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B-1 HYDROLOGIC HAZARD ANALYSIS

B-1.1 Key Concepts

This chapter is under revision. The contents of this chapter include information regarding probabilistic hydrologic hazard analysis (HHA) and reservoir level exceedance curves that used to be in separate chapters in previous versions of this manual. Some of the figures and references have been updated in this revision to reflect guidance shown in the presentation.

Risk informed decision making is used to assess the safety of dams and levees, recommend safety improvements, and prioritize expenditures. Risk estimates, from a hydrologic perspective, require estimation of the full range of hydrologic loading conditions to evaluate Potential Failure Modes (PFMs) tied to consequences of the failure mode of interest.

Often the level of the reservoir, or water surface stage, is a key loading parameter for evaluating a potential failure mode for dams and levees. Probabilities for branches that follow water surface stage in the event tree are often conditional on the magnitude of the load. Since the forces acting on a structure are generally proportional to the height of the water squared, the probability of failure typically varies with the water surface stage. Consequences are also influenced by the water surface stage and other related parameters such as reservoir volume. Consequences may be low to moderate below a certain stage (e.g. top of active storage), but could increase rapidly above that stage due to increased discharge releases. The probability of attaining a given range in reservoir elevation is therefore a key consideration in performing a risk analysis.

The loading input to a dam and levee safety risk analysis, for static and hydrologic/hydraulic PFMs, is a hydrologic hazard curve (HHC) that is developed from an HHA. An HHC is a graph of reservoir elevation (dams) (figure B-1-1) or river stage (levees) versus annual exceedance probability (AEP) (figure B-1-2). In some situations, peak flows, flood volumes (for a specified duration), or stage durations versus AEP are utilized. The range of AEPs that is displayed will depend on the data available for the study location, the PFMs under consideration (such as static, seismic, or hydrologic), the type of risk-informed decision, and the needs of the risk team and agency.

In addition to river stage frequency curves, water surface profiles along the length of the levee for various loadings are needed for levee safety risk analysis. 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.

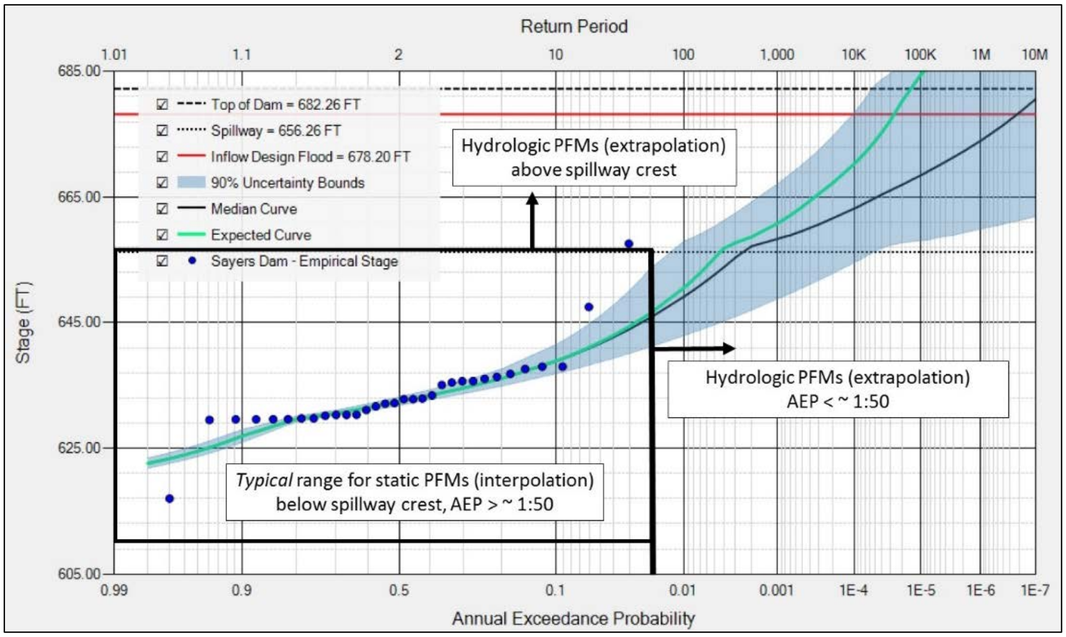


Figure B-1-1.—Example HHC for dams (Smith and Fleming 2018), modified to show typical static and hydrologic PFM zones.

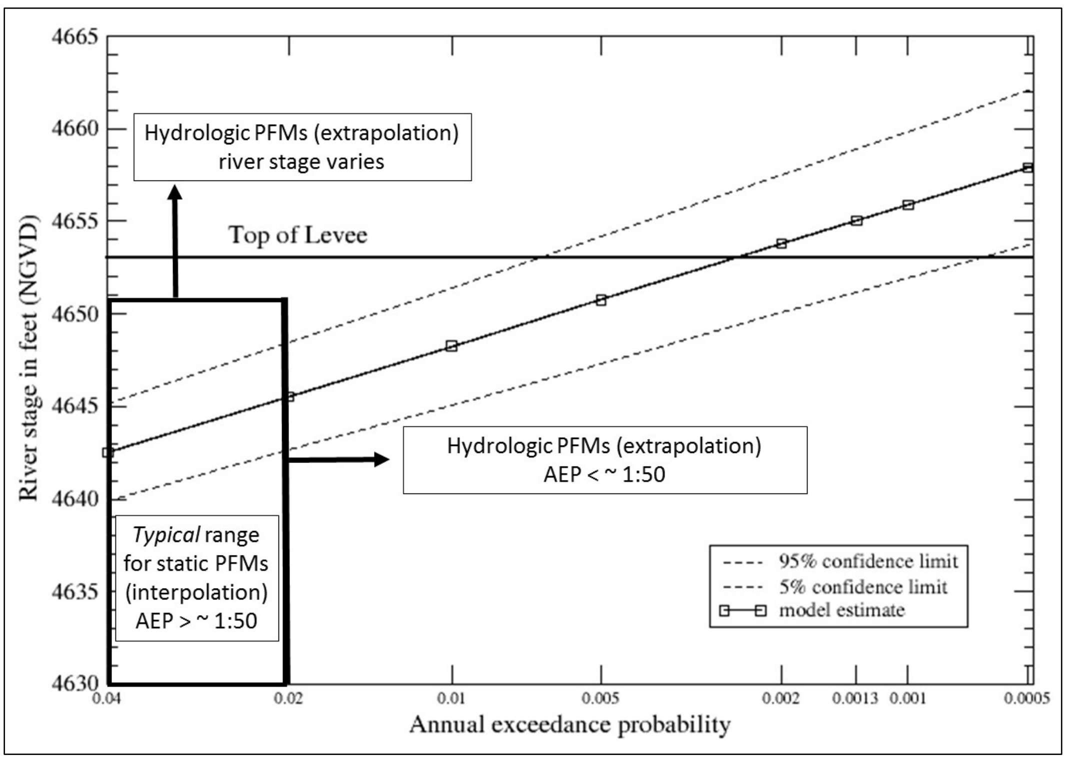


Figure B-1-2.—Example HHC for levees (river stage).

Stage duration curves (figure B-1-3) are used as an input with seismic hazard curves to evaluate risks associated with seismic PFMs. For seismic PFMs, the estimates are annualized by the seismic load probabilities, and the postulated earthquake(s) could occur at any time during the year. It is desired to know the percentage of time the reservoir is at or above a certain level when the earthquake occurs. A reservoir stage duration curve provides this relationship. A stage duration curve is not an annual probability curve, because elevations are correlated between successive time intervals, and elevation characteristics are dependent on the season of the year (Mosley and McKerchar 1993; Salas 1993).

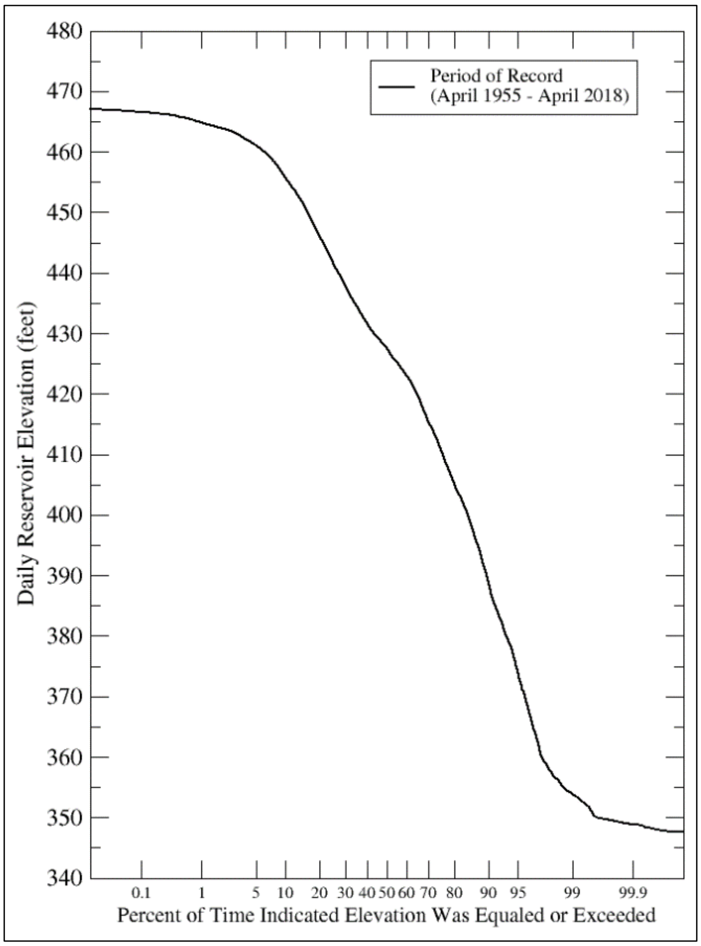


Figure B-1-3.—Example stage duration curve for seismic PFMs.

B-1.2 Hydrologic Hazards for Risk Analysis

B-1.2.1 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 construction following a certain flood event (i.e., “1957 flood”), rather than an AEP. When this occurs, the team should determine a “best” estimate of the AEP (with uncertainty) for the design flow or water surface elevation for the levee as it stands today (USACE 1996), with appropriate consideration of current data, methods, and present watershed conditions. 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.

B-1.2.2 Dams

HHCs 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 probability of overtopping, and probabilities of water levels in spillway crests or crest structures to assess erosion, chute wall overtopping, or other PFM. Inflow and outflow hydrographs for various water levels provides peaks, volumes, and durations of loadings. To satisfy agency risk guidance for dam safety risk assessments, HHCs of high hazard dams need to extend beyond AEPs of 1×10^{-4} (1 in 10,000), and have involvement by the flood hydrologist that performed the analysis.

Peak discharge data are used to estimate the peak flow HHC from annual peak inflow data, typically with a Log-Pearson III distribution. Historical and paleoflood data are used to provide better estimates of the distribution parameters and extrapolate beyond at-site data and regional information (if available). An example HHC for peak flows is shown on figure B-1-4. In this case, it combines peak flows from a stream gage, historical peak flows and paleohydrologic data to estimate the hazard curve to about 0.001 AEP (1/1,000) (England et al. 2006; England et al. 2018). This HHC is then significantly extrapolated based on the fitted probability distribution to provide AEP estimates in the range of interest for dam safety. Uncertainty estimates for the HHC need to be provided and shown; they 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. Similar HHCs are estimated for various flood durations (1-day, 3-day, 5-day, etc.) using flow volume data.

