II-2. Probabilistic Hydrologic Hazard Analysis

Historically, dam and levee design and analysis methods have focused on selecting a level of protection based on a particular frequency or loading event. Traditionally, the protection level for dams is based on the Probable Maximum Flood (PMF) (Cudworth, 1989; FEMA, 2013) for High Hazard Potential Dams; the design level for levees used various methods including the Standard Project Flood (SPF), the historical flood of record, or a return frequency.

Risk informed decision making is currently used to assess the safety of dams and levees, recommend safety improvements, and prioritize expenditures in more recent years risk analysis has started to be implemented on the nation’s levees. Risk estimates, from a hydrologic perspective, requires an evaluation of a full range of hydrologic loading conditions and possible failure mechanisms tied to consequences of failure.

The flood loading input to a dam and levee safety risk analysis is a hydrologic hazard curve (HHC) that is developed from a Hydrologic Hazard Analysis (HHA). Hydrologic hazard curves combine peak flow, reservoir stage or river stage, and volume probability relationships plotted against Annual Chance Exceedance (ACE) or the equivalent Annual Exceedance Probability (AEP). These terms are used in lieu of the “100-year flood”; see Stedinger et al. (1993) and Holmes and Dinicola (2010) for definitions. The range of ACEs or AEPs that is displayed will depend on the data available for the study location, and the needs of the risk team and agency.

The flood loading input to a levee safety risk analysis consists of water surface profiles along the length of the levee for various loadings; common loadings used for discussion include those at the levee toe, authorized capacity, historical flood events, and initial levee overtopping. In many situations, an analysis to determine if the levee meets National Flood Insurance Program (NFIP) requirements is also needed. In addition, water surface profiles for varying degrees of overtopping may be necessary during consequence discussions.

The water surface profiles and HHCs can be used to assess potential hydrologic-related failure modes, such as overtopping, seepage/piping at various levels, erosion in earth spillways, and overstressing structural components, as well as the risk that is associated with these failure modes. This chapter presents general guidelines for producing these relationships. The methods described are scalable; however, not all methods will be appropriate for all studies.

Hydrologic Loads for Risk Analysis

Levees

The risk associated with levee segments and systems are heavily influenced by the water surface profile along those levees. Unlike most dams, the water surface profile may vary along the length of the levee, seasonally, and may also vary over the life of the levee. The water surface profiles used in discussion will generally include loadings at the toe, authorized capacity, initial overtopping, and for various amounts of overtopping as well as any significant historical events. NFIP determination may also be required. Many levees were authorized for a certain flood event (i.e. "1957 flood"), rather than an ACE. When this occurs, the team should determine a "best" estimate of the ACE (with uncertainty) for the design flow or water surface elevation for the levee as it stands today (USACE 1996). If additional flood control or other impacting structures have been constructed upstream of the levee it should be noted in the analysis.

Water surface profiles determined for constant cross-section, uniformed sloped, concrete channels would be expected to be more accurate than those determined for a complex, natural, stream. The stability of the water surface profile throughout the life of the project can be influenced by bed load, bed material, bed forms, shoaling and scouring tendencies, bank erosion, unforeseen embankment settlement, the accumulation of trash or debris, aquatic or other growth in the channels, and variation in resistance or other coefficients from those assumed in design. Levee projects may also be influenced by ice; ice jams and anchor ice may result in a higher water surface elevation for a given flow than if no ice were present. When ice needs to be considered the team should maintain at least a general awareness of how it may impact the water surface profile if more detailed studies have not been completed. Water surface profiles may also vary along the length of the levee; levees with long lengths may experience different loadings depending on the location along the levee. Water surface profiles for levee tie-backs along tributaries to the main stream will be required and will need a consideration of coincident flow conditions.

Another key component is the duration of the loading on the levee. Some levee systems generally experience shorter duration loadings, the flood wave may rise from the toe of the levee to the top and return to the toe in the course of a day or several days while other levee systems may experience a flood loading for several weeks to several months. Levees differ from dams in the sense that the loading is not controlled by the levee; there often is no way to draw the level in the river down to alleviate the loading on the levee if distress is observed.

Because the location of failure along the levee will impact the consequences; water surface profiles are helpful in determining what the loading at that particular location. Also, the location of a potential breach with respect to population centers, travel time of the flood wave, and depth of inundation all influence predictions of life loss and economic consequences. With extensive interior leveed areas or when duration of loading is important, flood hydrographs may be required to determine the depth of flooding in the interior leveed areas.

Dams

Hydrologic hazard curves provide magnitudes and probabilities for the entire ranges of peak flow, flood volume (hydrograph), and reservoir elevations, and do not focus on a single event. Reservoir elevation curves can be used to assess the likelihood of overtopping, while hydrograph information can be used to provide peaks, volumes, and durations of loading. To satisfy agency risk guidance for dam safety risk assessments, HHCs of high hazard dams need to extend beyond ACEs (AEPs) of 1×10^{-4} (1 in 10,000), and have involvement by the flood hydrologist that performed the analysis.

