultural Colleges in the western US, and from a recent USGS study conducted by Sanford and Selnick (Dec 2012).

R19.7.5.3 Snowpack Data

Snowpack data are collected at selected NOAA stations and available through NCDC, NCAR, and WRCC. In the western US, data for snow-water equivalent, snow depth and density are collected at SNOTEL sites operated by the National Resources Conservation Service (NRCS). Snow courses are also operated by some western states and private companies and snowpack data can be obtained from these organizations.

R19.7.5.4 Soils

Data for the hydrologic properties of soils are available from the NRCS in electronic databases (STATSGO, SSURGO) in formats compatible with GIS spatial mapping. GIS maps of surficial geology are often useful in understanding the hydrologic response of a watershed and are available from State agencies responsible for management of Natural Resources.

R19.7.5.5 Air Temperature and Freezing Level

Daily maximum and minimum air temperature data are available for NOAA stations. Hourly air temperature data are available for first-order NOAA weather stations. These data are available from NCDC, NCAR, and WRCC. Data from Radiosondes for air temperature lapse rates and freezing levels in the free atmosphere are available through NOAA.

R19.7.5.6 Streamflow

Daily streamflow data for seasonal analysis of baseflow can be obtained from the US Geological Survey (USGS) and also from some hydropower utilities that collect streamflow data for their business uses. Hourly streamflow data for historical floods for use in model calibration can also be obtained from the USGS or computed through reverse reservoir routing using reservoir level and reservoir discharge data (Zoppou – Aug 1998).

R19.7.5.7 Reservoir Level and Reservoir Operations

Reservoir level data are usually available from the operators of specific dams whether the dams are Federal, State or privately owned. Rule curves for reservoir operations and manual for flood operations are available from the dam owners/operators.

R19.7.6 Methods of Analysis for Watershed Models

The basic concept for developing HHCs using a watershed modeling approach is to generate a large sample of flood hydrographs for the full range of storm characteristics and watershed conditions that occur during the season(s) when storms occur. Monte Carlo sampling methods can be used (typically in Category 2 or 3 models) to assemble the large number of datasets for numerous combinations of the hydrometeorological inputs. Flood simulations are then conducted using the input datasets to generate the resultant flood hydrographs. HHCs are then assembled by analysis of the flood characteristics of interest from the flood hydrographs generated by the watershed model. The key components of this stochastic approach can be summarized as follows:

- basin-average precipitation-frequency relationship for the watershed (Figure 19-10 below) developed using regional frequency analysis methods (Hosking and Wallis - 1997) and spatial analyses of historical storms;
- representative collection of storm temporal and spatial patterns;
- hydrometeorological inputs treated as variables;
- particular attention given to seasonal variability of watershed antecedent conditions due to seasonal variability of hydrometeorological inputs;
- account for any dependencies between hydrometeorological inputs;
- conduct sufficient number of flood simulations to account for the large number of combinations of values of the hydrometeorological inputs and seasonal variability; analyze the flood hydrographs generated by the watershed model to assemble the dataset of flood characteristics of interest; and construct the HHCs from the dataset of flood characteristics of interest.

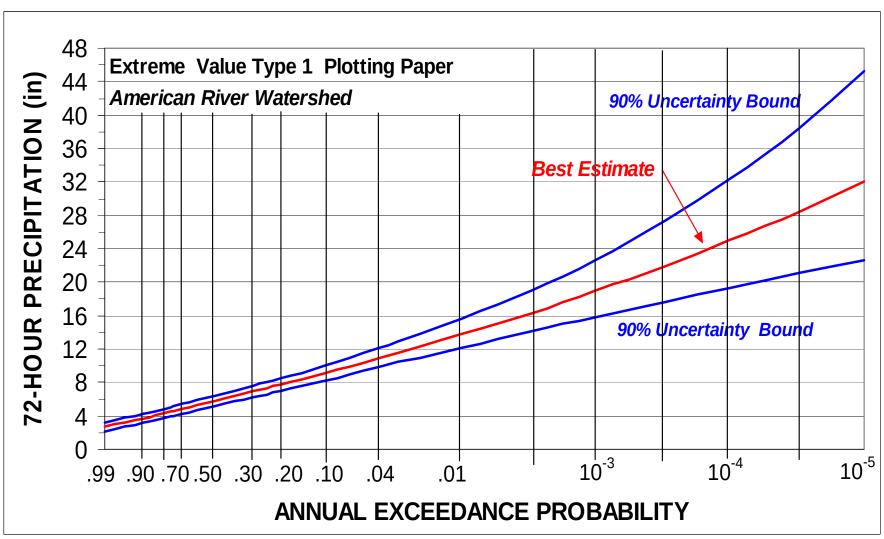


Figure 19-10 – Example of Basin-Average Precipitation-Frequency Relationship for a Watershed

The distinguishing features between the Category 1, 2 and 3 watershed modeling approaches are described in Table 19-4.

ITEM	CATEGORY 1 WATERSHED MODELING	CATEGORY 2 WATERSHED MODELING	CATEGORY 3 WATERSHED MODELING
Basin-Average Precipitation-Frequency Relationship for Watershed	NOAA Atlas 14 and Areal Reduction Factors	Regional Precipitation-Frequency Analysis and Areal Reduction Factors	Regional Precipitation-Frequency Analysis and Spatial Analysis of Storms
Storm Characteristics	Single representative temporal and spatial pattern	Suite of storm temporal and spatial patterns One temporal pattern for each storm	Suite of storm temporal and spatial patterns Temporal patterns vary spatially within each storm
Storm Seasonality	Single storm date	Full range of storm dates	Full range of storm dates
Hydrometeorological Inputs	Single representative values for chosen storm seasonality	Analyses of selected hydrometeorological inputs, judgment in selection of some inputs and model parameters	Detailed analyses of hydrometeorological inputs and model parameters
Rainfall-Runoff Modeling and Transformation to Streamflow Hydrograph	Simplified approaches commonly used	Varies from simplified to detailed approaches	Detailed rainfall-runoff modeling and surface and interflow responses
Examples of Modeling Approaches and Computer Models	Washington State Dam Safety Hydrologic Modeling Approach	Stochastic Modeling using Australian Rainfall-Runoff Model	Stochastic Event Flood Model (SEFM)

Table 19-4 – Key Differences in Category 1, 2 and 3 Watershed Modeling Approaches

Important features of the stochastic approach to watershed modeling can best be explained by comparison with conventional deterministic design storm watershed modeling such as used for computing a Probable Maximum Flood (PMF). Table 19-5 lists the key differences between the detailed Category 3 HHC watershed modeling approach and the deterministic design storm approach. Differences for the Category 1 and 2 modeling approaches would be similar to those listed in Table 19-5 except that a variety of simplifications are made for various hydrometeorological inputs for the Category 1 and 2 approaches.

