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Technical Basis for Extending Flood Frequency Curves Beyond Current Consensus Limits

Date Published: February 2022

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Research Information Letter
Office of Nuclear Regulatory Research

United States Nuclear Regulatory Commission
Protecting People and the Environment

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ABSTRACT

This work is part of the Nuclear Regulatory Commission's (NRC) Probabilistic Flood Hazard Assessment (PFHA) research plan to support development of a risk-informed approach for addressing flood hazards at nuclear facilities. The intent is to provide information the NRC can use to develop guidance for developing extreme flood frequency estimates beyond the current consensus limits (Annual Exceedance Probabilities (AEPs) less than 1×10^{-4}) from the context of the Bureau of Reclamation (Reclamation).

Historically, deterministically derived conservative estimates have been used in nuclear regulation in the U.S., although these estimates are not explicitly quantified physically or probabilistically. For facilities in riverine environments, the design-basis flood has typically been the Probable Maximum Flood, which theoretically approaches the limits of physical plausibility. Probabilistic treatment of flood hazard phenomena can provide quantitative estimates (in terms of probability or frequency of exceedance) and thus contribute to the risk-informed assessment of flooding hazards.

Reclamation, the owner of approximately 370 dams and dikes in the Western U.S., pioneered conducting flood frequency analyses to support dam safety risk-informed decision-making. For Reclamation dam safety risk assessments, flood estimates are needed for AEPs of 1 in 10^4 and down to as low as 1 in 10^8. Reclamation has published methodology and guidance to develop hydrologic hazard estimates over the past quarter of a century. The primary purpose of these published guidelines, procedures, and standards was to provide state-of-the-practice methodology for developing hydrologic hazard curves (and supporting flood hydrology information) to be used for evaluating facilities, prioritizing dam safety modifications, and supporting planning and design decisions.

From a hydrologic perspective, risk estimates require 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 safety risk analysis is a hydrologic hazard curve (HHC) that is developed from a hydrologic hazard analysis (HHA). Hydrologic hazard curves combine peak flow, water surface elevation, and volume probability relationships plotted with respect to their AEPs. Information derived in HHAs, including HHCs and associated flow and stage frequency hydrographs, can be used to assess the risk of potential hydrologic-related failure modes.

The objective of the research project is to collect, document and review technical methods for PFHA developed and/or used by Reclamation for dam safety risk-informed decision-making that may be useful for NRC in its efforts to develop risk-based riverine flood hazard assessment guidance. This project is part of the NRC's wider PFHA research program to support development of a risk-informed approach for addressing flood hazards at nuclear facilities. The primary task of this research is to provide input for development of technical guidance to extend frequency analysis beyond current consensus limits for rainfall and riverine flooding applications.

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EXECUTIVE SUMMARY

The purpose of this document is to provide the U.S. NRC an overview of technical methods for probabilistic flood hazard assessment (PFHA) developed and/or used by Reclamation for dam safety risk-informed decision-making support. The information provided in this document is not intended for technical guidance but rather a summary and review of the technical methods Reclamation has used for assessing hydrologic risk on past projects. This document also provides excerpts from five Reclamation hydrologic hazard studies that illustrate the application of the technical methods used to estimate the PFHA.

Reclamation has developed an approach toward developing hydrologic hazard curves for use in evaluating dam safety issues. The procedure relies on extracting information from various sources that include existing studies, hydrometeorological data, historic data, and pre-historic (paleo) data. The extracted information, in turn, is used to develop probabilistic hydrologic hazard curves that can be used for assessing the risk for high-hazard structures such as dams and levees. Although the methods applied by Reclamation allow the possibility of developing floods with peak flows and volumes exceeding the probable maximum flood (PMF), Reclamation considers the PMF as the upper limit of hydrologic risk [1].