Discharge frequency curves are used to create the peak flow HHC from annual peak inflow data over the period of record, typically with a Log-Pearson III distribution. If available, additional extreme flood data points are included to better define the extrapolation beyond historical data. An example HHC for peak flows is shown below in Figure II-2-1. This peak flow HHC shows data used to estimate the HHC with each step requiring increasing levels of effort. In this case, it combines peak flows from a streamgage, historical estimated peak flows and paleohydrologic data to extend the curve to about 0.001 ACE

(1/1,000) (example from England et al., 2006). This HHC is then significantly extrapolated based on the fitted probability distribution to provide ACE (AEP) estimates in the range of interest for dam safety. Uncertainty estimates for the HHC should be depicted, and are a function of the data and method used. HHC estimates of peak flow are typically the main loading curve required for levees, low head navigations dams, and other dams where the storage volume is not sufficient to alter the relationship between peak flow and peak stage.

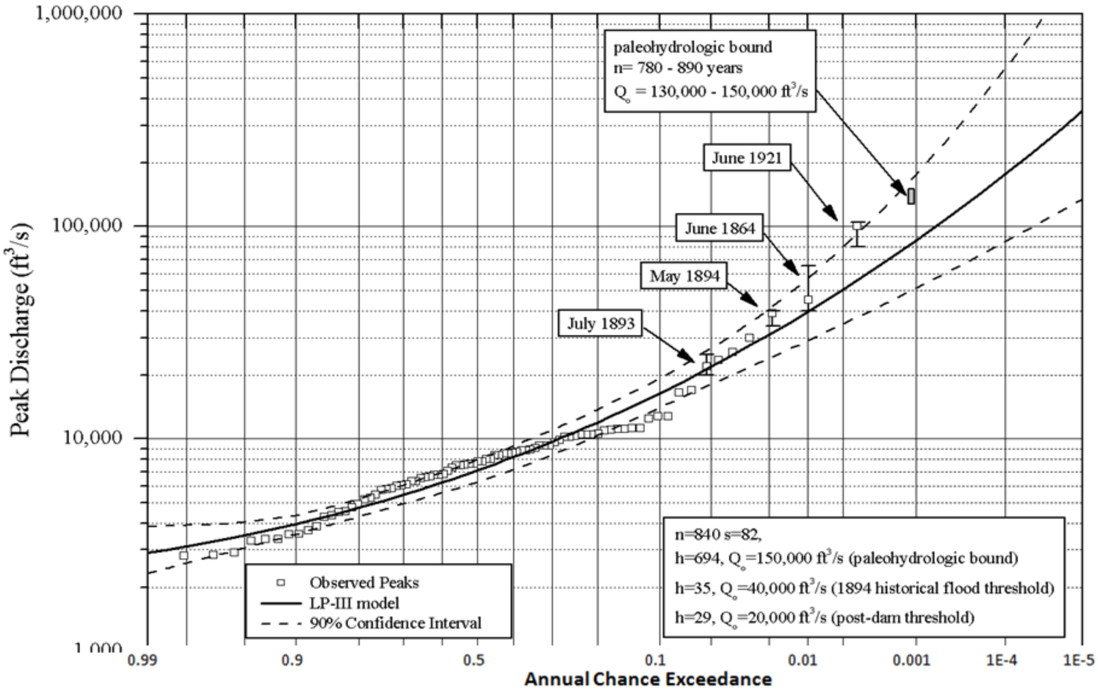

Figure II-2-1. Example peak flow hydrologic hazard curve showing recorded events, historical estimates and paleoflood data, and includes uncertainty (90% confidence interval)

When structures require more than a peak flow HHC, additional methods should be developing including volume frequency analysis coupled with patterned hydrographs, balanced hydrographs, or rainfall-runoff model-based hydrographs and inflow routing can be used to define the shape of the upper stage frequency curve. With this method, a volume frequency analysis is performed on the daily average inflows for the period of record (regulated inflows can be transformed by a regulated to unregulated analysis) for the project. Combining the durations and estimated volumes from the volume frequency with a patterned hydrograph that represents regional extreme storm hydrographs, a range of hydrologic load scenarios can be created. This results in one or many inflow hydrographs for the specific project all based on a specific ACE (AEP) as illustrated below in Figure II-2-2. In addition, the simplified method of scaling Probable Maximum Flood (PMF) or Inflow Design Flood (IDF) hydrographs can be used to estimate flood runoff from regional major storm events that are not likely found in the at-site period of record within the watershed of interest.