ITEM	HYDROLOGIC HAZARD CURVE CATEGORY 3 WATERSHED MODELING	DETERMINISTIC DESIGN STORM APPROACH (PMF)
Primary Deliverable	Hydrologic Hazard Curves	Inflow flood hydrograph
Number of Flood Simulations and Flood Hydrographs	Less than 20 simulations for Category 1 modeling Many thousand simulations for Category 2 and Category 3 modeling	Single inflow flood hydrograph Additional simulations for sensitivity analysis
Hydrometeorological Inputs	Treated as variables	Treated as fixed values
Storm Magnitudes	Full range of storm magnitudes defined by basin-average precipitation-frequency relationship for watershed	Single design storm
Storm Seasonality	Full range of storm dates observed in historical record for climatic region	Month yielding largest flood response
Storm Temporal Pattern	Suite of temporal patterns based on historical storms	One synthetic or historical temporal storm pattern
Storm Spatial Pattern	Suite of spatial patterns based on historical storms	"Critical" spatial pattern for maximizing precipitation on the watershed
Antecedent Soil Moisture	Full range of soil moisture conditions for storm seasonality	Wet antecedent conditions
Antecedent Snowpack	Full range of snowpack conditions snow-water equivalent, depth and density observed in historical record for climatic region	Heavy snowpack, often 0.01 exceedance probability
Air Temperatures for Snowmelt	Air temperature temporal patterns and freezing levels observed in historical storms with variable temperature lapse rates	Conservative air temperature patterns and fixed temperature lapse-rates
Rainfall-Runoff Modeling	Based on soil moisture conditions with surface runoff (quickflow) and interflow responses	Commonly lumped surface and interflow response
Snowmelt Runoff	Based on snow density and snow-water accounting with energy-budget method	"Ripe" snowpack and energy-budget method
Baseflow	Based on historical record for full range of storm seasonality	Conservative baseflow for month chosen for design storm
Initial Reservoir Level	Based on historical record for full range of storm seasonality	Conservative selection of initial reservoir level
Watershed Model Calibration	Calibration to large historical floods, Calibration to flood responses for a range of storm magnitudes, Calibration to historical flood-frequency curve (peak, 24-hr, 72-hr discharge)	Calibration to large historical floods
Sensitivity Analysis	Global sensitivity analysis	One-at-a-Time sensitivity analysis
Uncertainty Analysis	Can be accomplished with numerous flood simulations	Not previously done

Table 19-5 – Comparison of Watershed Modeling for Development of HHCs Versus Deterministic Design Storm Approach

R19.7.6.1 Dams with very Low AEP Flood Loading

Analysis of dam performance under extreme hydrologic loadings with very low AEPs is often needed for higher-consequence dams because of tolerable risk considerations. Also high uncertainty and large estimated remedial costs can drive the need for a more rigorous analysis. Estimation of hydrologic loadings for very low AEPs requires detailed watershed modeling with reduction of uncertainties wherever possible. A watershed modeling approach will generally have more success in depicting representative HHCs when the model development includes:

- analyses of historical data to the maximum extent practicable to represent the full range of antecedent watershed conditions;
- use of regional analyses methods to reduce sampling variability and uncertainties;
- inclusion of a diverse suite of storm temporal and spatial patterns;
- attention given to the seasonal variation in hydrometeorological inputs;
- selection of algorithms that best replicate the hydrological runoff processes and transformation to streamflow for the watershed under study;
- attention given to calibration of the watershed model for a wide range of storm magnitudes and antecedent soil moisture conditions.

R19.7.6.2 Watershed Model Calibration

Calibration of the watershed model is more extensive than conventional deterministic modeling for the Category 2 and 3 watershed modeling approaches. Three levels of model calibration are conducted. First, calibration is conducted for a range of storm magnitudes to replicate the flood response for a range of soil moisture conditions. This approach is taken to improve the estimates of soil moisture and subsurface storage capacity. This is more readily accomplished for continuous models than for event models. Second, calibration of watershed model parameters would be conducted for the largest floods observed in the historical record. Third, flood simulations would be conducted to replicate the flood-frequency relationship for observed flood peaks and/or maximum 24-hour and 72-hour discharges. This three level approach to calibration has been generally found to provide a robust calibration of the watershed model.

R19.7.6.3 Mixed Populations of Storms/Floods

Situations arise where large floods can be produced on a watershed from different storm types. This may occur from some combination of local thunderstorms, mesoscale convective systems, synoptic scale extratropical cyclones and tropical cyclones. When a mixed population of storm types with distinctively different storm temporal and spatial patterns can produce large floods, separate analyses and flood simulations must be conducted for each storm type. The flood-frequency curves for each storm type are then combined to produce the HHCs applicable to the dam and watershed.

R19.7.6.4 Considerations in the Choice of Continuous or Event Watershed Models

There are advantages and disadvantages to the choice of using continuous or event models. Continuous watershed models offer a more holistic approach to calibration of the watershed model parameters, particularly for soil moisture and subsurface storage capacities. Continuous models also allow resampling approaches to be used with long-term simulations of the historical record. This provides a straight-forward procedure for setting spatially varying soil moisture and snowpack conditions in the watershed. Resampling methods can be used for baseflows and initial reservoir levels for both continuous and event watershed models.

Flood simulations can be time-consuming, particularly if conducting an uncertainty analysis. Whether a continuous or event model is chosen, there are savings in computational time to be gained if flood simulations are conducted in an "event" mode where only the time span encompassing the storm event is simulated.R19.8 Levels of Risk - Scalability

Sometimes, a simple hydrologic method is needed that can be used in a risk-screening evaluation, i.e., a method that is simple to perform but yields a reasonable, but conservative result for full range of AEPs. See Chapter R24 for a discussion of levels of risk analysis (RA); the screening estimate is a Level 1 RA.

As can be seen by the discussion above, the rarer events need more rigorous methods to provide reasonable results. The preference in probabilistic risk analysis is to have a competently conducted HHC using streamflow and watershed models. Eventually all FERC-regulated high and significant hazard dams should have these types of HHCs. An interim goal would be to have all FERC-regulated high and significant hazard dams with a reasonably accurate flood frequency curve developed for floods with an AEP of up to 1/500.

For now, the method discussed below should be with the recognition that it very simplistic and inadequate for higher levels of risk analysis. It should be used with engineering judgment and care and only for screening characterizations of risk. The method proposes using Bulletin 17B (or 17C when completed) to develop the frequency of floods in the AEPs from $1x10^{-2}$ up to $2x10^{-3}$ (1/500)or$1x10^{-3}$ (1/1000). For rarer floods, a simple conservative assumption is used to set the PMF equivalent to an AEP of $1x10^{-4}$ to $1x10^{-5}$, as discussed below.