Structures with significant storage and/or flood control functions (such as dams) typically require a reservoir frequency HHC. Key components are volume frequency analysis, initial reservoir elevation distributions, representative hydrograph shapes, and inflow reservoir routing or stochastic rainfall-runoff modeling to define the shape of the upper stage frequency curve. Combining the durations and estimated volumes from the volume frequency with patterned hydrographs that represents floods from regional extreme storms, a range of hydrologic hazards can be estimated. This results in many inflow hydrographs for the facility of interest all based on a specific volume AEP as illustrated below on figure B-1-5. Scaling one set of hydrographs does not properly represent the total hydrologic risk that is possible. Varying the shapes of the hydrographs can drastically change the ultimate loading a dam may experience, based on, for example, different precipitation spatial and temporal patterns experienced within the watershed.

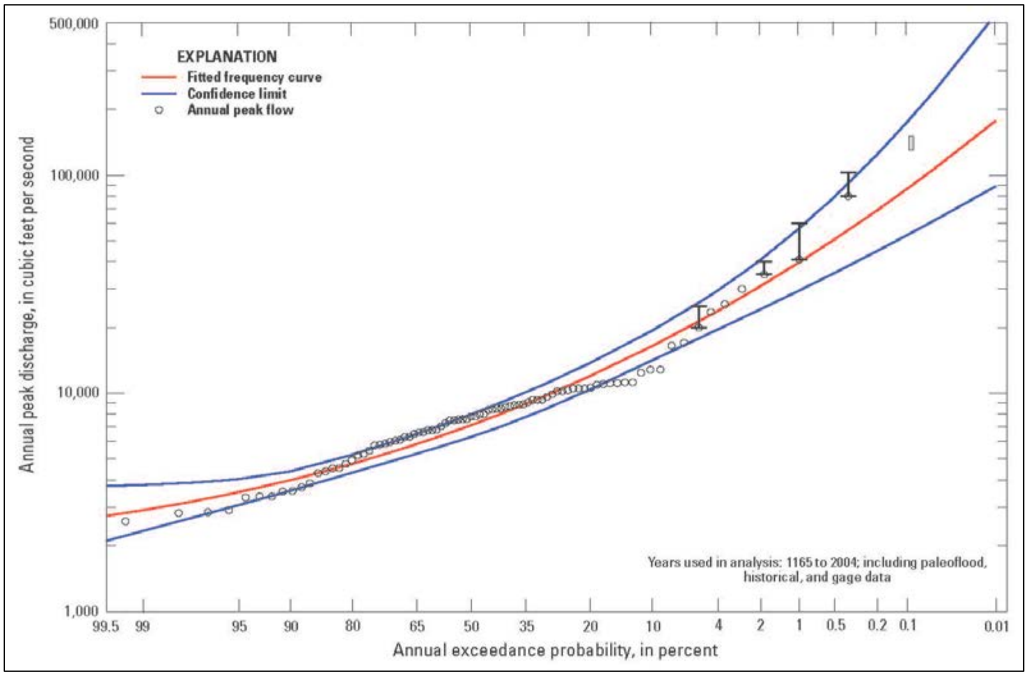


Figure B-1-4.—Example peak flow HHC showing gage, historical data, and paleoflood data, with uncertainty (90% confidence interval) (England et al. 2018).

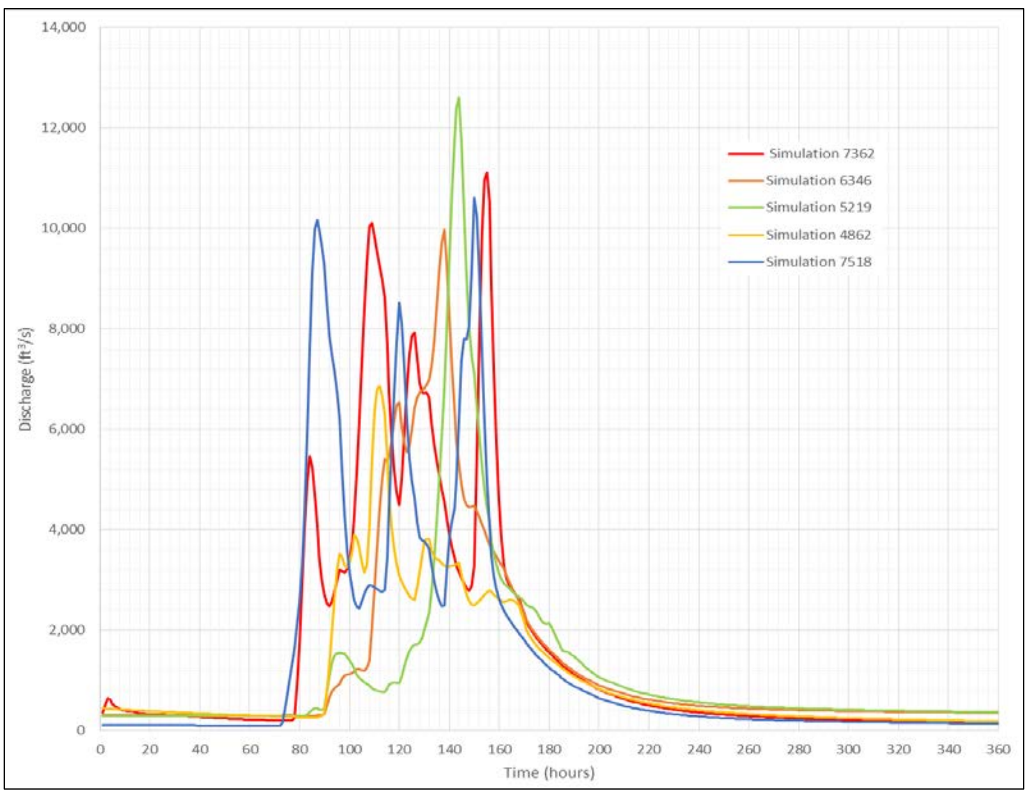


Figure B-1-5.—Example reservoir inflow frequency hydrograph variations, based on a 1/10,000 AEP volume, for reservoir routing.

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 and flood durations 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 on figure B-1-6, where the reservoir water surface elevation corresponding to the top of the dikes has an AEP of about 1 in 5,000. Reservoir elevation frequency curves are computed based on Monte Carlo simulations from streamflow volumes and rainfall-runoff models that account for watershed characteristics, regional precipitation frequency analysis, extreme storm spatial and temporal patterns, flood seasonality, antecedent conditions, snowmelt, and flood control operations within the watershed and system, as appropriate. For maximum reservoir stages of interest, inflow, routed outflow, and stage hydrographs (figure B-1-7) provide critical information to evaluate risks for hydrologic PFMs of interest.

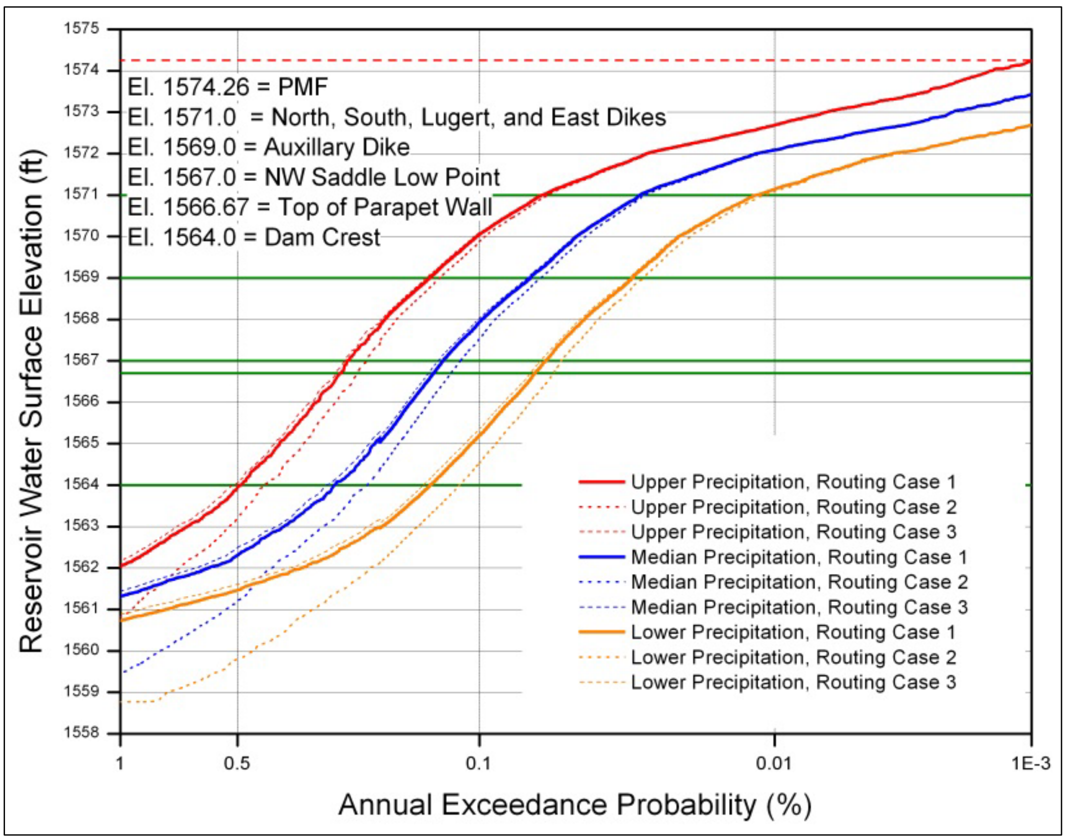


Figure B-1-6.—Example reservoir elevation frequency curve with uncertainty (Novembre et al. 2012).

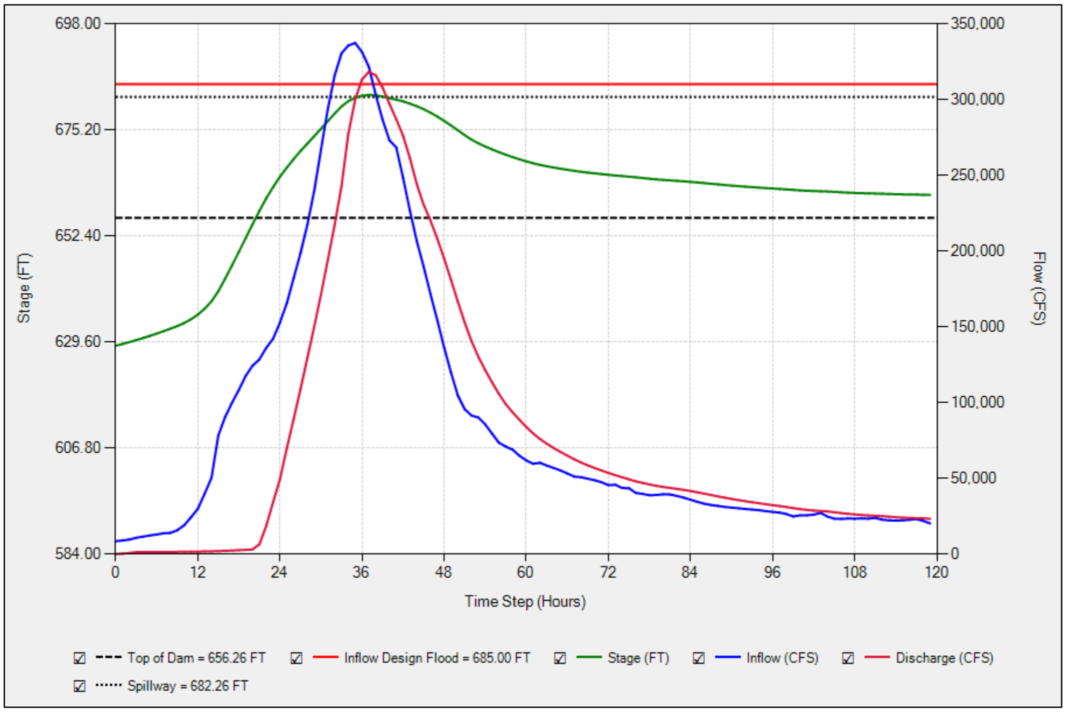


Figure B-1-7.—Example inflow, outflow, and reservoir stage hydrographs for a simulated maximum reservoir elevation of interest (Smith and Fleming 2018).