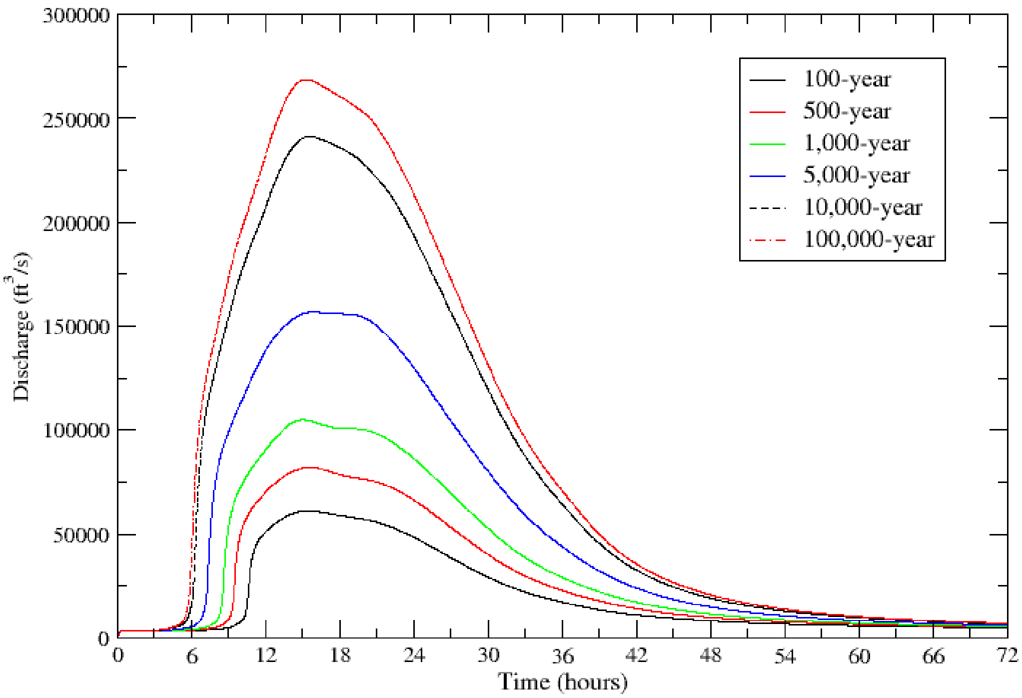

Figure II-2-2. Example patterned hydrographs showing range of hydrologic loading for reservoir routing

In general, hydrograph shapes reflect watershed characteristics, rainfall magnitudes, rainfall spatial and temporal patterns, and antecedent wetness (snowmelt or rainfall). Specific hydrograph shapes depend on the individual watershed characteristics and the hydrologic hazard method used in their development. The hydrographs can then be routed to estimate reservoir levels which can be used to estimate failure probabilities for specified failure modes, such as overtopping, internal erosion from seepage above a core wall, etc. An example elevation frequency HHC is shown in Figure II-2-3, where the reservoir water surface elevation corresponding to the top of the dam has an ACE of about 1 in 60,000. Reservoir elevation curves should be computed based on a graphical analysis that account for regulation priorities, initiation of spillway flows, potential upstream regulating projects and events that exceed the historical record. While analytical curves are generally easily calculated, these curves will not be adequate for most reservoirs once the aforementioned conditions are considered.

Routing of the hydrographs (PMF, IDF, balanced, scaled, modeled, etc.) can be accomplished by many methods ranging from simplified mass balance models to detailed watershed routing models. While a detailed and calibrated model will provide the best estimates and is desired for detailed analysis, simple mass balance rainfall-runoff models may be sufficient for routine investigations. With these models, input hydrographs are routed based on simplified relationships for reservoir storage and reservoir outflows. In addition, additional hypothetical hydrographs can be compiled using pre-calculated and probabilistic values for precipitation from NOAA Atlas 14 for routine assessments. These values, up to the 1/1,000 ACE (AEP) can be found for various durations at http://hdsc.nws.noaa.gov/hdsc/pfds/index.html. As of 2015, this information is available for most states except for the northwest US and Texas. The northeast US is expected to be completed in 2015. Extrapolation of these estimates beyond 1/1,000 ACE is required for most high-hazard dams. Extreme storm spatial and temporal patterns would need to be developed for the site of interest.

Antecedent reservoir stage is usually an important factor in routing flood hydrographs to produce the reservoir elevation frequency curve. A series of one or more hydrologic events may result in filling a significant portion of the active storage in a reservoir before the beginning of a major flood hydrologic event. Standard USACE guidance states the minimum starting elevation for routing a flood event be at either: full flood control pool elevation: or the elevation prevailing following a five day dry period after a hydrologic event equivalent to one half of the event of interest (ER 1110-8-2(FR)) for design meeting essential guidelines. Both cases should be investigated and a determination of how sensitive the peak reservoir stage is to antecedent conditions. For risk assessments, USACE uses a best estimate of the initial pool elevation based on the appropriate seasonal starting pool or a pool duration frequency (coincident pool) analysis. For screening-level assessments, Reclamation utilizes a worst-case scenario with a maximum initial reservoir elevation at the top of active conservation. Seasonal reservoir elevation frequency curves or resampling of historical operations is performed by Reclamation for higher-level studies.