R19.8.1 Level 1 (Screening) HHCs –Floods with AEP from 1x10-2 to 2x10-3

The following is taken from Table 19-1 above.

CLASS	METHOD OF ANALYSIS AND MODELING	DATA SOURCES	LEVEL OF EFFORT
Streamflow-based Statistics	Peak-flow frequency analysis with historical data – Bulletin 17B	At-site streamflow data	Low

As discussed above, Bulletin 17B methods can typically be used. However, Bulletin 17B has many limitations. There are many FERC dams located in ungaged basis, or near gages with very short records. For these dams, we recommend using the USGS Streamstats website for coming up with flood frequencies up to the $2x10^{-3}$ AEP event. The following is taken from the Streamstats website.

"StreamStats is a Web-based Geographic Information System (GIS) that provides users with access to an assortment of analytical tools that are useful for water-resources planning and management, and for engineering design applications, such as the design of bridges. StreamStats allows users to easily obtain streamflow statistics, drainage-basin characteristics, and other information for user-selected sites on streams."

StreamStats users can choose locations of interest from an interactive map and obtain information for these locations including a USGS station. If a user selects a location where no data are available (an ungaged site), StreamStats will delineate the drainage-basin boundary, measure basin characteristics and estimate streamflow statistics for the site. These estimates assume natural flow conditions at the site. StreamStats also allows users to identify stream reaches that are upstream or downstream from user-selected sites, and to identify and obtain information for locations along the streams where activities that may affect streamflow conditions are occurring.

Web services have been developed for drainage-area delineation, regression estimates for ungaged sites, streamgaging station information, and stream reach address determinations. For more information refer to the StreamStats website.

The other typical problem for AEP floods less than $2x10^{-3}$ is for basins with multiple dams including storage dams. Flood storage changes the downstream routing of the inflow and generally requires routing the floods through the watershed using reasonable flood operations assumptions. The screening methods above only compute the peak annual flow, not a full hydrograph, so flood routing through a storage reservoir would need to be performed with routing software such as HEC-HMS.

In addition, additional hypothetical hydrographs can be compiled using pre-calculated and probabilistic values for precipitation from NOAA Atlas 14 for screening-level assessments. These values, up to the $1x10^{-3}$ AEP can be found for various durations at http://hdsc.nws.noaa.gov/hdsc/pfds/index.html. This information is to be available for most states by the end of 2014.

Use the appropriate method to develop the flood frequency curve appropriate to the dam under review.

R19.8.2 Level 1 RA - Screening HHCs – AEPs up 1x10-5

For floods with AEPs less than $2x10^{-3}$, make a simple conservative assumption that the PMF flood is equivalent to an AEP $1x10^{-4}$. This should be done with judgment. Please note that the AEP equivalent of the PMF depends on many factors including assumptions made during the PMF calculation and whether the PMF is based on the HMRs or is a site-specific PMF. The $1x10^{-4}$AEP equivalent flood should use the HMR calculated value.

Generally, the closer the dam is to the warm ocean moisture source the more frequent the flood. This means that coastal and southern PMF floods are more likely to have a higher frequency than those in the inland and north. However, the flood equivalency for the PMF is also dependent on assumptions made during the PMF calculation.

Typically assume an AEP flood equivalent of $1x10^{-4}$and extrapolated the HHC from the $2x10^{-3}$ AEP peak flow estimate through this PMP flood. For screening levels, this assumption for extrapolating the HHC is generally conservative. For more northerly and inland dams, using a $1x10^{-5}$ AEP assumption might be appropriate. For more southerly coastal dams, a more frequent estimate might be appropriate.

Note that the $1x10^{-5}$ assumption is strictly for the purpose of risk screening. This does not mean that the PMF has an AEP of $1x10^{-5}$. To calculate the HHC, the methods described above should be used.

The assumption of an AEP equivalent for the PMF is generally acceptable for screening, because many PFMs are relatively insensitive to this assumption. This is because at the screening level, the risk team is estimating likelihoods in orders of magnitude. Except for overtopping floods, the initiating loading may be fairly low and very difficult to estimate. For instance, a PFM of debris plugging of the spillway during a flood might occur over a range of flood probabilities, and the exact flood frequency is difficult to characterize, particularly for a screening level estimate. Debris build-up in the reservoir is highly dependent on watershed conditions and the size of the spillway openings. Debris plugging could occur during storms may occur during storms with less than a $1x10^{-2}$

annual exceedance probability (AEP) if the spillway openings are small relative to the size of debris in the watershed and/or there is a significant debris load in the watershed as might be present after a long period of drought or after a major forest fire. The other factors in PFM likelihood would include likelihood of log boom failure, how much the spillway gates might be blocked, and how likely that dam is to be overtopped and fail during this event. All of these other factors have likelihoods that contribute to the overall estimate that are difficult to estimate at the screening level, i.e. without additional analyses. The differences in estimation of the PMF may not change the final likelihood estimation that much.

For screening, assume that a dam that can pass the PMF has a remote likelihood of dam failure. Any higher level risk analyses will reevaluate this assumption by developing better HHCs..

During screening, if a PFM-likelihood is found to be of concern using the assumptions listed above, a more rigorous method may be needed to confirm the loading. For instance, an internal-erosion PFM might be sensitive to reservoir level and plots in the red on the RIDM Matrix (as shown in Chapter R24) based on the curve generated from this process. If refining the HHC might change the PFM likelihood, then additional analyses might be needed.

R19.9 Multiple Methods and Uncertainty

No single hydrologic hazard analysis approach is capable of providing the needed characterization of extreme floods over the full range of AEPs required for risk analysis. Results from several methods and sources of data should be combined to yield a hydrologic hazard curve. Ideal situations would utilize multiple methods to estimate HHCs due to the significant extrapolation of the flood frequency relationships and the uncertainties involved in the analysis. When multiple methods have been used to determine the hydrologic hazard, sound physical and scientific reasoning for weighting or combining results is needed. Clearly, a measure of judgment is required to ensure that appropriate information is included in the dam safety decision-making process. The selection is based on the experiences of the team members and the assumptions used in each of the analyses. Methods for expert selection of models and final HHC curves are further discussed below in Section R.10.5.

The specific elements selected to be incorporated in an analysis of hydrologic hazards should consider the level of uncertainty based on the data and models used to make the estimate. Reducing the uncertainty in the estimates may require additional data collection and use of more sophisticated solution techniques. It is believed that increasing the level of data collection, level of effort, and the sophistication of analysis techniques increases the reliability and level of confidence associated with the results.