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. For risk assessments, United States Army Corps of Engineers (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, Bureau of Reclamation (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.

B-1.3 Hydrologic Hazard Levels of Study

Hydrologic hazard information is required for all dam and levee safety studies and varies in the level of detail necessary. Hydrologic hazard studies are conducted at various levels for risk assessments and to meet the needs of specific dam and levee safety programs within various agencies. Hydrologic hazard studies generally depend on the flood information available, type of risk analysis or dam safety decision being made, agency considerations, and budget and schedule considerations. The components within each study are generally scalable to meet these considerations.

There are three basic levels of study for USACE risk assessments in dam safety and similar levels for levee safety (USACE 2014): Periodic Assessment (PA) and Semi-Quantitative Risk Assessment (SQRA); Issue Evaluation Study (IES); and Dam Safety Modification Study (DSMS). Hydrologic hazard analyses are performed at two levels: PA/SQRA and at IES. The IES level is scalable and requires increasing hydrologic hazard data collection and modeling efforts beyond the PA and SQRA to provide high confidence in HHC extrapolations and results, and design flood estimates if needed. On occasion, hydrologic hazards and design floods are estimated at the DSMS level to assist in risk reduction estimation and evaluation of alternatives. 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 hazards. 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 generally correspond to routine assessment and 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) (Reclamation 2011). 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.

The Federal Energy Regulatory Commission (FERC) and Tennessee Valley Authority (TVA) have dam safety risk study levels similar to USACE and the Bureau of Reclamation. There are four levels of risk analyses used by FERC: Level 1 Screening; Level 2 Periodic; Level 3 Semi-Quantitative; and Level 4 Quantitative Risk Analyses (FERC 2016). Hydrologic hazard studies are conducted for each risk analysis level, with increasing data collection, analysis, and modeling for each level (FERC 2014). Refer to Reclamation (2013), FERC (2014), and USACE (2015) for further guidance and information on appropriate hydrologic hazard levels of study.

B-1.4 Data and Hydrologic Hazard Principles

B-1.4.1 Data and Extrapolation

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 represent current operations is recommended. 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 warranted. USACE and Reclamation's criteria is to use all relevant extreme flood data for the site and watershed of interest, including historical and paleoflood data (England et al., 2018). 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 (NRC 1988). Regional data (or regional analysis) consists of pooling streamflow and/or precipitation data from many sites around the location of interest to substantially increase the information on extreme floods that are used to estimate HHCs. An HHA 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 (mixed populations); 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 (1982) and in Bulletin 17C (England et al. 2018).

Dam Safety decisions are often required for AEPs much less than 0.01 (1/100) and therefore extrapolation is a necessity. Depending on the hydrologic hazard method being employed (listed below), the sources of information used for the hydrologic hazard analyses may use combinations of streamflow, precipitation, and paleoflood data and are summarized in table B-1-1; typical and optimal AEP credible extrapolation ranges are also listed. 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), Swain et al. (2006), England et al. (2018), and Smith and Fleming (2018).

Table B-1-1.—Data Types and Extrapolation Ranges for HHA (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. USACE uses paleoflood data for some IES and DSMS studies; recent investigations include sites in Colorado (Pearce 2017), Vermont (Kelson et al. 2017), and Oregon (Kelson et al. 2018). 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 common in the western United States; investigations are currently being performed throughout the United States, including in the Southeast for TVA. House et al. (2002) and Swain et al. (2006) provide some relevant background and examples; England et al. (2018) describe data sources and applications for flood frequency. 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., stream gage).

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 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 AEP 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.

B-1.4.2 Key Hydrologic Hazard Principles

Some key principles to estimate hydrologic hazards are the following (see NRC 1988, Reclamation 1999, Swain et al. 2006, Merz and Bloschl 2008a and b, and England et al. 2018, for technical details and additional references):

- No single approach describes flood hazards over the range of AEPs needed
- Multiple methods: combine flow frequency curves and rainfall-runoff curves
- Greatest gains from incorporating regional precipitation, streamflow, paleoflood data – lots of data
- Honestly represent uncertainty – explicitly quantify uncertainty
- Temporal information: expand data in time
- Spatial information: expand data in space
- Causal information: utilize hydrological understanding of flood-producing processes
- Do not assign an AEP to the PMF

For hydrologic risk analysis, some key concepts are the following:

- Variables, magnitudes, and ranges of interest for risk estimate
- Stage, discharge, volume, velocity, others
- Peak, timing, duration
- Entire distribution shape matters
- Load partitioning important to develop a proper event tree
- Integration of hazard with failure modes and consequences
- Deterministic floods not easily mapped to hazard curves

B-1.4.3 Key Hydrologic Hazard Analysis Factors

The following are some of the major flood hydrology-related factors that affect the HHC 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)
- Regional precipitation frequency distribution and parameters
- Rainfall magnitudes, durations, temporal and spatial distributions
- Skew coefficients of flood frequency
- 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

B-1.5 Hydrologic Hazard Methods

General approaches for estimating hydrologic hazards for static, seismic and hydrologic failure modes are presented. The methods described are scalable; however, not all methods will be appropriate for all studies. The methods for estimating HHCs considers the dam safety decision criteria, potential dam failure mode and dam characteristics, available hydrologic data, possible analysis techniques, resources available for analysis, and tolerable level of uncertainty. Dam and levee safety risk guidelines are used in determining the probabilistic range of floods needed to address potential hydrologic issues. The potential dam or levee failure mode and dam (or levee) characteristics impact the type of hydrologic information needed to assess the problem. The specific elements selected to be incorporated in a HHA should consider the tolerable level of uncertainty. To reduce the uncertainty in the estimates, additional data collection and use of more sophisticated solution techniques may be required (Swain et al. 2006).

There are several methods available to estimate magnitudes and annual exceedance probabilities of extreme flood events and hydrologic loadings for dam and levee safety studies. Methods can generally either be classified as streamflow-based statistical analysis or rainfall-based with statistical analysis on the generated runoff. Methods that principally use streamflow data are presented in table B-1-2; rainfall-runoff methods are listed in table B-1-3. The data inputs and assumptions; with some of their strengths and limitations, are described in various technical reports on methods and study reports for individual dams and levees listed in the References. Some agency methods (Reclamation, USACE, FERC, TVA, and National Research Council (NRC)) and references are presented in Swain et al. (2004), Nicholson and Reed (2013), NRC (2013), FERC (2014), USACE (2015), and England and Stedinger (2017).

Table B-1-2.—Current Streamflow HHC Methods, Inputs, Assumptions, and Products

Method (Agency)	Description (Reference)	Inputs	Assumptions	Hydrologic Hazard Curve Product	Why Choose	Level of Effort
Bulletin 17C (EMA-LP-III) USGS PeakFQ; HEC-SSP (USACE, Reclamation, FERC)	Peak-flow and volume frequency analysis with historical/ paleoflood data - EMA (*Cohn et al. 1997, England et al. 2018*)	Peak flow, historical data, paleoflood data, regional skews	LP-III flood frequency distribution with moments and regional skew	Peak flow frequency and confidence intervals; Volume Frequency	Federal guidelines for flood frequency; uses historical and paleoflood data when available	Low to moderate
FLDFRQ3 (USBR)	Bayesian 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
Hydrograph Scaling (USACE and Reclamation)	Balanced Hydrographs and Pattern Scaling (*England 2003, Smith and Fleming 2018)*	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
Reservoir Frequency Analysis (RMC-RFA) (USACE)	Streamflow Volume Stochastic Modeling with reservoir routing *(Smith 2018)*	Volume frequency, hydrographs, flood season, initial reservoir stage	Inputs defined by distributions, volume-frequency, observed hydrographs, and pool duration frequency	Reservoir elevation and confidence intervals	Monte-Carlo methods to sample inputs; combine inflows and routing, quantify uncertainty	Low to Moderate
Watershed Analysis Tool (HEC-WAT) (USACE)	Streamflow Volume Stochastic Modeling for Flood Risk Analysis with HEC-ResSim (within HEC-WAT)	Pool duration, volumes, and Hydrographs	Inputs defined by distributions, volume-frequency observed hydrographs, and pool duration frequency	Reservoir elevation and confidence intervals	Monte-Carlo methods to sample inputs; quantify uncertainty; system/downstream effects with coincident frequency	High

Table B-1-3.—Current Rainfall-Runoff HHC Methods, Inputs, Assumptions, and Products

Method (Agency)	Description (Reference)	Data Inputs	Assumptions	Hydrologic Hazard Curve Product	Why Choose	Level of Effort
Australian Rainfall-Runoff (Reclamation, FERC)	Australian Rainfall-Runoff Method (Nathan and Weinmann 2016)	Probable Maximum Precipitation (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 to High
Stochastic Event Flood Model (SEFM) (Reclamation, FERC)	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
HEC-WAT (USACE and Reclamation)	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 meteorologic 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

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.

HHCs 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, under guidance from the hydrologic loading specialist, for particular failure modes. For example, reservoir elevation frequency curves (see figure B-1-6) can be used to assess an overtopping failure mode. The duration information from hydrographs (see figures B-1-5 and B-1-7) 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 are listed under "Section B-1.4.3, 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 HHC for the particular site of interest. Estimation of fragility curves for hydrologic PFMs is presented in other chapters of this guidance document.

B-1.6 Design Floods, Probable Maximum Floods, and Limits to Extrapolation

Historically, dam and levee design and analysis methods have focused on selecting a level of protection based on a particular AEP (levees) or a maximum flood (dams). Traditionally, the protection level for high hazard potential dams is the Probable Maximum Flood (PMF) (Cudworth 1989, USACE 1982, FEMA 2013, FERC 2015). The design level for levees is usually based on the Standard Project Flood (SPF) (USACE, 1966), the historical flood of record, or a peak flow with a specified AEP (e.g. 1 in 500).

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 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 underestimated, a site-specific study could be performed which might supersede the generalized methods from the National Weather Service (NWS) Hydrometeorological Report (HMR) for the area of interest. Assumptions, sensitivities, and uncertainties associated with PMP and PMF estimates need to be quantified and documented in technical reports by the hydrologist.

PMF 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 conducted for evaluation of spillway capacity for overtopping PFMs. In this case there is an implicit assumption that there is minimal overtopping risk. However, these assessments should consider the potential for spillway mis-operation or blockage. If a dam has a hydrologic hazard deficiency using the PMF, aN HHC is needed to estimate risks.

Within in the context of HHC development, the PMF can be considered as a limit to HHC extrapolations (Reclamation 1999, 2013). Reclamation uses the PMF as the upper limit of flood potential at a site for storm durations defined by the PMP (Swain et al. 2004). If an HHA produces peak flows or volumes that exceed the PMF, then the PMF can be used in evaluating the hydrologic risk and as a theoretical and practical upper limit to statistical extrapolations. Before applying the PMF as the upper limit, the hydrologist should ensure that it has been developed using current procedures with up-to-date data and for a PMP duration suitable for the site of interest.