Reclamation's procedure for developing hydrologic hazard curves considers the dam safety decision criteria, potential dam failure mode, dam characteristics, available hydrometeorological data, possible analysis techniques, resources available for analysis, and acceptable level of uncertainty. Dam safety decision criteria determine the probabilistic range of floods needed to address hydrologic issues. The potential dam failure mode and dam characteristics impact the type of hydrologic information needed to assess the problem. Reclamation considers a tolerable level of uncertainty when selecting specific elements used for analysis of hydrologic hazards. If justified, efforts to reduce uncertainty and increase analysis confidence may include additional data collection and using more sophisticated analysis techniques [1].

The amount of effort Reclamation uses for analyzing a hydrologic hazard depends on the nature of the problem and the potential cost of the solution. A staged approach toward evaluating a hydrologic safety issue is common. Initially, little effort is expended to determine the magnitude of a hydrologic hazard. Reclamation attempts to make use of all available hydrologic studies for the site of interest. Often the PMF and initial flood frequency study are the only available hydrologic studies available. Other hydrologic studies, if available, are used to provide an overall initial assessment of hydrologic risk. Such studies are periodically used to characterize the hydrologic risk as part of Reclamation's Comprehensive Facility Review (CFR) process. If the hydrologic risk, assessed during the CFR, exceeds Reclamation guidelines, additional analysis may be required [1].

For situations requiring additional hydrologic analysis addressing hydrologic issues exceeding Reclamation guidelines, Reclamation's goal is to achieve a balance between the amount of hydrologic analysis needed to address the issues and the level of effort required to conduct the study. As hydrologic hazard studies become more detailed, the results should become more precise and contain less uncertainty [1].

ABBREVIATIONS AND ACRONYMS

AEP	Annual Exceedence Probability
ARR	Australian Rainfall Runoff
BIA	Bureau of Indian Affairs
CAS	Corrective Action Studies
CDEC	California Data Exchange Center
CR	Comprehensive Review
CFR	Comprehensive Facility Review
EMA	Expected Moments Algorithm
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System (model)
HEC-RAS	Hydrologic Engineering Center – River Analysis System (model)
HEC-ResSIM	Hydrologic Engineering Center – Reservoir Simulation (model)
HHA	Hydrologic hazard analysis
HMR	Hydrometeorolgical Report
GEV	Generalized Extreme Value (distribution)
GIS	Geographic Information System
GHCN	Global Historial Climatology Network
IACWD	Interagency Advisory Committee on Water Data
IDF	Inflow Design Flood
IE	Issue Evaluation
LN-2	2-Parameter Log-Normal (distribution)
LP III	Log Pearson III (distribution)
MOVE	Maintenance of Variation Extension
NCDC	National Climatic and Data Center (now National Centers for Environmental Information)
NOAA	The National Oceanic and Atmospheric Administration
NRC	U.S. Nuclear Regulatory Commission
NRCS	Natural Resource Conservation Service (formerly Soil Conservation Service)
NSS	National Streamflow Statistics
NWS	National Weather Service (formerly U.S. Weather Bureau)
OSL	Optically-Stimulated Luminescence

PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
Reclamation	Bureau of Reclamation
SAC-SMA	Sacramento Soil Moisture Accounting (model)
SCS	Soil Conservation Service (now Natural Resource Conservation Service)
SEFM	Stochastic Event Flood Model
SNOTEL	Snow Telemetry (data collection network)
SRH-2D	Sedimentation and River Hydraulics – Two-Dimensional (model)
SST	Stochastic storm transpostion
SWE	Snow Water Equivalent
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Society
USWB	U.S. Weather Bureau (now National Weather Service)
WMO	World Meteorolgical Organization
WRF	Weather Research and Forecasting (model)

1 INTRODUCTION

1.1 Addressing Probabilistic Flood Hazard within the Framework of U.S. Nuclear Power Regulation

The U.S. NRC regulatory basis governing flood hazards assessment is provided in the appropriate sections of 10 CFR Part 50, Part 52 and Part 100. The regulatory criterion for protection of structures, systems, and components (SSCs) important to safety against natural phenomena is provided in 10 CFR Part 50 Appendix A, General Design Criterion (GDC) 2:

"Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and (3) the importance of the safety functions to be performed."