R19.10 Accounting for Uncertainty

Several methods are used to reduce uncertainty in developing HHCs including sensitivity analyses as described below.

In general, sensitivity analyses are conducted for numerical models to evaluate the sensitivity of an output variable or variables to changes in an input variable, collection of input variables or model parameters. The term sensitivity can take on a number of meanings and measures depending upon the application. With regard to watershed modeling, sensitivity means quantitative measures used to identify the relationship between the variation in the model outputs and the variation of the model inputs and model parameters. A comprehensive discussion of sensitivity and uncertainty analysis is provided in Saltelli, et. al. (Nov 2001).

R19.10.1 One-at-a-Time Sensitivity Analysis

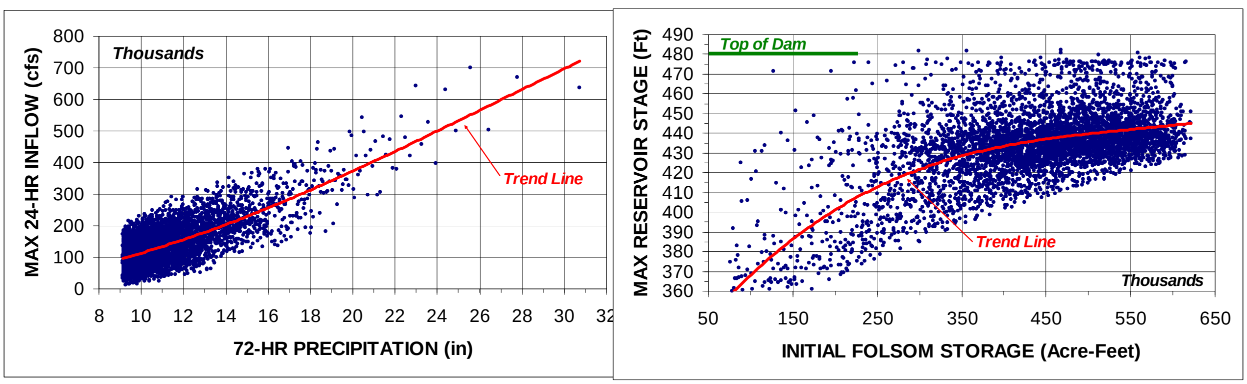
One-at-a-time (OAT) sensitivity analysis is one of the simpler forms of sensitivity analysis and has been commonly used by hydrologists in examining the behavior of the flood outputs from watershed models. Each of the hydrometeorological inputs and watershed model parameters are initially set at a nominal value which taken together is termed the "control group". Computer model runs are then executed where one of the model inputs or model parameters is varied over the range of possible values. Plots are then constructed depicting the variation in flood outputs such as flood peak discharge or runoff volume versus the variation in model inputs or model parameters. Model sensitivity can be measured quantitatively by the variance in the flood output and qualitatively by the linearity/non-linearity of the flood output.

<u>Applications</u> – OAT sensitivity is useful in developing a watershed model for application on a specific watershed. It can be used in conjunction with calibration of the watershed model to historical floods to identify the hydrologic processes that are most important for mimicking the flood response of the watershed. OAT sensitivity can also be helpful with Category 1 watershed modeling in assessing values of the hydrometeorological inputs and estimating AEP Neutral values (Nathan and Bowles – Nov 1997) for use in developing HHCs.

R19.10.2 Global Sensitivity Analysis

Global Sensitivity Analyses (GSA) is a natural choice for use with stochastic flood modeling. The term global refers to the ability to characterize the sensitivity of model outputs across the full range of model inputs and model parameters. This includes the ability to measure the effect of interactions between inputs and parameters and to handle non-linear behavior. In contrast, OAT sensitivity is a local method where the sensitivity measures are affected by the choice of values for the control group.

In stochastic flood modeling, the watershed model is executed for numerous combinations of values of the model inputs which generate a large number of realizations of flood outputs such as flood peak discharge, runoff volume and maximum reservoir level. Scatterplots can then be constructed for pairings of the flood outputs and a selected hydrometeorological input (Figures 10.a,b) which allows qualitative assessment of the strength of the relationship between flood outputs and selected inputs and identification of non-linearity and non-random patterns (Schaefer and Barker – Sept 2005a,b). Methods of rank correlation, stepwise regression and partial correlation coefficients can also be used to provide numerical measures to identify those hydrometeorological inputs and model parameters that have the greatest effect on flood outputs. GSA and use of Monte Carlo sampling methods for sensitivity and uncertainty analysis are discussed at length in Saltelli, et. al. (Nov 2001).



Figures 10a,b – Examples of Scatterplots for Global Sensitivity Analyses

<u>Applications</u> – Global sensitivity analysis is useful in developing a Category 2 or 3 watershed model for application on a specific watershed. This includes use of GSA during calibration of the watershed model to identify the hydrologic processes that are most important for mimicking the flood response of the watershed. GSA is particularly useful for identifying those hydrometeorological inputs and watershed model parameters to be included in an uncertainty analysis which is discussed in the following section. An example of a GSA using an HMR 57 rainfall input and varying all other factors can be found in the P-2150, Baker River PMF Study, February 2008 (Tetra Tech – Feb. 2008)

R19.10.3 Uncertainty Analyses for Watershed Modeling

Sensitivity analyses in hydrologic analysis are often only used to identify the most sensitive parameters and do not specifically calculate the uncertainty. However, understanding the sensitivity of the parameters is essential in evaluating the uncertainty, as described below. The primary products of an uncertainty analysis for RIDM are the mean frequency HHC and uncertainty bounds for flood characteristics of interest and quantitative/qualitative information useful for decision-making. The process of conducting the uncertainty analysis requires thoughtful consideration of the primary sources of uncertainty and how those uncertainties can be characterized by description by conventional probability distributions or empirical likelihood shape functions or alternative choices of models for specific hydrological processes. Appendix A discusses how to evaluate these sources of uncertainty and develop the characterizations of the parameters, probabilities distributions, likelihood shape functions, and choices of models.

There are a number of technical terms used in describing aspects of uncertainty analysis. Several of those terms are defined below.

Aleatory Uncertainty – Aleatory uncertainty generally refers to the uncertainty of the value of a variable or parameter due to chance. It can have a variety of meanings depending on the specific application. For example, the soil moisture condition at a specific location in a watershed at a specific time of year is due to the chance occurrence of prior climatic conditions and the hydrologic soil properties. The hydrometeorological inputs in stochastic flood modeling are treated as stochastic variables because their values are subject to chance. The primary purpose of stochastic flood modeling is to address the aleatory uncertainties associated with the hydrometeorological inputs.