B-1.7 Multiple Methods and Uncertainty

The methods presented in this chapter are not 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 data available and 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 mechanisms contributing to runoff generation (snowmelt, 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, time, and data 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 B-1-8 shows example ranges of hydrograph shapes and variations in peak flows (six hydrographs) that have the same 1/10,000 AEP flood volume. In this scenario, all of the hydrographs need to be included in design and risk analysis to properly characterize the flood loading. Maximum reservoir water surface elevations are also caused by combinations of peak, volume, and initial reservoir level, as shown in table B-1-4. 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.

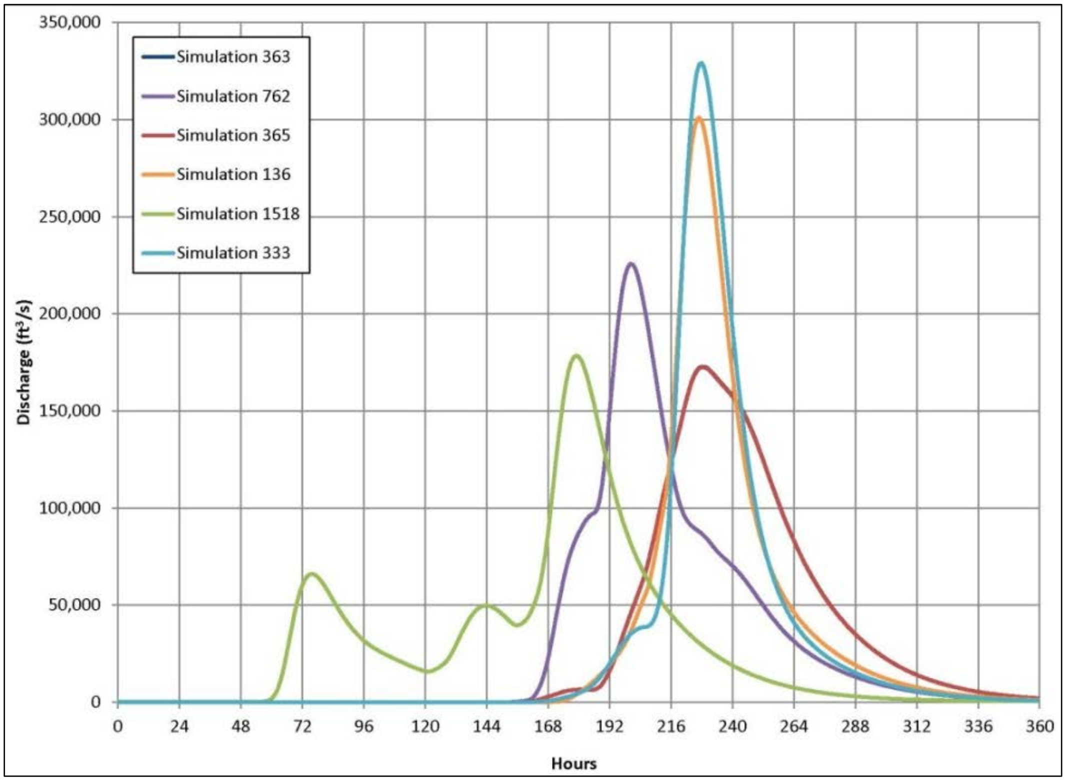


Figure B-1-8.—Example reservoir inflow frequency hydrograph variations, based on a 1/10,000 AEP volume.

Table B-1-4.—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 HHA 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 an HHC. The recommended approach is to combine streamflow peak or volume-based frequency analysis with stochastic rainfall-runoff models. 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.

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 tables B-1-2 and B-1-3 include procedures for rigorously quantifying uncertainty. Uncertainty estimates are available for EMA/LP-III (Cohn et al. 2001; England et al. 2018), FLDFRQ3, RMC-RFA, and rainfall frequency with L-Moments (Hosking and Wallis 1997) using Stochastic Event Flood Model (SEFM) or HEC-WAT. For other methods, where uncertainty estimates are currently lacking, this is an area in need of applied flood hydrology research. Qualitative methods and/or expert elicitation may be considered in this situation, as well as when weighting and combining results. When methods for quantifying uncertainty are not available, it is required by the loading specialist to make a strong effort in characterizing the possible uncertainty to the risk team so that the uncertainty is taken into account during risk analysis.

While the extension of the hydrologic loading curve will result in an AEP 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 AEP based on the uncertainty and then stating the AEP based on the best or expected probability 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 AEP. 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 AEP needs to include quantitative uncertainty with expected probability estimates; that uncertainty should be communicated in the risk assessment. Reclamation (2013) has some additional guidance on this topic for Reclamation and other Department of Interior facilities.

B-1.8 Climate Variability and Change

Uncertainty estimates for HHCs may 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 CRs (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). USACE considers qualitative climate change impacts at the IES level (USACE 2016a).

B-1.9 Use of Reservoir Exceedance Curves

Reclamation develops separate PFMs for different loading categories. In other words, there are normal operation (static) PFMs, hydrologic PFMs, and seismic PFMs. In some cases, a given failure mechanism (say, internal erosion through the embankment) may be evaluated for each of the three loading conditions. With this type of categorization, historical normal reservoir operating levels are utilized for static PFMs, while hydrologic PFMs require flood frequency curves that provide the exceedance probability of a given reservoir water surface. USACE evaluates PFMs over the full range of hydrologic loading, from normal operations through various flood loadings. USACE exceedance curves include both normal operations as well as projected flood-induced levels.

The fundamental difference in the two agencies' approaches is simply this: Reclamation reservoir exceedance curves are based solely on historic recorded reservoir level data, while USACE exceedance curves also include expected levels resulting from floods. Additional discussion about the different uses is presented below.

B-1.9.1 Use of Reservoir Exceedance Curves in Risk Analysis – Reclamation Approach

The data to be used in the reservoir exceedance evaluation is dependent on the potential failure mode to be evaluated, such as static, seismic or hydrologic.

- For static PFMs, such as seepage and internal erosion modes that could occur under normal operations, the estimates are annualized by considering the likelihood that the reservoir will rise to a specified level in any given year. Thus, only the maximum values for each year of record are used in the evaluation, as it is most likely that an internal erosion failure would take place with a nearly full pool.

- For seismic PFMs, the estimates are annualized by the seismic load probability, and the postulated earthquake(s) could occur at any time during the year. Therefore, it is desired to know the chances of the reservoir being at or above a certain level when the earthquake hits. For this evaluation, all of the data is used (typically daily reservoir elevations), and the percentage of time above a given elevation is used. It is important to note that these estimates are not annual probability estimates, but simply the percentage of time the reservoir has exceeded user-defined elevations. To be clear, a reservoir percentage of time curve is not a probability curve, because elevations are correlated between successive time intervals, and elevation characteristics are dependent on the season of the year (see, e.g. Mosley and McKerchar 1993, and Salas 1993).

Flood-related PFMs could require even a different approach. For example, if the critical floods seem to be general storm rain-on-snow events, flood season could occur for a few months in the spring of the year. The starting reservoir elevation could be critical to the results of flood routings (maximum reservoir elevation) for a given flood loading range. Therefore, the likelihood of exceeding certain starting reservoir elevations when the flood occurs could be important, and only reservoir elevations during flood season are used in the evaluation.

B-1.9.2 Use of Exceedance Curves in Risk Assessment - USACE Approach

Water surface stage (reservoir pool level for dams or river elevation for levees) and its associated probability of occurrence is a key parameter used to define the loading conditions for a dam or levee risk analysis. For flood loading, the exceedance probability for water surface stage is used as the basis for annualizing the risk estimate. For seismic loading, the exceedance duration for water surface stage is used to evaluate the outcome of a particular stage coincident with the earthquake.

Record data of reservoir levels forms the basis for that portion of the reservoir exceedance curve that deals with relatively frequent annual probabilities. Extrapolation of the period of record data to stages higher than those previously observed is usually required. This can be accomplished by routing hydrographs using information from the HHA.

Other parameters that may be related to water surface stage (e.g. discharge, velocity, volume, or duration) can also be important. These parameters can be considered in the risk analysis by implicitly associating a representative hydrograph or other related piece of information with its corresponding water surface stage. An explicit approach can also be implemented by including the additional parameters in the event tree along with their associated probabilities.

B-1.10 Development of Exceedance Curves

Because Reclamation and USACE consider the effect of reservoir level differently in their analysis of risk of PFMs, the USACE and Reclamation reservoir exceedance curves are unique and are thus developed differently. The following section details the procedures used by each agency to develop these curves.

B-1.10.1 Reclamation Approach for Developing Reservoir Exceedance Curves

B-1.10.1.1 Procedure for Developing the Exceedance Curve

The following steps are typically followed in developing reservoir level exceedance curves.

- The first step is to collect the reservoir level data in terms of date and associated reservoir elevation. Each Region is a little different in how this information is accessed. Most of the data can be accessed through the intranet or internet. For some Regions, like the Great Plains and Pacific Northwest Regions, the data can be found with relative ease from their intranet sites, which access the Hydromet system. For the Mid-Pacific Region, you may be directed to state sites in order to find the information. It may take a little searching to find the information on some of the other Regional or Area Office web sites. Once the data is found, it is highlighted, copied, and pasted or imported into an Excel spreadsheet. Links to archive (period of record) reservoir data (as of July 2018) are:

- GP Region Hydromet: https://www.usbr.gov/gp/hydromet/hydromet_arcread.html
- PN Region Hydromet: https://www.usbr.gov/pn/hydromet/arcread.html
- LC Region: https://www.usbr.gov/lc/riverops.html
- UC Region CRSP: https://www.usbr.gov/uc/water/index.html
- MP Region (via California Data Exchange Center): https://cdec.water.ca.gov/

The key parameter of interest from the Hydromet system is FB (reservoir ForeBay elevation). A secondary parameter is AF (total storage in acre-feet) (sometimes called active storage), which can be used to estimate reservoir forebay elevation with a reservoir capacity-elevation table, if storage is reported instead of elevation.

- The electronic reservoir data may only extend back for a short period, e.g., back to 1986. If so, it may be important to look for additional data from prior years. One straightforward way to do this is to contact the Area Office where the dam is located via email (e.g. CVO, ECAO, etc.). The Area Office usually has reservoir data in electronic format that in many cases is not in various on-line databases. In some cases, such data can be found in the instrumentation data base at the Technical Service Center. The instrumentation plots typically only have a limited portion of the reservoir level data set, so it is important to search for all available data. In other cases, it may be necessary to obtain hardcopy records of reservoir level and enter the data manually.

- After data collection, it is important to determine the frequency of collection and data quality. At most sites, daily reservoir elevations and storages are collected. At some sites, only monthly (typically end of month contents) data are collected or reported. There may be seasonal interruptions in data collection as well. This is sometimes the case when an irrigation district makes measurements. Also, for high-elevation sites winter records can be fragmentary or incomplete due to ice and snow effects. Check the last CR report and make sure the historical high reservoir level is in the data base. Usually the daily reservoir levels are taken at a certain time each day, and may miss the peaks if the reservoir is rapidly rising or falling. This may be important if the reservoir storage volume or surcharge volume is small in relation to the drainage area of the watershed, or has no carry-over storage from one year to the next.