If highly sensitive, other methods that investigate distribution and durations should be investigated. One method is developing inflow volumes consistent with the ACE of inflows. Another method is using a balanced storm distribution that is of sufficient duration to account for all inflow volume that might impact reservoir elevation. Other methods may be suitable with the end result being a reasonable best estimate scenario to create the relationship of ACE of reservoir elevations. Antecedent conditions should be developed consistent with the relationship for ACE of inflow volumes.

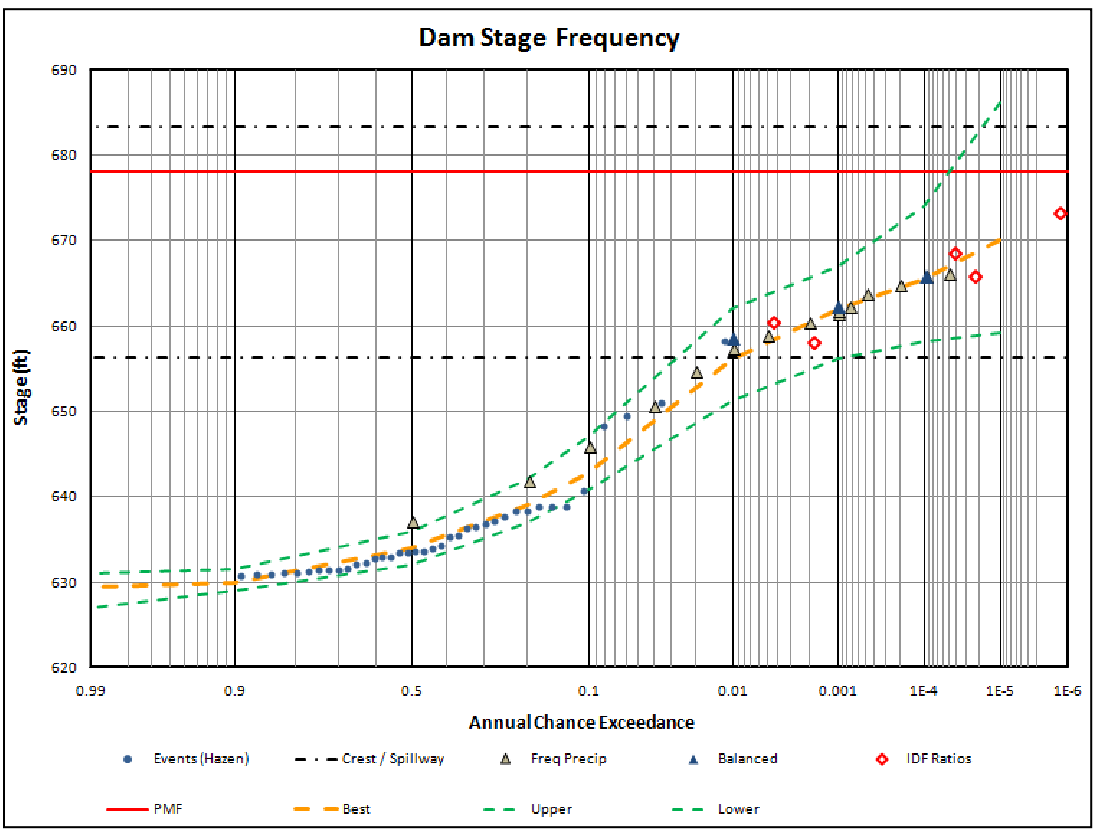

Figure II-2-3. Example (hypothetical) reservoir elevation frequency curve with uncertainty

Hydrologic hazard information is required for all dam safety studies and varies in the level of detail necessary. Typically, routine (screening level) assessments require minimal effort, with basic information used in the analysis coming from existing USACE sources such as the water control manual or other regulation decision document. Reclamation conducts limited field investigations for screening-level assessments. For detailed studies like those required for dam modifications, many methods like paleohydrology, historic research, detailed watershed models, regional rainfall analysis, site specific rainfall analysis and others should be used to give a greater confidence in the HHC extrapolation. In this instance, the goal is to have highest confidence possible utilizing several hydrologically-relevant, detailed methods and models to best evaluate any risk reduction alternatives.