Epistemic Uncertainty – Epistemic uncertainty generally refers to the uncertainty associated with the lack of knowledge or understanding about a particular variable or process. Epistemic uncertainty applies to a wide range of topics in watershed modeling which includes topics such as:

- incomplete knowledge or understanding of the underlying physics of behavior of a hydrometeorological or hydrological process and the adequacy of the algorithms used to mimic the process;
- cases where the physics and mathematics of a process are well understood but there are uncertainties in the values of the parameters of the model/algorithm for a specific application;
- identification/selection of a probability distribution for describing a phenomenon or hydrometeorological input;
- distribution parameters for a probability distribution (model) for describing a hydrometeorological input;
- representativeness of the sample set of spatial and temporal patterns of historical storms used for conducting stochastic flood modeling;
- uncertainty in the value of an important model parameter such as the surface infiltration rate at which surface runoff is generated or the deep percolation rate which determines the proportion of interflow runoff; and

- uncertainty in the stage-discharge relationship for operation of a spillway or spillway gate.

Model – The term *model* is generic and may have a wide variety of meanings. Stochastic models for analyses of extreme floods are comprised of many sub-models for hydrometeorological inputs and hydrological processes. Some examples include:

- numerical model for a hydrologic process, such as a rainfall-runoff model, or a model for transforming runoff to a streamflow hydrograph;
- a probability model in the form of a simple histogram such as used for the monthly distribution of storm seasonality;
- a probability distribution for a single hydrometeorological variable;
- a probabilistic model with a dependence structure (regression equation) with both deterministic and random components; and
- collection of algorithms used to simulate a hydrometeorological or hydrological process.

Model Uncertainty – Model uncertainty is a generic term which may refer to the watershed model taken as a whole or more commonly to a specific sub-model. Model uncertainty has both epistemic and aleatory components. In general terms, it can be considered to be the ability of the model to replicate real-world observations. A model with high predictive power (low uncertainty) would have low variance for the differences between predicted and observed outcomes.

Model Epistemic Uncertainty – Model epistemic uncertainty refers to the ability of the model to predict events/outcomes and the possibility of model bias that may systematically over or under-predict events/outcomes. This could also apply to the case of the choice of competing models for describing a specific hydrologic process; for example, choosing between two rainfall-runoff models for partitioning quickflow versus interflow runoff. It could also refer to the epistemic uncertainty in selection of the “true” probability distribution for characterizing some phenomenon.

Model Aleatory Uncertainty – Model aleatory uncertainty refers to the variance not explained by a model. The differences between the predicted and observed outcomes would be the aleatory component. In a well-formed model, the differences between observed and predicted outcomes would be random and unbiased.

Parameter Uncertainty – Parameter uncertainty refers to estimation of the model parameters that control the outcomes from a model and has both epistemic and aleatory components.

Parameter Epistemic Uncertainty – Parameter epistemic uncertainty refers to estimation of the model parameters given a sample set of data. This could apply to the case where the form of a model, say an infiltration equation, is taken as valid, but there is uncertainty in the parameters for the model. Parameter uncertainty would also apply to distribution parameters for a probability distribution used to describe a hydrometeorological phenomenon.

Parameter Aleatory Uncertainty – Parameter aleatory uncertainty refers to the random elements in the observed data that are used to estimate the model parameters and may be associated with a variety of instrumentation, observation and measurement errors or biases.

Flood Outputs– Flood outputs is a generic term used to describe a variety of flood characteristics that may be of interest in developing HHCs. All of the flood outputs are obtainable from inflow flood hydrographs or inflow hydrographs that have been routed through the reservoir. This would include flood outputs such as: inflow flood peak discharge; maximum discharge for a specified duration; runoff volume; maximum reservoir level; duration of floodwaters above a specified elevation threshold; maximum reservoir outflow; maximum discharge for a spillway(s); and duration of spillway or stilling basin operation above a specified discharge. The specific flood outputs of interest for a particular dam are selected to support failure mode analysis as part of the risk analysis process.

Flood Operation Uncertainty – Uncertainties associated with how the dam and reservoir project will actually be operated during rare and extreme floods are typically addressed in the fragility analysis component of the risk analysis and are not considered in developing uncertainty bounds for the HHCs. This approach is usually taken to simplify the uncertainty analysis and allow for flexibility in examining alternative operational schemes after the uncertainty analysis has been completed. The exception is where multiple dams are located on a river system and upstream reservoir operations can affect the performance of a downstream dam of interest. In this case, uncertainties in reservoir operation for floods at upstream dams can be included in the uncertainty analysis for the downstream dam of interest.

Mean Frequency HHC – The HHC comprised of the mean of the quantile estimates from the sample-set of quantile estimates for the various alternative watershed models. The mean frequency curve typically has higher likelihoods for flood hazards than the original HHC that was produced by the initial formulation of the watershed model. This occurs because of non-linearities in the alternative watershed models due to choices of alternative sub-models, algorithms, and model parameters.

Uncertainty Bounds– Uncertainty bounds are similar in concept to standard confidence bounds for interval estimation except that uncertainty bounds are intended to account for both epistemic and aleatory uncertainties. For the case of watershed modeling, 80% uncertainty bounds would be comprised of the bounds for the 90th percentile (upper bound) and 10th percentile (lower bound) flood outputs and would contain 80% of the flood outputs expected from the alternative watershed models.

R19.10.4 Underlying Concepts of Uncertainty Analysis Using Monte Carlo Sampling

The basic concept behind an uncertainty analysis is the recognition there are numerous plausible variations of the watershed model that is being used to generate flood hydrographs and to develop the HHCs. This occurs because of: uncertainties and inaccuracies in hydrometeorological inputs to the watershed model; imperfect understanding of the hydrometeorological and hydrological processes and the adequacy of the sub-models, algorithms and model parameters used to mimic these processes; and uncertainties and inaccuracies in the streamflows (flood hydrographs) used to calibrate the watershed model.

The uncertainty analysis attempts to characterize these uncertainties and to assess their effect in altering the flood outputs and HHCs. As a practical matter, this is an intractable problem both from the standpoint of the number of variables and processes involved and from the standpoint of characterizing the lack of knowledge/understanding in modeling the hydrometeorological and hydrological processes. The recommended approach is to identify those hydrometeorological inputs, model choices and model parameters that have the greatest effect on the flood outputs and for which there are the largest uncertainties. These specific sources of uncertainty would be characterized in conducting the uncertainty analysis. The next section discusses how to choose these inputs, choices, and parameters.