- Plot the reservoir elevation versus time as a series of single data points (no line, see figure B-1-9). Review the plot, looking for missing data and sudden shifts. Sudden shifts might be due to a datum change, in which case an adjustment will need to be made to some of the data. Other abnormalities, such as typos and missing or bad data should also be corrected or deleted from the data. Note the percent of the corrected record that is complete.

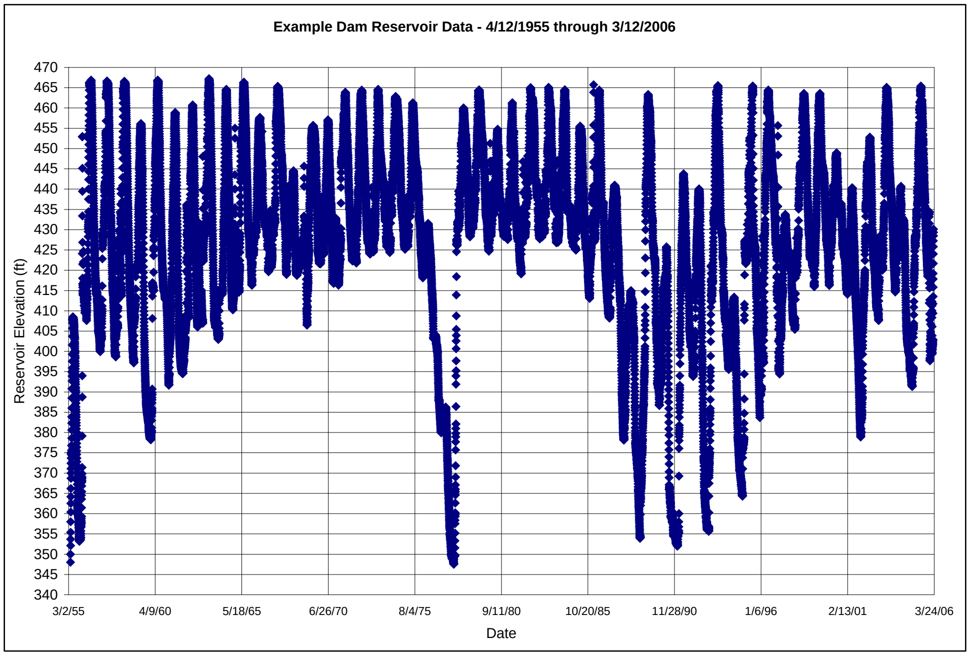


Figure B-1-9.—Time series plot of reservoir elevation.

- Find the minimum and maximum reservoir levels in the data to determine the range over which the plots need to be made. Then choose a calculation interval. Calculations are typically done every foot, but for smaller dams or dams where the reservoir doesn't fluctuate a lot, this could be taken as a smaller interval. Similarly, for high dams with significant reservoir fluctuation, a larger interval might be chosen.

- For seismic PFMs, one can set up a spreadsheet to perform the exceedance probability calculations for each reservoir level according to the increment selected above. This is done, for example, using an Excel function or with HEC-SSP.A similar calculation is performed for each reservoir elevation increment. A similar approach can be used for reservoir levels to be used increment. A similar approach can be used for reservoir levels to be used for evaluating "flood season" loadings. However, only those reservoir elevations for the months of interest are extracted from the data and used in the analysis.

- For static PFMs, it is necessary to extract the maximum reservoir elevation for each year and store the data in a separate spreadsheet list or other software. This can be done manually, use of a spreadsheet routine, HEC-DSSVue, or similar software can be used. The calculations can be performed in a manner similar to that described in the previous bullet. Alternatively, the data can be sorted in order of ascending reservoir elevation, and probabilities estimated from a plotting position. Example plots for exceedance probability and AEP are shown on figures B-1-10 and B-1-11, respectively.

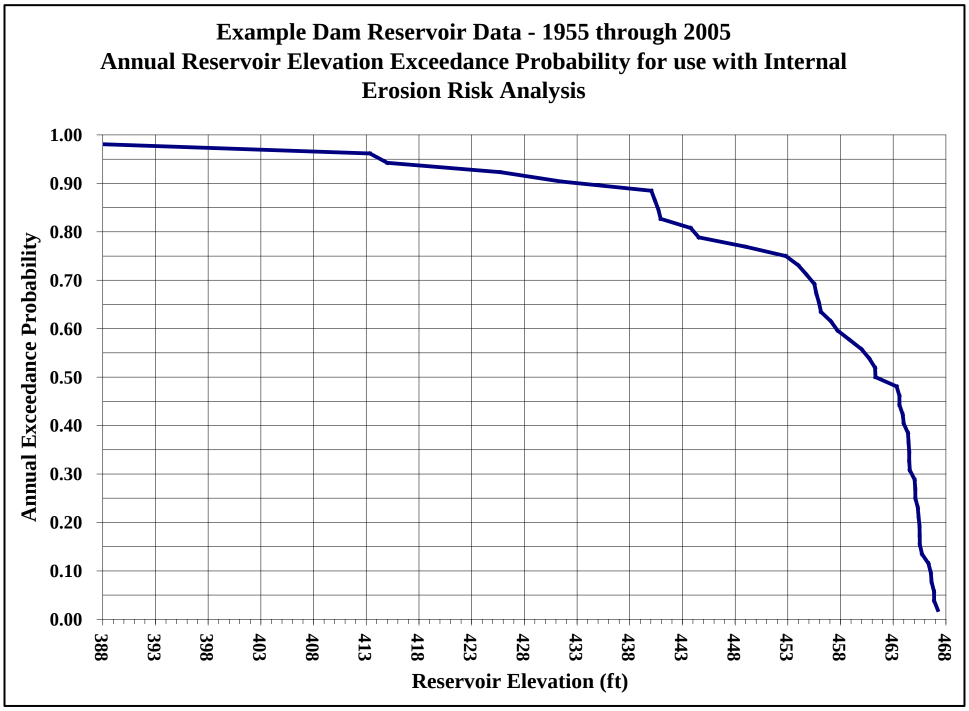


Figure B-1-10.—Example reservoir percentage of time exceedance plot.

B-1.10.1.2 Calculating Reservoir Load Range Probabilities

The event tree method of estimating risks, as adopted by Reclamation, requires the loadings to be divided into discrete ranges. This applies to reservoir load ranges as well as seismic and flood load ranges. The probability of being in a given reservoir range is the exceedance probability of the lower reservoir elevation for the range minus the exceedance probability of the upper reservoir elevation for the range. For example, from figure B-1-11, the probability of annually reaching a level between elevations 453 and 463 is approximately 0.75-0.48 = 0.27.

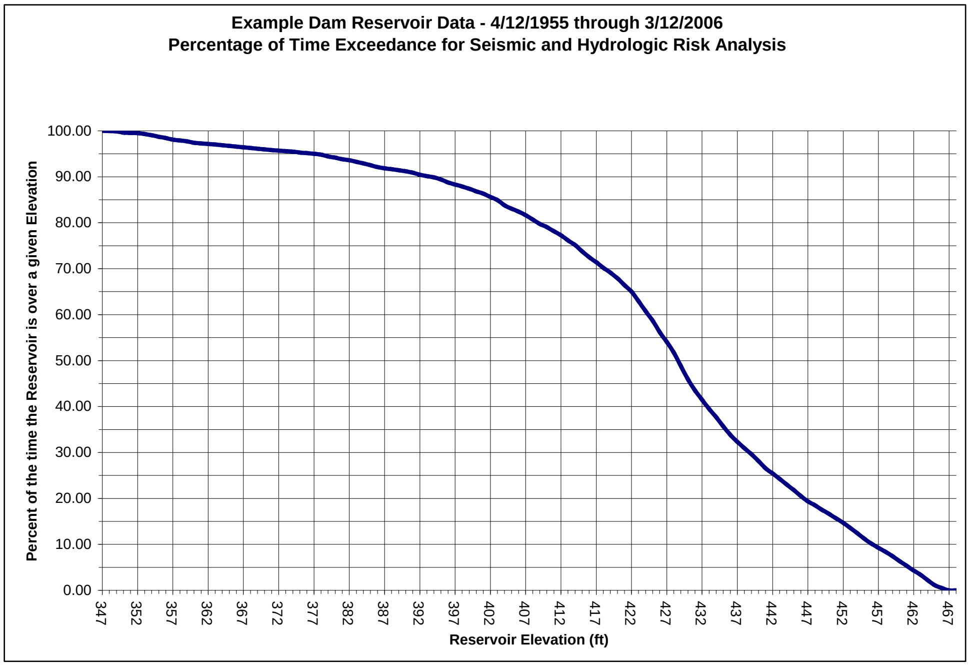


Figure B-1-11.—Reservoir annual maximum exceedance probability curve.

B-1.10.1.3 Handling Uncertainty

To date, Reclamation has not put uncertainty bounds on reservoir exceedance curves. Thus, only expected values are used in event tree analyses. However, uncertainty bounds could possibly be developed by plotting exceedance curves for each year, and then performing a statistical evaluation for each reservoir elevation or range to estimate confidence intervals. This type of information could be used with seismic or hydrologic PFMs. For static PFMs, it may be possible to fit a function to the "ratio of years" exceedance curves for the period of record, and then use the statistics of the function to develop confidence intervals. Procedures to estimate uncertainty bounds are being considered.

B-1.10.1.4 Considerations for Comprehensive Reviews

If reservoir exceedance plots are not already available, they typically would not be developed for a CR. Instead, a time plot of reservoir level, typically included with most instrumentation plots, would be reviewed, and needed reservoir exceedance probabilities would be estimated from the approximate number of spikes (AEP) or area of the curve (exceedance probability) above each reservoir level of interest.

B-1.10.2 USACE Approach for Developing Exceedance Curves

Similar concepts and methods are used for both dams and levee when estimating exceedance curves. The primary difference is that water surface profiles are rarely needed for dams but are usually needed for levees. When needed, water surface profiles can be developed using software packages such as HEC-RAS.

B-1.10.2.1 Exceedance Probability

When evaluating risks associated with flood loading it is necessary to consider the probability that the water surface will reach a particular stage within a given period of time. This is accomplished using an exceedance probability relationship that characterizes the likelihood that a random variable (e.g. peak water surface stage) will exceed a particular value over a given time period (e.g. one year). Risk analyses for dam and levee safety typically evaluate floods on an annual basis using the maximum stage obtained during a given year. Other approaches can be taken using different time periods (e.g. seasonal) and different flood parameters (e.g. discharge, velocity) if needed to represent the flood loading characteristics at a particular site.

AEP relationships can be developed from a combination of period of record information and synthetic events generated from the hydrologic hazard information.

B-1.10.2.2 Period of Record Analysis

The first step in developing an exceedance probability relationship involves collecting, assembling, and reviewing the period of record data. Plotting the data can assist with evaluating data quality. An example data set showing daily average reservoir stages for a dam is presented on figure B-1-12. For this example, it is assumed that daily average values are appropriate for the risk analysis and that the risk analysis is based on ‘normal’ operating conditions. Adjustments to the data time interval are not needed in this case. The plot, however, reveals several potential data quality issues. The time periods associated with the initial reservoir filling, the dam safety emergency, and the pool restriction for interim risk reduction may not be representative of normal operation. Some of the data also appears to be missing and incorrect based on a visual inspection of the plot.