Historically, deterministically derived conservative estimates (e.g., the probable maximum estimates of precipitation, flood, hurricane, windstorm, and storm surge) have been used to provide the sufficient margin called for in GDC-2, although the degree of conservatism in these estimates is not explicitly quantified in either a physical sense or probabilistically. For facilities in riverine environments, the design-basis flood has typically been the Probable Maximum Flood (PMF), which theoretically approaches the limits of physical plausibility [2]. Probabilistic treatment of flood hazard phenomena can provide quantitative estimates of conservatism (in terms of probability or frequency of exceedance) and thus contribute to the risk-informed assessment of flooding hazards.

The objective of this work is to collect, document and review technical methods for probabilistic flood hazard assessment (PFHA) developed and/or used by Reclamation for dam safety risk-informed decision-making that may be useful for NRC in its efforts to develop risk-based riverine flood hazard assessment guidance. This project is part of the NRC's wider PFHA research program to support development of a risk-informed approach for addressing flood hazards at nuclear facilities. The primary task of this research is to provide input for development of technical guidance to extend frequency analysis beyond current consensus limits for rainfall and riverine flooding applications (Annual Exceedance Probabilities (AEPs) less than 1×10^{-4}).

For risk assessment and design, a hydrologic load is a watershed response from a climatic event which causes stress on the system in question. This watershed response is commonly analyzed as a time series of inflow to a system. The fundamental goal for the analyst or designer is determining the ultimate stress a system can handle before failure. Although the watershed response is independent from the system in question, the stress endured by the system is not. For this reason, the hydrologic load is sometimes expressed as a system response combining the watershed's climatic response and the effects it has on the system in question. An example of such a response might be a maximum reservoir elevation during a climatic event such as seasonal snowmelt runoff. Other examples include maximum inflow or outflow, and exceedance durations of a specified reservoir elevation.

The probability of a hydrologic load is needed for use with a risk-informed approach. Although the probability of the watershed response is independent, if the load is expressed as a system response, the probability may depend on other factors. The probability of a hydrologic load must include not only the probability of the watershed response but also the probability of a system response given the watershed response.

1.2 Reclamation's Use of Probabilistic Flood Hazard Assessment

The Bureau of Reclamation (Reclamation) is responsible for approximately 370 high and significant hazard dams and dikes that constitute a significant component of the water resources infrastructure of the Western U.S. As the owner of these facilities, Reclamation is committed to providing the public and the environment with adequate protection from the risks which are inherent to collecting and storing large volumes of water for subsequent distribution and/or release [3]. Pioneering the use of risk-informed decision-making for dam safety in the U.S., Reclamation has used risk practices to assess the safety of dams, recommend safety improvements, and prioritize capital improvements since 1995.

From a hydrologic perspective, risk estimates require 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 safety risk analysis is a hydrologic hazard curve (HHC) that is developed from a hydrologic hazard analysis (HHA). Reclamation hydrologic hazard curves combine peak flow, water surface elevation, and volume probability relationships plotted with respect to their AEPs. Information derived in HHAs, including HHCs and associated flow and stage frequency hydrographs, can be used to assess the risk of potential hydrologic-related failure modes including overtopping, internal erosion under various reservoir levels, erosion in earthen spillways, and overstressing of structural components.

The amount of data and flood experience for any site or region constrain the range of the floods to which AEPs can be assigned based solely on data. In general, the scientific range to which the flood frequency relationship can be credibly extended, based upon any characteristics of the data and the record length, will fall short of the PMF for a site. However, there is a need in risk assessment to determine the probability of occurrence of very large floods with very rare AEPs, and therefore flood frequency relationships are extended to cover the full range of AEPs needed for risk assessment. The sources of information used for flood hazard analyses include streamflow and precipitation records and paleoflood data.