Hydrologic Hazard Levels of Study

Hydrologic hazard studies are conducted at various levels; they generally depend on the flood information available, type of risk analysis or dam safety decision being made, and budget and schedule considerations. There are three basic levels of study for USACE risk assessments in dam safety and similar levels for levee safety. The USACE levels are Periodic Assessment (PA) and Semi-Quantitative Risk Assessment (SQRA), Issue Evaluation Study (IES), and Dam Safety Modification Study (DSMS). These three levels are scalable and will usually require increasing hydrologic hazard data collection and modeling efforts for each progressive level. The decision to proceed to the next level of risk assessment should always consider how sensitive the total project risk and dam safety decision is to hydrologic loadings. This sensitivity should be considered when developing the scope of the required level of hydrologic analysis for the next phase of the study. Within Reclamation, there are three hydrologic hazard levels of study that correspond to appraisal, feasibility, and final design levels. For the Reclamation Dam Safety Program, the typical study levels are Comprehensive Review (CR), Issue Evaluation (IE), and Corrective Action Study (CAS). These levels are approximately equivalent to appraisals for CRs and some IEs and feasibilities for some IEs and CASs. At Reclamation, it should be noted that dam safety studies do not involve design until the CAS takes place. Refer to Bureau of Reclamation (2013) and USACE (2015) for further guidance and information on appropriate hydrologic hazard levels of study.

Hydrologic Hazard Methods

There are numerous methods available to estimate magnitudes and probabilities (ACE or AEP) of extreme flood events and hydrologic loadings for dam safety studies. Methods can generally either be classified as streamflow-based statistical analysis or rainfall-based with statistical analysis on the generated runoff. A list of currently available methods is presented below in Table II-2-1 along with the data methods, inputs and assumptions; with some of their strengths and limitations described in Swain et al. (2004). Since each study site is a unique combination of climatic, hydrologic, and watershed parameters with different levels of data availability and required level of confidence, no single method or approach will address all hydrologic issues. Improvements to these current methods and other tools and approaches may be added as project needs, research, and experience dictates.

Table II-2-1. Current hydrologic hazard curve methods, inputs, assumptions, and products

Class	Method *(Agency)*	Method of Analysis and Modeling *(reference)*	Data Inputs	Assumptions	Hydrologic Hazard Curve Product	Why Choose	Level of Effort
Streamflow-based statistics	Graphical Flood Frequency *(USBR)*	Peak-flow frequency analysis with historical/paleoflood data - Graphical method (*Swain et al., 2004*)	Peak flow, reconnaissance paleofloods, PMF hydrograph	LogNormal flood frequency; PMF hydrograph represents volume	Peak flow frequency, volume frequency; hydrographs	Initial HHA estimate	Low
Streamflow-based statistics	EMA-LP-III and Bulletin 17C USGS PeakFQ; HEC-SSP *(USACE and USBR)*	Peak-flow and volume frequency analysis with historical/paleoflood data - EMA (*Cohn et al., 1997; England et al., 2003; England et al., 2015*)	Peak flow, historical data, regional skews, detailed paleofloods	LP-III flood frequency distribution with moments and regional skew	Peak flow frequency and confidence intervals	Federal guidelines for flood frequency; uses historical and paleoflood data when available	Low to moderate
Streamflow-based statistics	FLDFRQ3 *(USACE and USBR)*	Peak-flow frequency analysis with historical/paleoflood data - FLDFRQ3 (*O'Connell et al., 2002*)	Peak flow, detailed paleofloods	Various flood frequency distributions with likelihood	Peak flow frequency and confidence intervals	Detailed paleoflood data available; need FFA confidence intervals, choice of distribution	Low to moderate
Streamflow-based statistics	Hydrograph Scaling *(USACE and USBR)*	Hydrograph Scaling and Volumes (*England, 2003*)	Hydrographs and volumes	Hydrographs represent extreme flood response; requires FFA for scaling	Hydrographs and volumes; based on peak flow and volume frequency	Ratios of the IDF hydrograph and statistically based balanced and patterned hydrographs	Low

Streamflow-based statistics	Streamflow Volume Stochastic Modeling (MCRAM)		Pool duration, volumes, and Hydrographs	Main inputs defined by distributions, volume-frequency observed hydrographs, and pool duration frequency	Reservoir elevation	Monte-Carlo methods to sample input distributions	Moderate
Rainfall-based statistics and Runoff Transfer	GRADEX USACE and USBR	GRADEX Method (*Naghettini et al., 1996*)	Rainfall gages/regional statistics; streamflow volumes	Flood frequency same shape as rainfall frequency with exponential tail; saturated basin	Volume frequency; hydrographs	Rainfall-driven flood; rainfall samples extremes; compare to streamflow-based methods	Moderate
Rainfall-based statistics and Rainfall-Runoff	Australian Rainfall-Runoff *(USBR)*	Australian Rainfall-Runoff Method (*Nathan and Weinmann, 1999*)	PMP design storm; rainfall frequency; watershed parameters	Exceedance Probability of PMP; average watershed parameter values; runoff frequency same as rainfall frequency	Peak flow and hydrographs; based on rainfall frequency and PMP	Similar runoff model as PMP/PMF; familiar design concepts	Moderate
Rainfall-based statistics and Rainfall-Runoff	SEFM *(USBR)*	Stochastic Event-Based Precipitation Runoff Modeling with SEFM (*MGS,2005, MGS, 2009; Schaefer and Barker, 2002*)	Rainfall gages/ detailed regional rainfall frequency, watershed parameters, snowpack, reservoir data	Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEV/L-moments	Peak flow frequency; hydrographs; volume frequency; reservoir elevation frequency	Monte-Carlo methods to sample input distributions	High