The full period of record should be considered for the exceedance probability relationship unless there are significant issues with the data not being representative of the operating conditions assumed for the risk analysis. The

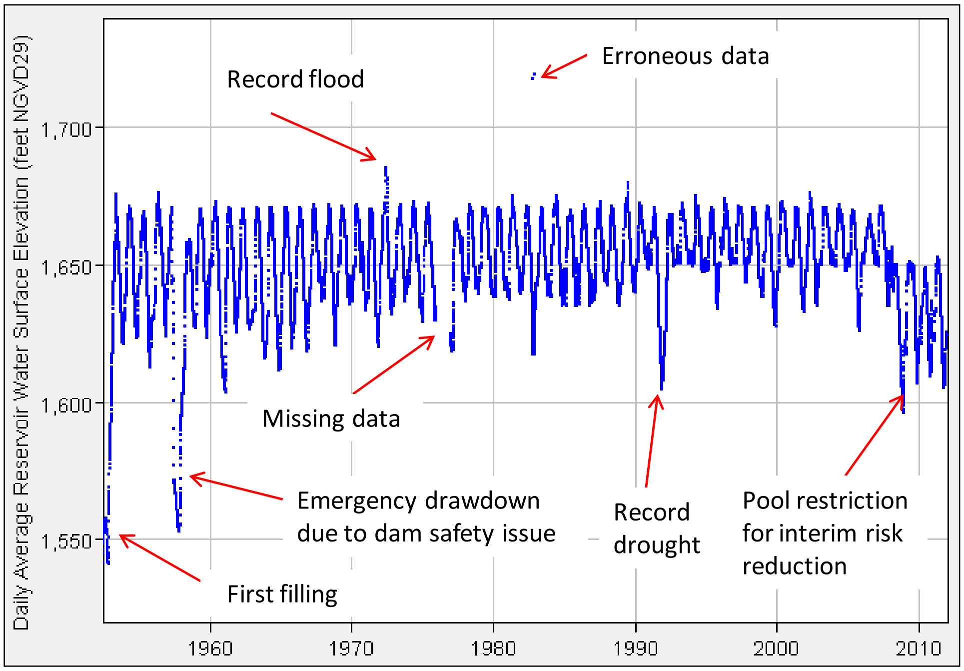


Figure B-1-12.—Daily average reservoir stage data.

maximum water surface stage obtained each year (annual peaks) needs to be extracted from the daily data. The data extraction can be based on calendar year, water year, or some other interval appropriate for the site.

Assuming the risk analysis for the example dataset is based on a normal operating condition, a decision is made to exclude periods associated with the first filling, dam safety emergency, and pool restriction. The adopted period of analysis includes calendar years 1953-1956 and 1959-2007. Annual maximum water surface elevations are extracted for each calendar year in the period of analysis and the results are presented on figure B-1-13.

The exceedance probability relationship is then computed by sorting the annual peak data for the adopted period of analysis in descending order, ranking the sorted data from 1 to n, and computing the AEP for each data value using a plotting position. A plot of the resulting exceedance probability relationship is presented on figure B-1-14.

B-1.10.2.3 Partial Duration Series

The binomial distribution assumptions (statistically independent trials) are not always valid particularly for relatively frequent events with an AEP greater than about 0.1 (more frequent than a 10-year return period). A partial duration series

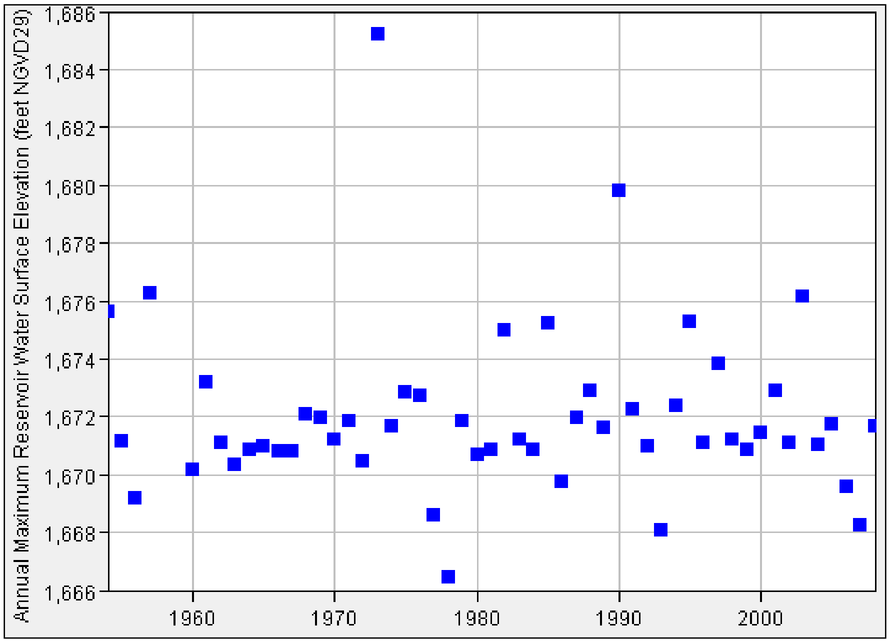


Figure B-1-13.—Annual peak reservoir stage data.

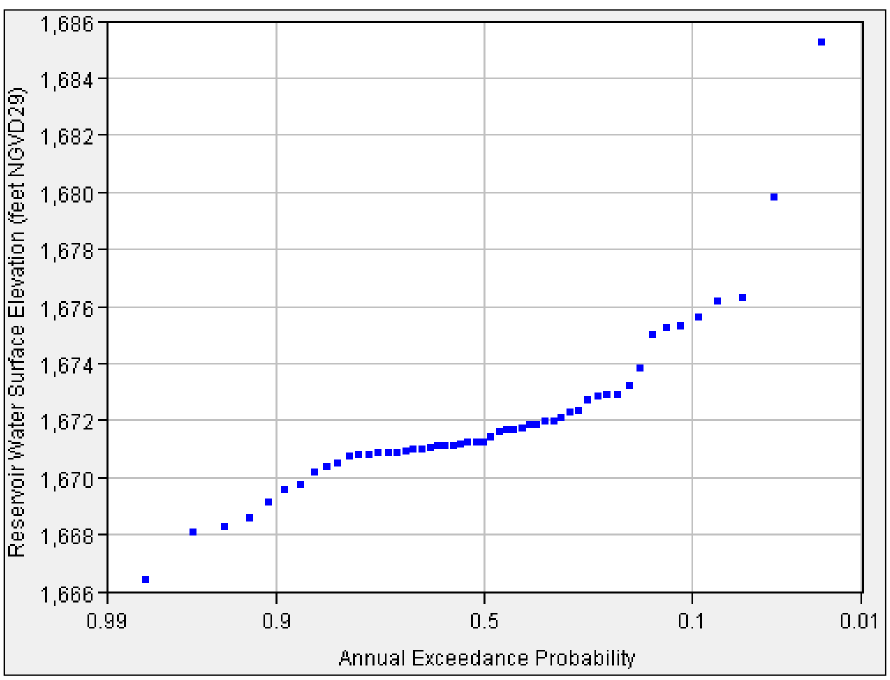
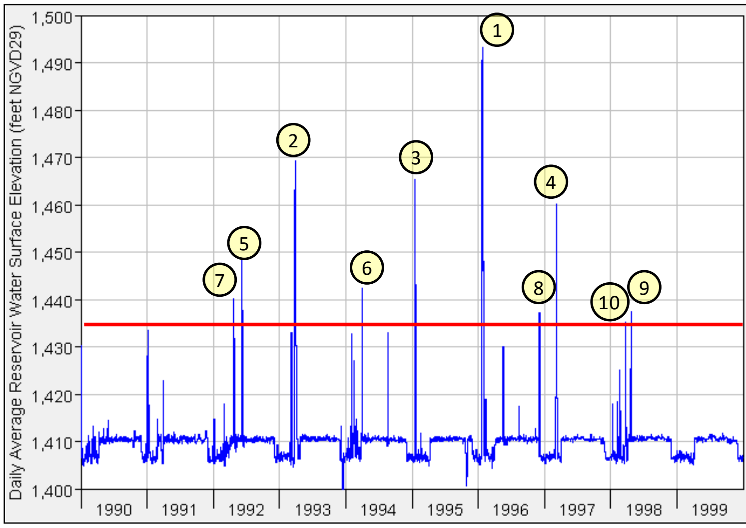


Figure B-1-14.—Exceedance probability relationship.

analysis can be applied to the period of record data to improve the exceedance probability estimate for frequent events. A threshold is selected and all independent events above the threshold are extracted from the data. This accounts for the possibility of multiple statistically independent floods occurring within a single year.

The resulting data is sorted in descending order and ranked from 1 to n. The AEP for each data value is computed using a plotting position. An example of the approach is presented on figure B-1-15.



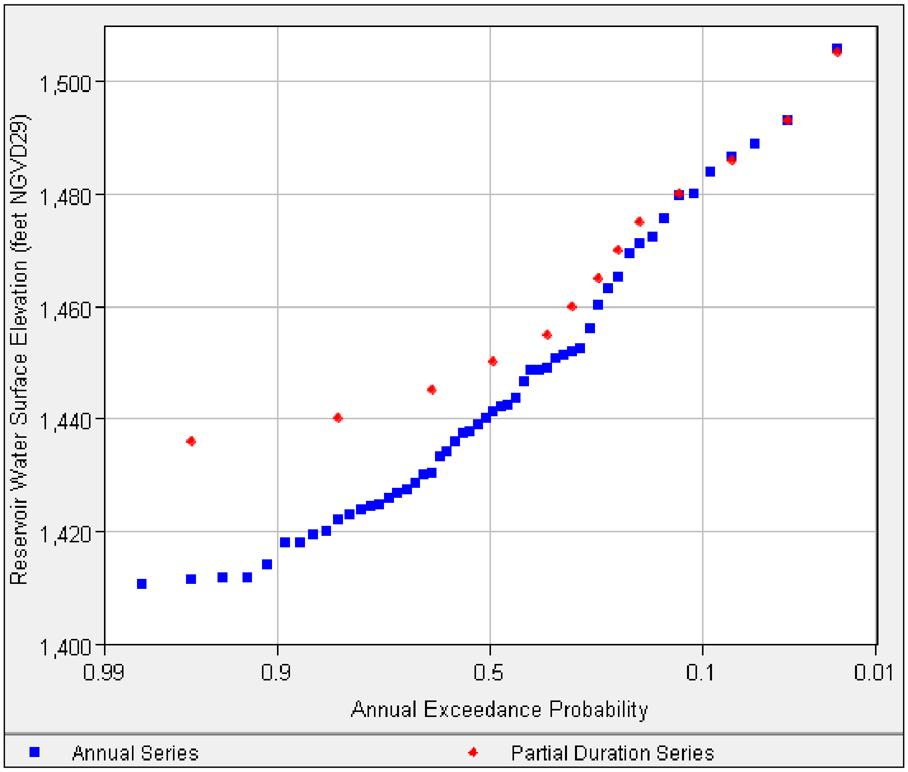
Period of Analysis (M=10 Years)		
Threshold = 1435 feet		
Elevation	Rank (n)	AEP
1493	1	0.09
1469.2	2	0.18
1465.2	3	0.27
1460.1	4	0.36
1448.4	5	0.45
1442.3	6	0.55
1440	7	0.64
1437.2	8	0.73
1437	9	0.82
1435.2	10	0.91

Figure B-1-15.—Partial duration series.

Figure B-1-16 illustrates a situation in which ignoring the partial duration series approach can significantly under represent the magnitude of frequent flood events. A reservoir stage of about 1,440 feet would be expected to occur about once each year on average based on historic observations and the partial duration series analysis. The annual series analysis would indicate a much less frequent (and incorrect) recurrence interval of about once every two years for the 1,440 feet stage.