When evaluating hydrologic hazards, a systematic means of developing flood hazard relationships is needed for risk-based assessments to determine hydrologic adequacy for Reclamation dams [1]. The nature of the potential failure mode and characteristics of the dam and reservoir dictate the type of hydrologic information needed. The selected approach should also consider available hydrologic data, potential analysis techniques, available resources for analysis, and an acceptable level of uncertainty. For some projects, only a peak-discharge frequency analysis may be required; while for others, flood volumes and hydrographs may be necessary. The goal of any hydrologic analysis is to provide hydrologic information to the necessary level (i.e. minimum effort and cost) to make effective dam safety decisions.

1.3 Hydrologic Hazard Study Levels

Hydrologic hazard studies at Reclamation are conducted at various levels of complexity and effort, dependent on flood information available, type of risk assessment or dam safety decision being made, and budget and schedule considerations. Hydrologic hazard information is generally required during Reclamation's four levels of the dam safety program process. These four levels include the Comprehensive Review (CR), the Issue Evaluation (IE), the Corrective Action Study (CAS), and the Final Design (FD). These levels are scalable (such that successively more sophisticated approaches can build upon information from lower-level estimates) and generally require increased data collection and more extensive analysis for each progressive level. Most projects do not progress through each level because the process is intended to address dam safety deficiencies, and many projects either do not have deficiencies or the safety issues can be resolved without a need for structural modifications. The decision to proceed to the next level of risk assessment considers how sensitive the total project risk and dam safety decision is to hydrologic loadings.

Reclamation performs CRs on all its high hazard facilities once every 8 years to identify risks and prioritize further work (screening level assessment). This is the minimum amount of effort used to determine the hydrologic load for a facility and is often limited to 15 days. The method usually consists of assimilating any available local or regional paleoflood data and combining it with local or regional peak discharge data to develop a peak discharge frequency curve. Frequency hydrographs are often developed by scaling an existing hydrograph (usually a deterministic Inflow Design Flood (IDF) or PMF) such that peak discharge is associated with specific exceedance probabilities defined in the discharge frequency curve. It is determined in the CR risk assessment whether additional hydrologic studies are required to make decisions during subsequent levels of the process.

If the CR-level hydrologic loadings suggest that flood risks at a facility are too high, better estimates of flood risk (and associated uncertainties in these estimates) may be necessary to confirm and better understand identified issues. IEs focus on improving risk estimates – this generally entails additional data collection, quantifying uncertainty, and presenting hydrologic loadings as a range of values (often broken down into quantiles). These studies typically use multiple statistical approaches as well as physical-based modeling methods to determine the hydrologic load. An IE-level study will refine a larger data set for hydrologic analysis in an effort to extend the period of record and extrapolate to rarer events while quantifying uncertainty. Such data typically includes regional precipitation, peak discharge, and storm patterns. A moderate effort between 50 and 70 days typically produces both a statistical model of peak discharge and a physical based rainfall-runoff model that is AEP-neutral [3]. (In an AEP-neutral model, parameters are adjusted such that the AEP of the 1 in Y rainfall amount produces a flood with a 1 in Y AEP) More sophisticated IE studies typically develop a stochastic rainfall-runoff model in addition to a statistical model. At the conclusion of an IE, decision-makers determine whether or not actions are required to reduce risk at the dam [4].

When it is determined that an action is necessary to reduce risk at a facility, a CAS is conducted to formulate and evaluate risk reduction alternatives, which can include structural modifications or change in reservoir operations. The level of effort (moderate or high) is determined by the expected benefits the hydrologic CAS might deliver. Data is collected and analyzed to the extent necessary to develop details of identified alternatives, estimate project costs, and provide sufficient information to allow decision-makers to select and justify the proper course of action. The baseline risk analysis is updated to show the risk reduction potential of each of the developed alternatives [4]. The final alternative is selected by comparing cost-benefits (risk-reduction per cost) of viable alternatives.

If the selected alternative involves structural modification, additional data collection and analysis is necessary in FD to improve the design, reduce and refine project costs, and finalize design drawings and specifications [5]. Reclamation uses a risk-based design approach, in which collaboration between the hydrologic loadings analyst and design engineer is critical. This necessitates an iterative process in which the design is modified based on information provided by hydrologic loadings.