R19.10.5 Expert Elicitation and Structured Expert Interaction

As discussed above, analyses require judgments about parameters that are used in the model. For instance Monte Carlo analyses use a range of values for a specific parameter. The judgment of what the reasonable range of values is not always easy. For these situations expert judgment is needed.

The process of conducting the uncertainty analysis requires thoughtful consideration of the primary sources of uncertainty and how those uncertainties can be characterized by description by conventional probability distributions or empirical likelihood shape functions or alternative choices of models for specific hydrological processes. Risk analyses typically use a process called expert elicitation for selection of probability distributions, etc. The expert(s) chosen for this process need to have adequate experience and skill in using the methods described above. Procedures for expert elicitation or structured expert interaction are often used in these circumstances as described in Chapters R24 – Risk Analysis and R25 Probability and Uncertainty.

Appendix B has an overview and a discussion of a generalized procedure for uncertainty analyses of watershed models.

Appendix A Basic Definitions

Aleatory Uncertainty: Aleatory (Aleatoric) uncertainty generally refers to the uncertainty of the value of a variable or parameter due to chance.

Annual Exceedance Probability (AEP): AEP is the probability of equaling or exceeding a given amount in any given year.

Bulletin 17B: Guidelines for Determining Flood Flow Frequency, Bulletin No. 17B of the Hydrology Subcommittee (revised September 1981; Editorial Corrections march 1982) provides a more complete guide that Bulletin No. 15 for determining flood flow frequency. Bulletin No. 17B provides regional generalized skew coefficients based on analysis of multiple stream gauge records within a given area. Bulletin No. 17B defines flood potentials in terms of peak discharge and exceedance probability at locations where a systematic record of peak flood flow is available.

Deterministic Model: A model (equation, algorithm, or computer model) whose outcome(s) is determined by application of physical laws and/or mathematical relationships. The outcome is always the same for a given input. Most watershed models are deterministic models with sub-models for the prediction of surface runoff, subsurface flow, transformation of runoff to a streamflow hydrograph, and channel routing. Deterministic models are best applied when natural variability of parameters and uncertainties are small and are not deemed to significantly affect the outcome.

Epistemic Uncertainty: Epistemic uncertainty generally refers to the uncertainty associated with the lack of knowledge or understanding about a particular variable, parameter, or process.

FLDFRQ3: A US Bureau of Reclamation computer program developed by O'Connell (1999) that fits several types of distributions to flood data and accounts for data uncertainties with Bayesian techniques. The approach incorporates systematic, historical, and paleoflood data into flood frequency analysis.

Frequency Analysis: A generic term for the process of computing sample statistics for a dataset, solving for the distribution parameters for a chosen probability distribution, and computing estimates for user-specified magnitudes of non-exceedance or exceedance probabilities. An at-site frequency analysis is a special case where the data are obtained from, and representative of, a specific geographic location.

Frequency Curve: A generic term for the curve that shows the mathematical relationship between a variable of interest and exceedance or non-exceedance probability. In flood-frequency analyses, frequency curves are commonly used to depict the estimated mathematical relationship between flood peak discharge and annual exceedance probability.

Gumbel Distribution: A probability distribution that was derived from the theory of extremes. This 2-parameter distribution is often used to model the distribution of the maximum (or the minimum) of a number of samples that originated from a parent distribution. Extremes drawn from a number of commonly used distributions (Normal, Gamma, Exponential) have the Gumbel Distribution as the limiting form.

HEC-SSP (Version 2.0): Computer program developed by the USACE's Hydrologic Engineering Center. HEC-SSP is capable of performing flood flow frequency analyses based on Bulletin 17B Guidelines, general frequency analyses, volume frequency analyses, duration analyses, coincident frequency analyses, and curve combination analyses.

Hydrologic Hazard: A hydrologic hazard is any characteristic of a flood that poses a threat to life or property. In the context of dam safety, this would be flood characteristics such as inflow peak discharge, maximum reservoir level, depth and/or duration of reservoir level above a critical elevation, peak reservoir outflow, spillway discharge, etc that could result in the uncontrolled release of the reservoir contents through a variety of dam failure modes.

Hydrologic Hazard Curves (HHCs): HHCs are a type of frequency curve or probability-plot that depicts the relationship between a flood hazard characteristic and annual exceedance probability. HHCs can be developed for any flood hazard characteristic of interest such as inflow peak discharge, maximum reservoir level, depth and/or duration of reservoir level above a critical elevation, peak reservoir outflow, spillway discharge, etc.

Hydrometeorological Reports (HMR): A series of reports produced by the National Weather Service, NOAA, that provide generalized estimates of the greatest rainfall depths (PMP) for specified durations and locations. The reports typically provide all-season general-storm PMP estimates for durations from 1 to 72 hours for specific area sizes. Local-storm estimates are also provided for durations of 15 minutes to 6 hours for specific area sizes.

Inflow Design Flood (IDF): See RIDM EG Chapter F.5, Consequence Assessment
Log-Normal Distribution: Probability distribution for which the log of the random variable is normally distributed.

Log-Pearson Type III Distribution (LP3): The LP3 distribution is a 3 parameter probability distribution commonly used by hydrologists for developing flood-frequency relationships for peak discharge for streams and rivers (see Bulletin 17B above). This distribution was first used to describe the probability of annual peak discharges by H. Alden Foster in 1924.

NOAA Atlas 14: NOAA Atlas 14 is published by the National Weather Service and contains precipitation frequency estimates with associated confidence limits for the United States and is accompanied by additional information such as temporal distributions and seasonality. The Atlas is divided into volumes based on geographic sections of the country. The Atlas is intended as the official documentation of precipitation frequency estimates and associated information for the United States. It includes discussion of the development methodology and intermediate results. The Precipitation Frequency Data Server (PFDS) was developed and published in tandem with this Atlas to allow delivery of the results and supporting information in multiple forms via the Internet.

Normal Distribution: A 2-parameter probability distribution in which values are symmetrically distributed about a central value with a common mean, mode and median. The Normal Distribution is universally recognized by the public as the bell-shaped curve.

Paleoflood Hydrology: The study of past or ancient flood events which occurred before the time of human observation or direct measurement by modern hydrological procedures.

PeakFQ: PeakFQ is a computer program that provides estimates of instantaneous annual-maximum peak flows having recurrence intervals of 2, 5, 10, 25, 50, 100,200, and 500 years (annual-exceedance probabilities of 0.50, 0.20, 0.10, 0.04, 0.02, 0.01, 0.005, and 0.002, respectively).

Probabilistic Model: A model whose outcome(s) express the probability of an event or events occurring, the magnitude of some item of interest being exceeded (non-exceeded) or being within certain limits.