B-1.10.2.4 Extrapolation

The range of frequency represented by the period of record AEP relationship is constrained by the length of the period of analysis. In most cases, this is an insufficient range to support a dam or levee safety risk analysis and extrapolation of the relationship is needed. Exceedance probability relationships can be extrapolated based on methods described earlier in this chapter.



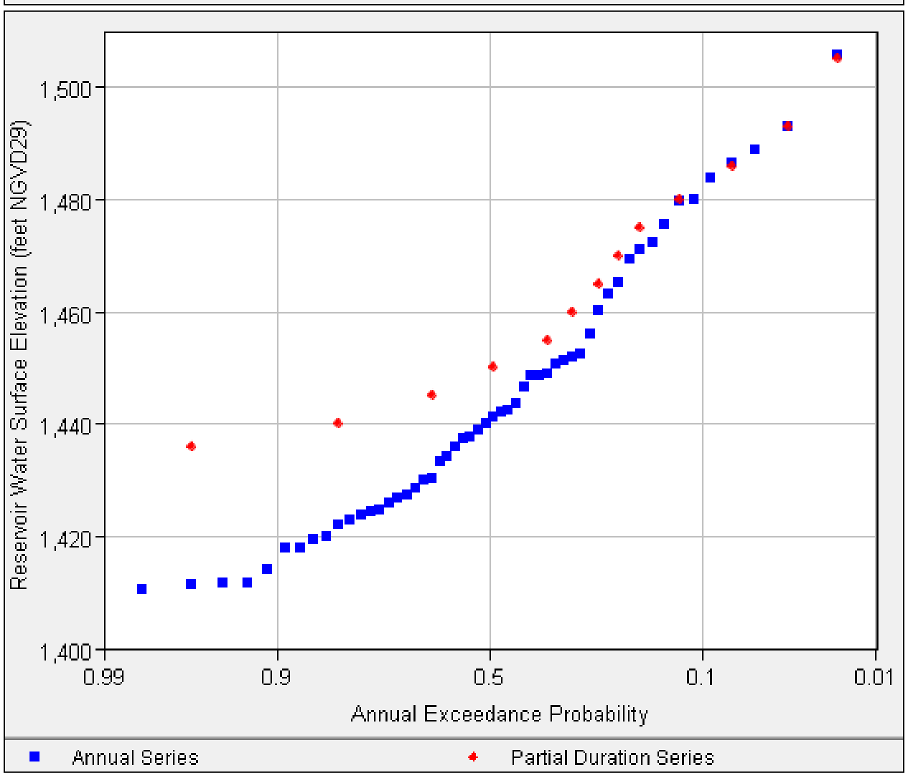


Figure B-1-16.—Comparison between annual and partial duration series.

B-1.10.2.5 Exceedance Duration

When a non-flood event (e.g. seismic) imparts a load on a dam or levee, the risk analyst needs to consider the coincident hydraulic load conditions (typically water surface stage) that can exist when the non-flood event occurs. The combination of the load imparted by the non-flood event and the coincident hydraulic load are then considered jointly in the development of other event tree inputs (e.g., system response functions). It is important to recognize that the coincident water surface stage is a random variable in the risk analysis. The risk analyst needs to estimate a reasonable range of possible coincident water surfaces stages along with their associated conditional probabilities [e.g., P(Stage|Earthquake)] for inclusion in the event tree. This can be accomplished using an exceedance duration relationship which characterizes the percentage of time that a random variable (e.g., water surface stage) exceeds a specified value. It is important to understand that an exceedance duration relationship is not a true probability distribution for water surface stage. It cannot be used to obtain an annual probability. The exceedance duration relationship is used to infer the conditional probability of obtaining a value (e.g., water surface stage) coincident with another independent non-flood event (e.g., seismic).

An annual exceedance duration relationship is usually sufficient; however, exceedance duration relationships can also be developed conditional on a particular time period (e.g. monthly or seasonal). This is not typical for most dam or levee safety risk analysis. An example where it might be needed would be when winds associated with seasonal hurricane events are combined with a coincident water surface stage to produce a wave loading on the dam or levee.

B-1.10.2.6 Period of Record Analysis

The first step in developing a stage duration relationship involves collecting, assembling, and reviewing the period of record data. This process is similar to that used for developing exceedance probability relationships. The reader is referred to the exceedance probability section of this chapter for more information on data acquisition and review. An example data set showing daily average reservoir stages for a dam is presented on figure B-1-17. This is the same data set that was used for the exceedance probability example with corrections having already being made for the missing and erroneous data.

Once data quality issues have been addressed, development of the duration relationship can proceed. The second step involves calculation of the duration relationship. A period of analysis is selected based on the nature of the data and the needs of the risk analysis. A minimum period of 10 years is recommended to provide a reasonable estimate of the duration relationship for duration values greater than about 0.1 percent. Longer periods of analysis should be used if data is readily available and the data is consistent with the operating conditions assumed for the purposes of the risk analysis. For this example, the period from

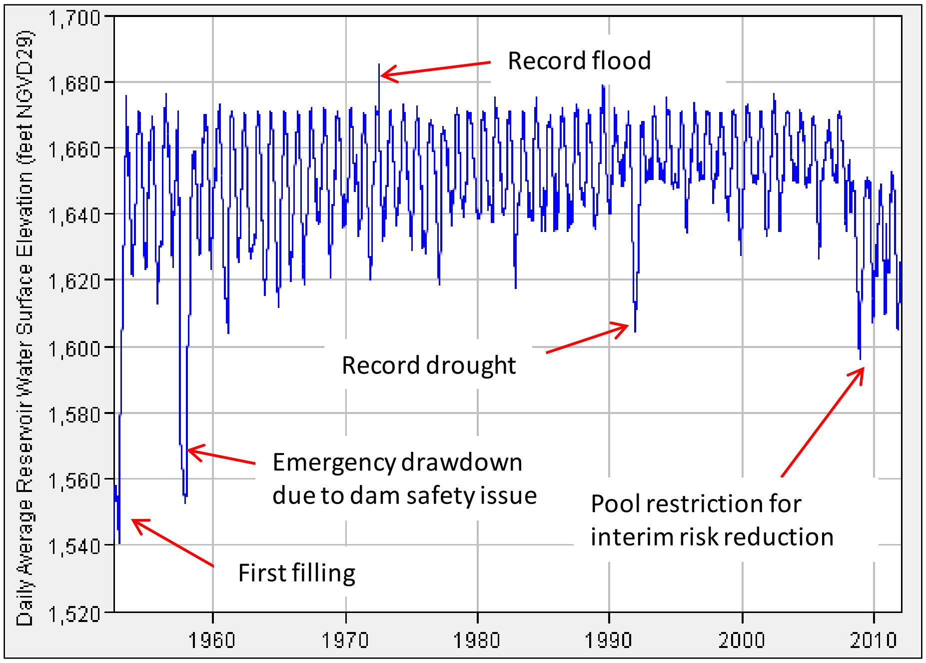


Figure B-1-17.—Daily average reservoir stage data.

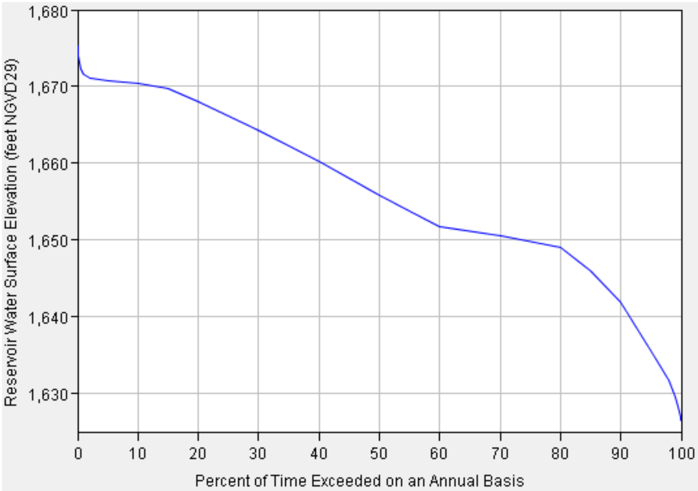
1997 through 2006 has been selected as being representative of normal operation in accordance with the authorized water control plan. The duration relationship is then computed by sorting the data values for the adopted period of analysis in descending order, ranking the sorted data values from 1 to n, and computing the percent of time exceeded for each data value using the following equation where M is the rank and n is the total number of data values.

A binning approach can also be used to develop the duration relationship from the data (USACE 1996). The computations needed to develop duration relationship can be accomplished using a spreadsheet. USACE recommends using either the HEC-SSP or HEC-DSSVue software packages (http://www.hec.usace.army.mil).

The resulting duration relationship for the sample data set is presented graphically on figure B-1-18 with a tabulation of the duration values.

B-1.10.2.7 Extrapolation

Duration relationships may need to be extrapolated in cases where the period of record is too short, and/or the risk associated with non-flood loading events is significant due to high consequences or other factors. This can be accomplished by routing representative discharge hydrographs for a range of frequency-based inflow volumes or by performing a stochastic simulation. The resulting synthetic stage hydrographs can be analyzed to infer a duration relationship.



Percent of Time Exceeded	Reservoir Water Surface Elevation (feet NGVD29)
0.1	1675.4
0.2	1673.9
0.5	1672.4
1	1671.6
2	1671.1
5	1670.7
10	1670.4
15	1669.8
20	1668.1
30	1664.3
40	1660.2
50	1655.7
60	1651.7
70	1650.5
80	1649
85	1646
90	1641.9
95	1635.5
98	1631.7
99	1629.4
99.5	1628.4
99.8	1627
99.9	1626.4

Figure B-1-18.—Example duration relationship.

B-1.11 References

Bahls, V.S. and Holman, K.D. 2014. Climate Change in Hydrologic Hazard Analyses: Friant Dam Pilot Study – Part I: Hydrometeorological Model Inputs, Bureau of Reclamation, Denver, Colorado.

Baker, V.R. 1987. "Paleoflood Hydrology and Extraordinary Flood Events," *Journal of Hydrology*, Vol. 96, Nos. 1-4, pp. 79-99.

Bureau of Reclamation (Reclamation). 1999. A Framework for Characterizing Extreme Floods for Dam Safety Risk Assessment, prepared by Utah State University and the Bureau of Reclamation, Denver, Colorado, 67 p.

_____. 2011. Interim Public Protection Guidelines

_____. 2013. Chapter 2: Hydrologic Considerations. Design Standards 14, Appurtenant Structures for Dams (Spillway and Outlet Works) Design Standards, Final, Bureau of Reclamation, Denver, Colorado. November 2013.

Cohn, T.A., W.L. Lane, and W.G. Baier. 1997. "An Algorithm for Computing Moments-Based Flood Quantile Estimates When Historical Information is Available," *Water Resources Research*, Vol. 33, No. 9, pp. 2089-2096.

Cohn, T.A., W.L. Lane, and J.R. Stedinger. 2001. Confidence Intervals for Expected Moments Algorithm Flood Quantile Estimates: *Water Resources Research*, Vol. 37, No. 6, pp. 1695–1706.

Cudworth, A.G., Jr. 1989. Flood Hydrology Manual, A Water Resources Technical Publication, Bureau of Reclamation, Denver, Colorado.