There is not a single approach that can be applied in developing hydrologic loads because each facility has different hydrology, available data, and hydrologically controlled potential failure modes. Additionally, the various levels of study for a particular facility often dictate the level of effort required to estimate the hydrologic hazard. The method (or methods) selected should consider climatic and hydrologic parameters, size of drainage basin, effect of any upstream regulation, data availability, and level of confidence needed in the results. The various methods described in this document are summarized by their expected level of effort in Table 1-1.

Table 1-1 Level of study of hydrologic hazard approaches used by Reclamation.

Method Level of Effort (Study Type)	Benefits	Limitations
Graphical Flood Frequency Low (CR, IE, CAS, FD)	Conservative, incorporates paleoflood information	Estimates far beyond credible extrapolation, conservative
EMA/FLDFRQ3 Low (CR, IE, CAS, FD)	Better estimate of uncertainty, incorporates paleoflood information	Estimates often extended beyond credible extrapolation
Australian Rainfall-Runoff Low (CR, IE)	Rarer events, very conservative (pragmatic)	Primarily intended for largely deterministic design use, very conservative
GRADEX Moderate (CR, IE)	Rarer events, conservative	Assumption of all rainfall to runoff, little physically based modeling
Regional Precipitation Frequency Moderate (IE, CAS, FD)	Better estimated of uncertainty, still conservative	Improved estimate of precipitation frequency, limited by AEP neutrality
Stochastic Rainfall-Runoff Modeling High (IE, CAS, FD)	Currently the best estimate of uncertainty, uses information from statistical frequency methods, physical understanding of driving factors/ processes	Extremely rare extrapolation is still uncertain and full range of aleatory variability and epistemic uncertainty is not understood, difficulties calibrating to extreme events

Modified from Guidelines for Evaluating Hydrologic Hazards [1].

Reclamation will typically spend 5-10 days (low level effort) for Comprehensive Reviews and preliminary analyses, and often includes EMA with regional paleoflood information. ARR (frequency PMF) is often used to deal conservatively estimate beyond credible extrapolation. For moderate level efforts, 15-45 days are often used to develop flood frequency estimates in Issue Evaluation, Corrective Action, and Final Design studies (as well as some higher-level Comprehensive Reviews). When the hydrologic risk at a facility is high and/or may require expensive mitigation (i.e., operations, mechanical, construction risk reduction measure alternatives), studies often require extensive time, effort, and cost to produce flood estimates.

1.4 Flood Frequency Extrapolation

Floods can be categorized, according to the Australian Rainfall and Runoff: A Guide to Flood Estimation [6, 7], as rare, very rare, and extreme. These flood categories are shown in Figure 1-1. Rare floods generally encompass events for which direct observations and measurements are available. Very rare floods represent events located in the region between direct observations and the credible range of extrapolation from the data. Extreme floods generally have very small AEPs, which are beyond the credible range of extrapolation but are still needed for dam safety risk assessments.