Rainfall-based statistics and Rainfall-Runoff	TREX *(USBR)*	Stochastic Rainfall-Runoff Modeling with TREX (*England et al., 2006, 2007, 2014*)	Regional extreme storm DAD data, watershed parameters, snowpack	Diffusive wave runoff; stochastic storm transposition rainfall frequency	Peak flow frequency; hydrographs; reservoir elevation frequency	Physically-based runoff approach; captures spatial variability of precip and watershed	High
Rainfall-based statistics and Rainfall-Runoff	HEC-WAT *(USACE and USBR)*	Watershed analysis tool coupling rainfall-runoff model (HEC-HMS), river routing (RAS), and reservoir operations for system-wide basin flood studies	Can be Regional extreme storm DAD data or meteorlogic extreme storm data, watershed parameters, snowpack	Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEV/L-moments or weather generator	Monte Carlo inputs and resampling; Reservoir elevation (pool) frequency curves, flood volumes, and hydrographs	Flexible framework for system-wide flood modeling with coupled components	High

Hydrologic hazard curves are developed by a specialist (hydraulic engineer or hydrologist) in flood hydrology. The curves are then provided to other engineers and risk analysis teams for use in estimating hydrologic risks for particular failure modes. For example, reservoir elevation frequency curves (Figure II-2-3) can be used to assess an overtopping failure mode. The duration information from hydrographs (Figure II-2-2) can be used as a critical factor in estimating overtopping fragility curves for embankment dams or levees. Duration information is also crucial for assessing other hydrologic-related PFMs, such as spillway erosion, cavitation, and stagnation pressure. The critical factors that engineers need to consider in reviewing and using hydrologic hazard curves are listed below under “Key Hydrologic Hazard Analysis Factors”. Typically, the flood specialist provides an overview of the hydrologic hazard results at an initial risk team meeting. 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 hydrologic hazard curve for the particular site of interest. Estimation of fragility curves for hydrologic PFMs is presented in other chapters of this guidance document.

Data and Extrapolation in Developing Hydrologic Hazards

Developing an HHC for risk assessment traditionally uses the length of record and type of data to determine the extrapolation limits for flood frequency analysis. The length of record is often 50 to 100 years at a particular site (at-site); note the length of record at the dam site could be influenced by operational changes that have occurred over the life of the project. Streamflow and reservoir inflow and operations data which corresponds to current operations is the only data that should be used in the study based on USACE criteria. Analyses can be performed to adjust the data to the current operations so that all data could be used but would likely only be considered for risk assessments where higher levels of effort are warrantred. USACE and Reclamation’s criteria is to use all relevant extreme flood data for the site and watershed of interest. Historical pool of record (POR) or other major flood events should be included even if they fall outside of the current operation plan. At-site data is defined as data that are measured or obtained within the watershed upstream of the dam of interest.

Data sets are significantly expanded by using regional information, using space-for-time substitution concepts. Regional data (or regional analysis) consists of pooling streamflow and precipitation data from many sites around the location of interest to substantially increase the information on extreme floods that are used to estimate hydrologic hazard curves. A hydrologic hazard analysis that is based on regional data collection and analysis results in reduced bias and uncertainty of the frequency distribution (e.g. Hosking and Wallis, 1997).

When developing frequency curves it is important to not mix data from different causative conditions; for example, along the Gulf Coast and Atlantic coasts floods may be caused by general cyclonic storms or by intense tropical storms. The frequency curves resulting from the two types of climatic conditions may have significantly different slopes; therefore, each should be computed separately then the curves can be combined to result in a computed frequency relation more representative of the observed events. If the basin is regulated by an upstream dam, this greatly influences the HHCs at the dam site and not all of the methods presented are applicable without completing a regulated to unregulated transformation on the affected data. Some guidance on mixed-population data is in USACE (1999) and the draft Bulletin 17C (England et al., 2015).

Dam Safety decisions are often required for ACEs (AEPs) much less than 0.01 (1/100) and therefore extrapolation is 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 and are summarized in Table II-2-2; typical and optimal AEP (ACE) credible extrapolation ranges are also listed Table II-2-3 (below). 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 as necessary in light of potential climate change and variability. There is evidence of climatic changes in the past 10,000 years, and supposition that changes will continue into the future. Further information on hydrologic hazard data sources is in Reclamation (1999) and Swain et al. (2006). When using the PMF to extend the frequency curve by USACE methods, Table II-2-2 should be used to determine the reasonable limit for extrapolation based upon methods used. It is also important to make note of the institutional range that is acceptable to each agency.