Probability-Plot: A probability-plot depicts the relationship between exceedance probability or non-exceedance probability and the observed data for a variable of interest. Values of exceedance or non-exceedance probability are commonly estimated from non-parametric plotting position formulas.

Stochastic Model: A model whose outcomes are the result of some combination of deterministic, probabilistic and random components. The current "state" is typically expressed as a function of the past "state" of the process. In short, the future is a function of the past and random chance. Stochastic models are typically used when natural variability is a significant consideration and there is a need to model real world behavior and account for the deterministic, probabilistic and random components of a process.

Probable Maximum Flood (PMF): The PMF is the flood that maybe expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study.
Probable Maximum Precipitation (PMP): The National Weather Service (NWS) and Hansen (Hansen et al., 1988) defines the PMP as, "…theoretically, the greatest depth of precipitation for a given duration that is physically possible for a given size storm area at a particular geographic location at a certain time of year."

Probable Maximum Storm (PMS): The PMS is the storm that produces the maximum precipitation for all durations that theoretically could occur over the watershed.
Reservoir Level Exceedance Curves: An annual exceedance curve shows the probability that the reservoir will exceed a specified elevation in any given year, but gives no indication of duration. A reservoir level duration curve, on the other hand, shows for what percent of time over all years the reservoir level would be expected to exceed a given value.

Sensitivity Analyses: Sensitivity analyses of a model are conducted to evaluate the sensitivity of an output variable(s) relative to changes to model input variables.

Regional Frequency Analysis: A type of frequency analysis where observations of the same phenomenon are available at different locations within a homogeneous region. The large dataset available from multiple samples results in reduction in sampling variability, improves identification of the best-fit probability distribution, and improves estimation of the distribution parameters. This results in more robust frequency estimates for each site and at other sites in the region where data were not available.

Regional Streamflow Analysis: A special case of regional frequency analysis where streamflow maxima for a specified duration (instantaneous peak, 6-hr, 1-day, etc) from multiple sites are analyzed. The data may be from annual maxima or peaks-over-threshold data series or for separate flood mechanisms such as: snowmelt; rain-on-snow; tropical storm or thunderstorm.

Regional Precipitation Analysis: A special case of regional frequency analysis where precipitation maxima for a specified duration (1-hr, 6-hr, 24-hr, 72-hr, etc) from multiple sites are analyzed. The data may be from annual maxima, peaks-over-threshold or seasonal data series or for separate storm mechanisms such as: local storms; mesoscale convective complexes; tropical storms; or mid-latitude cyclones.

Appendix B Uncertainty Procedures for Watershed Models.

B.1 Overview

The mean frequency curve and uncertainty bounds are developed for the HHCs by assembling plausible variations of the watershed model and using those models to generate flood hydrographs and develop alternative HHCs. The mean frequency HHC and uncertainty bounds are often computed in a non-parametric manner by simple ranking of flood outputs for specific AEPs from the group of alternative watershed models. For example, if 11 alternative watershed models were assembled, use of a non-parametric plotting-position formula (Cunnane – 1978) would have the 95th percentile and 5th percentile flood outputs (say maximum reservoir levels) being the highest and lowest reservoir levels generated from the 11 watershed models, respectively. The median value would be the 6th largest value (from ranking) and the mean value would be computed from the 11 reservoir levels generated for a specific AEP.

Nathan and Weinmann (2001) have created a flowchart (Figure 19-B.1) that nicely describes the process of conducting an uncertainty analysis using a Monte Carlo framework. However, dealing with reality is not quite as clean as indicated in the flowchart. There are aleatory uncertainties, particularly associated with estimation of model parameters that arise in the outer loop in assembling alternative configurations of the watershed model. Nonetheless, the flowchart provides a concise overview of the mechanics of conducting an uncertainty analysis.

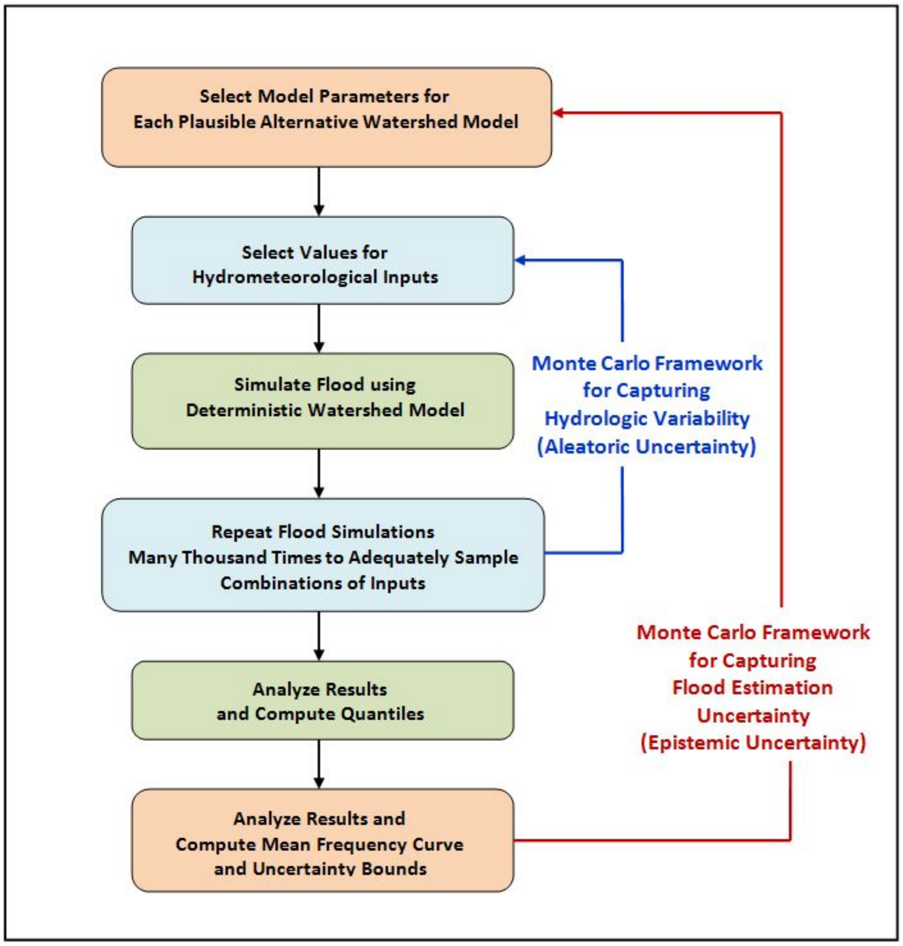


Figure 19-B.1 – Flowchart for Monte Carlo Frameworks for Stochastic Flood Analysis and Uncertainty Analysis

B.2 General Uncertainty Procedure

A comprehensive uncertainty analysis for watershed modeling can be labor intensive and challenging for complex watersheds and river systems with multiple dams. It is prudent to use parsimony in selecting the number of hydrometeorological inputs and watershed model parameters to include in the analysis. The general procedure for conducting an uncertainty analysis for watershed modeling applications is described below. It is expected that variations from this general procedure would be taken to meet project-specific needs.