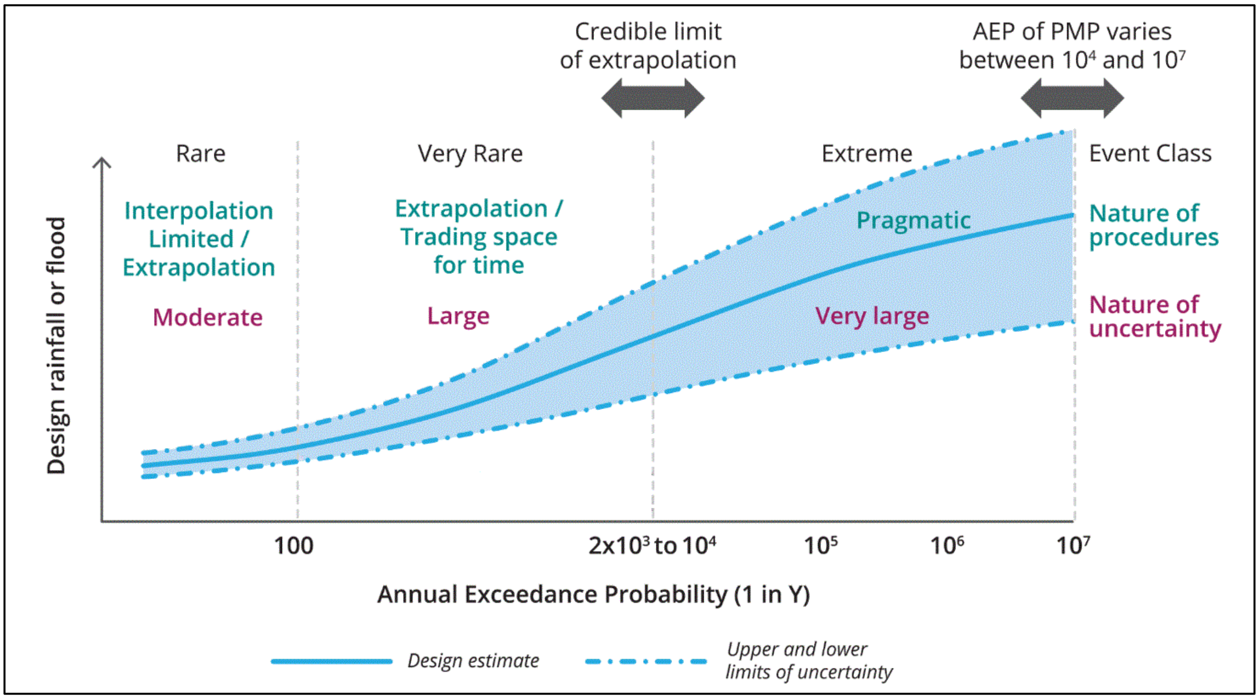

Figure 1-1 Procedures, credible limits of extrapolation, and levels of uncertainty for rare to extreme events as portrayed in Australian Rainfall and Runoff: A Guide to Flood Estimation [6].

To provide flood estimates for a full range of AEPs necessary for dam safety decision-making, it is usually necessary to extrapolate beyond the period of recorded data. 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. Streamflow and reservoir data corresponding to current operations and watershed characteristics should be used in FFAs. In higher level projects requiring more effort, data can be adjusted to represent the current conditions and operations to extend series for entire period of record. The data used in the analysis provide the only basis for verification of the analysis or modeling results, and as such, extensions beyond the data cannot be verified. The greatest gains to be made in providing credible estimates of extreme floods can be achieved by combining regional data from multiple sources. Thus, analysis approaches that pool data and information from regional precipitation, regional streamflow, and regional paleoflood sources should provide the highest assurance of credible characterization of low AEP floods.

For Reclamation dam safety risk assessments, flood estimates are needed for AEPs of 1 in 10^4 and down to as low as 1 in 10^8. Developing credible estimates at these low AEPs generally requires combining data from multiple sources and a regional approach [8]. Table 1-2 lists the different types of data that can be used as a basis for flood frequency estimates and the typical and optimal ranges of credible extrapolation for AEP. In general, the optimal ranges are based on the best combination(s) of data assumed for the Western U.S. Typical ranges are based on the combination(s) of data that are commonly available and analyzed for most sites. However, the limits of extrapolation for an individual site should be individually assessed, determined by evaluating the record length, number of stations in hydrologically homogeneous region, degree of correlation between stations, and other data characteristics which may affect the accuracy of the data [8].

Table 1-2 Data types and extrapolation ranges for flood frequency analysis (Western U.S.).

Type of data used for flood frequency analysis	Range of credible extrapolation for annual exceedance probability	
	Typical	***Optimal***
At-site streamflow data	1 in 100	1 in 500
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

Source: A framework for characterizing extreme floods for dam safety risk assessment [8].