Table II-2-2. Data types and extrapolation ranges for hydrologic hazard analysis (Reclamation, 1999)

Type of data used for hydrologic hazard analysis	Range of credible extrapolation for Annual Exceedance Probability	
	Typical	Optimal
At-site streamflow data	1 in 100	1 in 200
Regional streamflow data	1 in 500	1 in 1,000
At-site streamflow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional streamflow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

Reclamation routinely utilizes paleoflood data collected at the site of interest. 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). Paleoflood studies are more commonly used in the western United States; House et al. (2002 and Swain et al. (2006) provide some relevant background and examples. 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).

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 ACEs (AEPs) necessary for dam safety decision making. The data used in the analysis provide the only basis for verification of the analysis or modeling results, and as such, extrapolations of HHCs substantially 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 ACE floods. Since each study site is different, no single approach can be identified to address all hydrologic issues. The methods chosen should consider climatic and hydrologic parameters, drainage area size, amount of upstream regulation, data availability, and level of confidence needed in the results.

Key Hydrologic Hazard Analysis Factors

The following are some of the major flood hydrology-related factors that affect the hydrologic hazard curve estimates.

- Precipitation and streamflow data availability within the watershed and length of records;
- Relation between peak flows and historic floods and/or paleoflood data;
- Flood hydrograph shape (peak, volume, duration);
- Rainfall magnitudes, durations, and spatial distributions;
- Skew coefficients of flood frequency and precipitation frequency curves;
- Runoff processes: antecedent moisture, infiltration, snowpack and snowmelt, watershed slope, vegetation;
- River channel and floodplain storage, and channel network and routing;
- Reservoir characteristics (initial level, storage volume, spillway discharge relationship)
- Basin type, regulated versus unregulated upstream conditions and downstream regulation controls;
- System-wide watershed, reservoir, and flood control characteristics;
- Water Control Operations and changes at the site.

Multiple Methods and Uncertainty

The methods presented in this document are not in universal in that they may not be able to be easily applied to all projects. A great deal of judgment will be required to applying these methods to the various dams and levees and no single procedure will be applicable to the wide variation of structures ranging from navigation dams, high head dams, riverine levees, and coastal levees, and the level of risk/decision being made. The engineer/hydrologist will always need to determine the appropriate methods based on the specifics of the project and be able to explain why they apply. One of the building blocks to extending the frequency curve is the increased knowledge and understanding of the system hydrologic response gained by applying multiple methods.

Consider any given rainfall flood event upstream from a dam; the rainfall, peak discharge, volume, and resulting pool elevation would all have frequency estimates associated with the measured or estimated values. For most storms, it is unlikely the frequency estimates for these four observations would agree and may span an order of magnitude or more based on the assumptions made. This may be the result of varying antecedent conditions (previous rainfall infiltration, runoff, starting pool, etc), the method runoff is generated (snow melt, rainfall intensity and distribution, storm types, storm location, storm duration, vegetation changes, etc), and operational releases would impact observed data and frequency calculations based on that data. In fact, at some dams, similar inflows have resulted in significantly different pool elevation from operational differences based on different downstream flow conditions.

There are a number of methods that can be used to extend frequency curves, depending on the scale of the analysis. Some methods may be used for screening level analyses while other methods, with additional cost and time requirements, are better suited for more detailed analyses. These studies typically involve precipitation and extreme storm frequency analysis and modeling using Monte Carlo approaches, and more in-depth paleoflood studies. HHCs from these studies provide ranges on peaks, volumes, hydrographs, and reservoir levels, and include uncertainty. Figure II-2-4 shows example ranges of hydrograph shapes and variations in peak flows (six hydrographs) that have the same 1/10,000 AEP flood volume. Maximum reservoir water surface elevations are also caused by combinations of peak, volume, and initial reservoir level, as shown in Table II-2-3. Because these estimates are being used in a risk assessment, best estimates are recommended, with numerical estimates of confidence bounds or upper and lower limits based on sensitivity analysis or uncertainty bounds. Quantifying uncertainty, identifying key factors of uncertainty, and performing an elicitation on those key factors, are also recommended.