England, J.F. Jr. and Stedinger, J.R. 2017. Peer Review of TVA Probabilistic Flood Hazard Approach, Report RMC-TR-2017-06, United States Army Corps of Engineers Risk Management Center, Lakewood, Colorado, 18 p.

England, J.F. Jr., T.A. Cohn, B. Faber, J.R. Stedinger, W.O. Thomas, Jr., A.G. Veilleux, J.E. Kiang, and R.R. Mason Jr. 2018. Guidelines for Determining Flood Flow Frequency--Bulletin 17C, U.S. Geological Survey Techniques and Methods, Book 4, Chapter B5, 148 p.

England, J.F. Jr., J.E. Klawon, R.E. Klinger, and T.R. Bauer. 2006. Flood Hazard Study, Pueblo Dam, Colorado, Final Report, Bureau of Reclamation, Denver, Colorado, 160 p. and seven appendices, June 2006.

Federal Emergency Management Agency (FEMA). 2013. Federal Guidelines for Dam Safety: Selecting and Accommodating Inflow Design Floods for Dams, FEMA P-94, National Dam Safety Program, Mitigation Directorate, 38 p. August 2013.

Federal Energy Regulatory Commission. 2014. Probabilistic Flood Hazard Analysis, Chapter R19, FERC Engineering Guidelines, Risk-Informed Decision Making.

_____. 2015. Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 2 – Selecting and Accommodating Inflow Design Floods for Dams, FERC, Washington DC.

Federal Energy Regulatory Commission. 2016. Risk-Informed Decision Making, Chapter 2, Risk Analysis, Version 4.1. March 2016.

Helsel, D.M. and R.M. Hirsch. 2002. Statistical Methods in Water Resources, U.S. Geological Survey Techniques of Water-Resources Investigations Book 4, Chapter A3, 522 p.

Holman, K.D. and V.S. Bahls . 2015. Incorporating Climate Change into Comprehensive Review Studies, Pilot Study Methodology Report, Technical Memorandum 8250-2015-001, Bureau of Reclamation, Denver, Colorado.

Hosking, J.R.M. and J.R. Wallis. 1997. Regional Frequency Analysis - An Approach Based on L-moments, Cambridge University Press, New York.

House, P.K., R.H. Webb, V.R. Baker, and D.R. Levish. 2002. "Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology," *Journal of Applied Geophysics at ScienceDirect.com*, Series 5.

Kelson, K.I., B.M. Hall, R. Sasaki, C.M. Leonard, and S. Potts. 2017. Paleoflood Analysis for Ball Mountain Dam, Report RMC-TR-2017-08, United States Army Corps of Engineers Risk Management Center, Lakewood, Colorado, 74 p.

Kelson, K.I., B.M. Hall, G.S. Walters, A.M. Duren, and C.M. Leonard. 2018. Paleoflood Analysis for Lookout Point Dam, Report RMC-TR-2018-02, United States Army Corps of Engineers, Risk Management Center, Lakewood, Colorado.

MGS Engineering Consultants, Inc. (MGS). 2005. Stochastic Modeling of Extreme Floods on the American River at Folsom Dam, Flood Frequency Curve Extension, MGS Engineering Consultants, Inc., prepared for the United States Army Corps of Engineers Hydrologic Engineering Center, Research Document. RD-48.

_____. 2009. General Storm Stochastic Event Flood Model (SEFM) – Technical Support Manual, prepared for the Bureau of Reclamation, Flood Hydrology Group, Denver, Colorado.

Merz, R., Bloschl, G. 2008a. Flood frequency hydrology: 1, Temporal, spatial, and causal expansion of information, *Water Resources Research* 44, W08432.
http://dx.doi.org/10.1029/2007WR006744

Merz, R. and G. Bloschl. 2008b. Flood frequency hydrology: 2, Combining data evidence, *Water Resources Research* 44, W08433.
http://dx.doi.org/10.1029/2007WR006745

Mosley, M.P. and A.I. McKerchar. 1993. Handbook of Hydrology: Chapter 8 - Streamflow, D.R. Maidment (ed.), McGraw-Hill, New York, New York.

Nathan, R.J and Weinmann, P.E. 2016. Estimation of Very Rare to Extreme Floods, Book 8 in Australian Rainfall and Runoff – A Guide to Flood Estimation, Commonwealth of Australia.
http://arr.ga.gov.au

National Research Council (NRC). 1994. Estimating Bounds on Extreme Precipitation Events: A brief assessment, National Academy Press, Washington, DC., 29 p.

_____. 1988. Estimating Probabilities of Extreme Floods: Methods and recommended research, National Academy Press, Washington, DC., 141 p.

Nicholson, T.J. and W. Reed. 2013. Proceedings of the Workshop on Probabilistic Flood Hazard Assessment (PFHA), U.S. NRC Headquarters, Rockville, Maryland, January 29-31, 2013, NUREG/CP-0302.

Novembre, N.J., Holman, K.D., and Bahls, V.S. 2015. Climate Change in Hydrologic Hazard Analyses: Friant Dam Pilot Study – Part II: Using the SEFM with Climate-Adjusted Hydrometeorological Inputs, Technical Memorandum 8250-2015-005, Bureau of Reclamation, Denver, Colorado, 61 p.

Novembre, N.J., et al. 2012. Altus Dam Hydrologic Hazard and Reservoir Routing for Corrective Action Study, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado.

Nuclear Regulatory Commission (NRC). 2013. Workshop on Probabilistic Flood Hazard Assessment, Rockville, Maryland, January 29-31, 2013.

O'Connell, D.R.H., Ostenaa, D.A., Levish, D.R. and Klinger, R.E. 2002. Bayesian flood frequency analysis with paleohydrologic bound data, *Water Resources Research* 38(5), doi:10.1029/2000WR000028, 14 p.

Pearce, J.T. 2017 Limited Geomorphic Investigation of Paleoflooding for Cherry Creek Dam, Report RMC-TR-2017-10, United States Army Corps of Engineers Risk Management Center, Lakewood, Colorado, 26 p.

Salas, J.D. 1993. Handbook of Hydrology: Chapter 19 – Analysis and Modeling of Hydrologic Time Series, D.R. Maidment, (ed.), McGraw-Hill, New York, New York.

Schaefer, M. and B. Barker. 2002. "Stochastic Event Flood Model (SEFM)," Chapter 20 *in* V.P. Singh and D. Frevert (editors), Mathematical Models of Small Watershed Hydrology and Applications, 950, Water Resources Publications, Colorado, USA.

Smith, C.H. 2018. Reservoir Frequency Analysis - RMC-RFA, Software and User's Manual, Version 1.1.0, Risk Management Center, United States Army Corps of Engineers, Lakewood, Colorado.

Smith, H., M. Bartles, and M. Fleming. 2018. Hydrologic Hazard Methodology for Semi-Quantitative Risk Assessments, An Inflow Volume-Based Approach to Estimating Stage-Frequency for Dams, RMC-TR-2018-03, Risk Management Center, United States Army Corps of Engineers, Lakewood, Colorado, 132 p.

Swain, R.E., J.F. England, Jr., K.L. Bullard, and D.A. Raff. 2004. Hydrologic hazard curve estimating procedures, Dam Safety Research Program Research Report DSO-04-08, U.S. Department of Interior, Bureau of Reclamation, Denver, Colorado, 79 p.

_____. 2006. Guidelines for Evaluating Hydrologic Hazards, Bureau of Reclamation, Denver, Colorado, 83 p.

U.S. Army Corps of Engineers (USACE). 1982. Mixed-Population Frequency Analysis. Technical Report TD-17, United States Army Corps of Engineers, Hydrologic Engineering Center, 43 p.

_____. 1996. Risk-Based Analysis for Flood Damage Reduction Studies, Engineering Manual 1110-2-1619.

U.S. Army Corps of Engineers. 2014. Safety of Dams – Policy and Procedures – ER 1110-2-1156, Washington, DC.

_____. 2015. Hydrologic Loadings Methodology for Risk Assessment, USACE, Davis, California.

World Meteorological Organization. 2009. Manual on Estimation of Probable Maximum Precipitation (PMP), WMO No. 1045, Geneva, Switzerland.

_____. 2016. Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects, USACE *Engineering and Construction Bulletin No. 2016-25*.

B-1.11.1 Other Resources

Bureau of Reclamation. 2002. Flood Hazard Analysis - Folsom Dam, Central Valley Project, California. Bureau of Reclamation, Denver, Colorado, 128 p. and 4 appendices. January 2002.

Bureau of Reclamation (Reclamation). 2014. Climate Change Adaptation Strategy. Department of the Interior, Bureau of Reclamation, Washington, DC, 50 p.

England, J.F. Jr. 2003. Probabilistic Extreme Flood Hydrographs that Use Paleoflood Data for Dam Safety Applications, Dam Safety Research Report DSO-03-03, Bureau of Reclamation, Denver, Colorado, 29 p. January 2003.

England, J.F. Jr., Julien, P.Y., and Velleux, M.L. 2014. Physically-Based Extreme Flood Frequency Analysis using Stochastic Storm Transposition and Paleoflood Data on Large Watersheds, *Journal of Hydro*logy 510, doi:10.1016/j.jhydrol.2013.12.021, pp. 228-245.

England, J.F. Jr., M.L. Velleux, and P.Y. Julien. 2007. "Two-Dimensional Simulations of Extreme Floods on a Large Watershed," *Journal of Hydrology*, Vol. 347, Nos. 1-2.

Levish, D.R., J.F. England, Jr., J.E. Klawon, and D.R.H. O'Connell. 2003. Flood Hazard Analysis for Seminoe and Glendo Dams, Kendrick and North Platte Projects, Wyoming, Final Report, Bureau of Reclamation, Denver, Colorado, 126 p. and two appendices. November 2003.

Schaefer, M.G. 1990. Regional analysis of precipitation annual maxima in Washington State, *Water Resources Research* 26(1), pp. 119-131.

Schaefer, M.G. 1994. PMP and Other Extreme Storms: Concepts and Probabilities, Association of State Dam Safety Officials Annual Conference, Boston, Massachusetts, Supplement, pp. 61-73. September 11-14.

Searcy, J.K. 1959. Flow-Duration Curves. Manual of Hydrology: Part 2. Low-Flow Techniques. U.S. Geological Survey Water-Supply Paper 1542-A, 33 p.

Smith, C.H., G. Karlovits, D. Moses, and A. Nelson. 2015. Herbert Hoover Dike, Hydrologic Hazard Assessment. Prepared for the United States Army Corps of Engineers, Jacksonville District, by the USACE, Risk Management Center, Lakewood, Colorado.

Stedinger, J.R., R.M. Vogel, and E. Foufoula-Georgiou. 1993. Frequency Analysis of Extreme Events, in Handbook of Hydrology, McGraw-Hill, New York, New York.

World Meteorological Organization. 2016. HEC-SSP Statistical Software Package, User's Manual, Version 2.1, CPD-86, Hydrologic Engineering Center, Davis, California.

United States Army Corps of Engineers. 1991. Inflow Design Floods for Dams and Reservoirs, Engineering Report 1110-8-2(FR).

Vogel, R.M. and N.M. Fennessey. 1994. "Flow Duration Curves I: New Interpretation and Confidence Intervals," *Water Resources Research*, Vol. 120, No. 4, pp. 485-504.

Wright, J.M., V. Sankovich, J. Niehaus, N. Novembre, R.J. Caldwell, R. Swain, and J. England. 2013. Friant Dam Hydrologic Hazard for Issue Evaluation, Bureau of Reclamation, Flood Hydrology and Consequences Group, 225 p. September 2013.