Many factors can affect the equivalent independent record length (in substituting space for time) for the optimal case. For example, gaged streamflow records in the Western U.S. rarely exceed 100 years, and extrapolation beyond twice the length of record, or to about 1 in 200 AEP, is generally not recommended [9]. The optimal range of credible extrapolation for regional streamflow data, considering the number of stations in the region, lengths of record, and degree of independence of these data, is not recommended to exceed 1 in 1,000 AEP [10]. Considering paleoflood data, only floods that have occurred in the past 10,000 to 12,000 years (Holocene Epoch) should be used to develop hydrologic loadings because prior to this period the climate was distinctly different than what it is today. In particular, the controlling meteorological processes and flood mechanisms of extreme events would be different. This climatic constraint indicates that an optimal range for extrapolation from paleoflood data, when combined with at-site gaged data, for a single stream can reasonably be extended to 1 in 10,000 AEP. For regional precipitation data, a similar range is imposed because of the difficulty in collecting sufficient station-years of clearly independent precipitation records in the orographically complex regions of the Western U.S. Combined data sets of regional gaged and regional paleoflood data can be extended to smaller AEPs, perhaps to about 1 in 40,000, in regions with abundant paleoflood data. Analysis approaches that combine all types of data are judged to be capable of providing credible estimates for an AEP range up to about 1 in 100,000 under optimal conditions.

Often, credible extrapolation ranges may be less than optimal. Typical ranges would need to reflect the practical constraints on the equivalent independent record length that apply for a particular location. The ranges of extrapolation should be determined by evaluating the lengths of records, number of stations in a hydrologically homogeneous region, degree of correlation between stations, and other data characteristics that may affect the accuracy of the data.

The amount of data and flood experience for any site or region constrain the range of the floods to which AEPs can be assigned based solely on data. However, flood loadings need to be credibly extended to span the full range of AEPs needed for risk assessment. Therefore, a systematic approach is provided for providing reliable hydrologic hazard curves that can be used for decision making. When developing flood loadings for events rarer than 1 in 10,000, hydrologists and engineers must use their professional knowledge and understanding of hydrologic processes to estimate extreme floods. When peak flows or volumes calculated using probability or statistically based hydrology methods exceed those of the PMF, Reclamation uses the PMF to inform the hydrologic risk estimate. Extrapolation of statistical analyses can become unbounded for flood distributions that exhibit positive skewness; therefore, Reclamation uses the PMF to limit extrapolation to flood discharges that are physically possible.

To understand the potential range of hydrologic loadings, flood frequency relationships include an estimate of the uncertainty around the median estimates. As the AEP decreases, the uncertainty in the estimate increases (see Figure 1-1); and for extreme floods, the uncertainty is large and challenging to quantify. Floods may result from unforeseen and unusual combinations of hydrologic parameters generally not represented in the flood history at a particular location.

1.5 Content and Context

Much of the content in this document originates from published Reclamation methodology and guidance to develop hydrologic hazard estimates, particularly that described in i) *Guidelines for Evaluating Hydrologic Hazards [1]*; ii) *Hydrologic Hazard Curve Estimating Procedures* [3]; and iii) *Chapter 2: Hydrologic Considerations, Design Standards No. 14, Appurtenant Structures for Dams* [5]. For Reclamation, the primary purpose of these published guidelines, procedures, and standards was to provide state-of-the-practice methodology for developing hydrologic hazard curves (and supporting flood hydrology information) to be used for evaluating facilities, prioritizing dam safety modifications, and supporting planning and design decisions.

Table 1-3 Reclamation methodology and guidance to develop hydrologic hazard estimates.

Reclamation Methodology and Guidance Reports
Guidelines for Evaluating Hydrologic Hazards [1]
Hydrologic Hazard Curve Estimating Procedures [3]

Chapter 2: Hydrologic Considerations, Design Standards No. 14, Appurtenant Structures for Dams [5]

Following the introduction, the literature review includes a broad perspective on significant extreme precipitation, flood hydrology, and flood frequency literature relevant for dam safety and nuclear facilities. Included information includes U.S. and international approaches to flood frequency estimation and flood risk assessment from various agencies and academics. The literature review describes approaches to assessing flood hazard including extreme rainfall and flood flow estimation and concludes with summaries of a few Reclamation hydrologic hazard case studies.