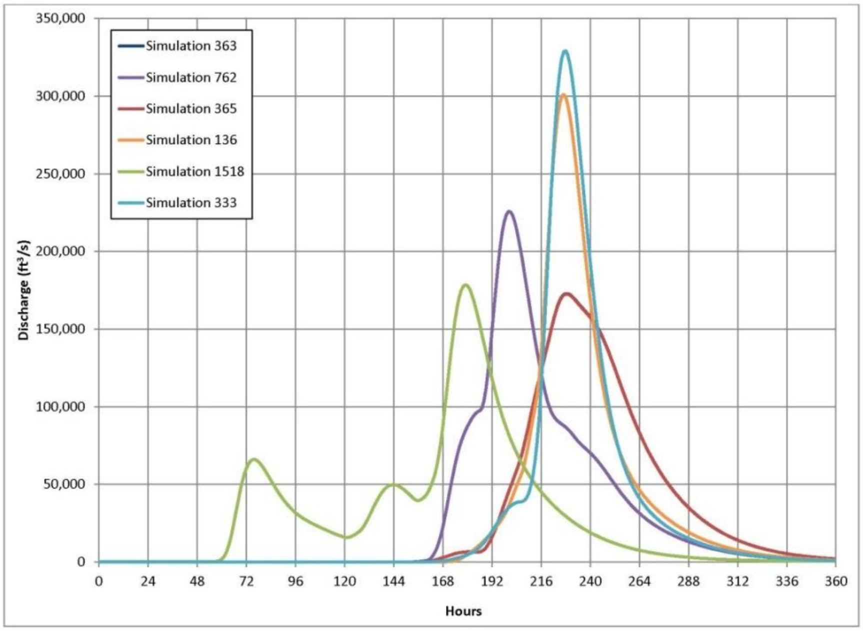

Figure II-2-4. Example reservoir inflow frequency hydrograph variations based on a 1/10,000 AEP volume

Table II-2-3. Example variations in peak inflow and initial reservoir level for a maximum reservoir water surface

AEP (%)	Max Reservoir Water Surface (feet)	Initial Reservoir Water Surface (feet)	Inflow peak (ft^3/s)	Volume (acre-feet)
4.56E-03	1572.98	1533.47	324,600	1,547,000
5.56E-03	1572.93	1549.97	320,100	859,000
6.56E-03	1572.93	1558.93	318,700	1,608,000

No single hydrologic hazard analysis approach is capable of providing the needed characterization of extreme floods over the full range of ACEs 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 hydrologic hazard curves 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.

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. Currently, in some cases, methods listed in Table II-2-1 include procedures for rigorously quantifying uncertainty. Uncertainty estimates are available for EMA/LP-III (Cohn et al., 2001; England et al., 2015), FLDFRQ3, and rainfall frequency with L-Moments (Hosking and Wallis, 1997). For other methods, where uncertainty estimates are currently lacking, this is an area in need of applied flood hydrology research, and qualitative methods may be considered.

While the extension of the hydrologic loading curve will result in an ACE estimate for the Inflow Design Flood (IDF), assigning a frequency to the IDF pool elevation should be done as first stating the range for the IDF ACE based on the uncertainty and then stating the ACE based on the best estimate. The intent of the hydrologic loading curve is to extrapolate as accurately as possible out through the 1/1,000 to 1/10,000 annual chance exceedance events. This is typically the portion of the loading curve that drives risk calculations when combined with the probability of failure and consequence estimates. Extrapolation past this ACE should be considered highly uncertain using current methods and that uncertainty should be communicated in the risk assessment. Bureau of Reclamation (2013) has some additional guidance on this topic for Reclamation and other Department of Interior facilities.

Uncertainty estimates for hydrologic hazard curves may also include relevant climate change information, as appropriate. This is an active area of research in flood hydrology, and guidance on specific methods and applications is not yet available. Reclamation has completed several pilot projects on the use of climate information in dam safety hydrologic hazard studies for comprehensive reviews (Holman and Bahls, 2015) and issue-evaluation studies (Bahls and Holman, 2014; Novembre et al., 2015), and additional work and pilot studies in this area are planned. Current Reclamation policy is to consider climate change information as part of adaptation, resilience, and infrastructure reliability in planning studies, including dam safety (Reclamation, 2014).

Probable Maximum Precipitation and Probable Maximum Flood

The Probable Maximum Precipitation (PMP) is defined as “the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a certain time of year” (WMO, 2009) while the Probable Maximum Flood (PMF) is defined as “the maximum runoff condition resulting from the most severe combination of hydrologic and meteorological conditions that are considered reasonably possible for the drainage basin under study” (Cudworth, 1989; FEMA, 2013). Due to watershed conditions, routing the PMP could result in flows less than the PMF, however, the converse is not true. If the PMF has been properly developed and uses the most up to date information and methodology, it is the best estimate of the maximum runoff that can theoretically occur at a particular site. However, even “[c]ompetent professionals can obtain different results because these procedures require some subjective judgment” (NRC, 1994). If the PMP is believed to be under estimated, a site specific study should be performed which will supersede the generalized regional methods from the National Weather Service (NWS) Hydrometerological Report (HMR) for the area of interest. Assumptions and uncertainties associated with PMP and PMF estimates need to be documented in technical reports by the hydrologist.

Probable Maximum Flood calculations are generally conservative estimates of flows generated from the most severe hydrologic and meteorologic parameters. If a dam can safely pass the PMF based on the most recent PMP, antecedent precipitation, snowmelt criteria, watershed parameters, and up-to-date-flood data, no further hydrologic studies are typically warranted for evaluation of spillway capacity for overtopping Potential Failure Modes. In this case there is an implicit assumption that there is minimal overtopping risk. However, these assessments should consider the potential for spillway misoperation or blockage. If a dam has a hydrologic hazard deficiency using the PMF a hydrologic hazard curve is often requested to determine risk.

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