1. Use the findings of global sensitivity analysis, results from watershed model calibration, and engineering judgment to identify the

hydrometeorological inputs and model parameters that have the greatest effect on the magnitude of the flood outputs of interest for a particular watershed and dam.

2. Use both quantitative measures and engineering judgment to identify those hydrometeorological inputs and model parameters which have the largest uncertainties.
3. Include in the uncertainty analysis those hydrometeorological inputs and model parameters which have both a significant effect on flood outputs and have sizeable uncertainties.
4. Characterize the uncertainties for each of the inputs/parameters chosen in Step 3 by using either a conventional probability distribution or an empirical likelihood shape function obtained through collaboration with technical specialists.
5. Select the number of alternative watershed models (*M*) to be used in the uncertainty analysis. This sets the number of repetitions for the outer loop in Figure 19-B.1 above and represents the number of plausible flood-frequency relationships that will be generated.
6. Use Latin-hypercube sampling methods (McKay et al – 1979 and Wyss et al – Feb 1998) to assemble a random combination of the chosen uncertainty inputs and parameters where each group of inputs/parameters comprises one of the alternative watershed models.
7. For each alternative watershed model configuration, conduct sufficient Monte Carlo flood simulations to generate the HHCs of interest (inner loop in Figure 19-B.1 above).
8. Compute the mean of the flood outputs from the *M* alternative watershed models for selected annual exceedance probabilities (AEPs). Use a non-parametric plotting position formula (Cunnane - 1978) to compute percentiles for the uncertainty bounds about the mean frequency curve. Alternatively, use standard parametric methods to fit a probability distribution to the flood outputs for a selected AEP.
9. Fit a smooth curve through the computed values for the mean frequency and separate curves for each of the values of the 95^{th} and 5^{th} percentiles for the 90% uncertainty bounds (similar to Figure 19-B.2 below).
10. Examine the variance in the flood outputs for selected AEPs to determine the contribution to the total variance from each of the inputs/model parameters.
11. Conduct additional analyses of the results of the uncertainty analysis (Saltelli et al – Nov 2001) as needed to assist in the risk-informed decision-making process.

B.3 Applications

Uncertainty analysis often requires a considerable investment in human resources, time and a very large number of Monte Carlo simulations to develop the mean frequency curve and uncertainty bounds for the HHCs of interest for a particular dam and reservoir project. For this reason, uncertainty analyses are typically associated with detailed flood analyses, primarily Category 3 watershed modeling, for dams where very low AEPs are needed for risk-informed decision-making. The guidance discussed below is offered based on experience with stochastic flood modeling and conducting uncertainty analyses. For further discussion of Monte Carlo simulations, please see Chapter R25, Probability and Uncertainty.

B.3.1 Basin-Average Precipitation-Frequency Relationship for Watershed

The basin-average precipitation-frequency relationship for the watershed is almost always a major contributor to the magnitude of flood outputs. Therefore, it should always be included in an uncertainty analysis. A properly conducted basin-average precipitation-frequency analysis for a watershed should be accompanied by its own uncertainty analysis (Figure 19-B.2) that can be applied directly in the uncertainty analysis for the flood outputs. This is a product that would typically be provided by a specialty contractor experienced in regional precipitation-frequency analysis and spatial and temporal analysis of extreme storms.

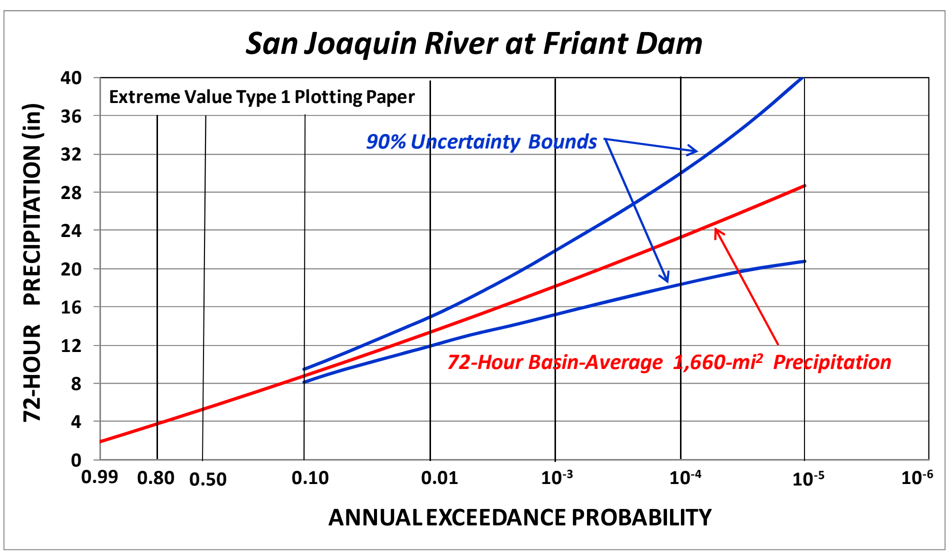


Figure 19-B.2 – Example Basin-Average Precipitation-Frequency Relationship for a Watershed in Southern California

B.2.2 Dam Projects Sensitive to Flood Peak

Dam and reservoir projects that have limited flood storage capacity relative to the volume of extreme floods will be sensitive to the magnitude of the flood peak. In formulating the uncertainty analysis, particular attention should be given to hydrometeorological inputs and model parameters that affect flood peak discharge. This would include the hydrologic response parameters (basin-lag/timing parameters) for transforming runoff into a streamflow hydrograph, soil infiltration characteristics that affect the magnitude of surface runoff, the seasonality of storms which affects initial soil moisture conditions, and precipitation intensities in the collection of storm temporal patterns.

B.2.3 Dam Projects Sensitive to Flood Volume

Dam and reservoir projects that have significant flood storage capacity relative to the volume of extreme floods will be more sensitive to the magnitude of runoff volume than inflow flood peak discharge. In these cases, particular attention should be given to hydrometeorological inputs and model parameters that affect runoff volume. This would include the hydrometeorological inputs and model parameters for antecedent soil moisture conditions, snowpack snow-water equivalent, deep percolation rates for soils, temporal patterns for long-duration storms, and initial reservoir levels.

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