The principal components of this work include information on data sources and model inputs, probabilistic hydrologic hazard methods, multiple methods and other considerations, and Reclamation case studies. In Chapter 3, streamflow and climate data necessary for statistical analyses as well as parameterization and calibration of hydrologic models are described. Chapter 4 details statistical methods physically based hydrologic modeling approaches, the Australian Rainfall and Runoff method, and the Stochastic Event Flood Model approach to estimate hydrologic hazards. Following, Chapter 5 describes dealing with mixed population systems, combining multiple methods, and uncertainty. Finally, Reclamation case studies that encompass the breadth of described probabilistic hydrologic hazard methods are included.

2 LITERATURE REVIEW

2.1 Approaches to Assessing Flood Hazard

Transitioning from a standards-based to a risk-informed decision-making process requires going beyond a single deterministic design flood to a broader range of extreme floods. This includes flood frequency analysis (and usually precipitation frequency analysis) in conducting PFHAs [11]. Probabilistic flood assessments have the benefit of defining the exceedance frequency of extreme events, and differ substantially from deterministic techniques that produce the same output from a given set of initial conditions and system inputs [12]. PFHA enables a risk-informed approach to decision making to facilitate identification, prioritization, and justification of structural and non-structural risk-reduction measures for critical infrastructure.

PFHA can be conducted more readily today because of advancements in statistical methods and probabilistic techniques, and improvements in computational processing power [2]. Application of tools to estimate rainfall and flood frequency with AEPs in the range of 0.01 to 0.005 using at-site data has become routine in the dam safety sector, and when regional and/or paleoflood data are included can extend estimates to AEPs less than 1×10^{-4} [8]. For estimating less frequent AEPs, different types of data and methods of analysis are generally combined, and information can be expanded temporally, spatially and causally [13].

Observation-based statistical techniques and physically-based probabilistic modeling (i.e., simulation) approaches are the two primary approaches use to conduct PFHAs [14]. Statistical approaches involve flood frequency analysis of at-site or regional datasets to estimate flood probabilities, and some methods can additionally incorporate historic and prehistoric observations in the analysis. More extreme values than observed data are ascertained from their fitted distributions [12]. Simulation approaches are typically more robust (although data intensive and computationally demanding) than statistical analysis yet offer the advantage of identifying primary drivers of extreme flows. Both statistical and simulation approaches are useful for extreme flood frequency estimation and can be used to quantify uncertainty in their estimates. Method selection is dependent on the extreme flows of interest, characteristics of the basin, and project needs.

In order to fit probability distributions to observed data, flood frequency methods have traditionally assumed that time series of hydrologic variables arise from stationary stochastic processes (i.e., do not change with time). However, hydrometeorological processes can be influenced by climatic change, and anthropogenic effects including changes in land use, river morphology and hydraulic structures, which can have a significant influence on hydrologic response [15]. Stationarity with respect to climate change is no longer generally assumed, as oscillatory behavior and sudden shifts have been observed within sample records and replicated in global and regional circulation models [16]. To date, there is little evidence to suggest climate-change-induced trends in flooding except for earlier spring flow in snow-dominated systems [17]. However, potential change with respect to both climatic inputs and hydrologic response should be evaluated and addressed when estimating flood frequencies for future time horizons [12].

2.2 Extreme Rainfall Estimation

Precipitation occurs when moist air is cooled sufficiently to become saturated with water vapor and condenses to form water droplets or ice crystals. Often this is associated with the process of uplift resulting from changes in pressure or orography. Two primary processes controlling the generation of extreme rainfall include available atmospheric moisture and rainfall production efficiency [18]. Different meteorological conditions and processes lead to different storm types, which can be responsible for initiating extreme flood hazards [19]. Additionally, different storm types can control flood flows in specific basins due to storm characteristics and unique hydrologic response [20]. It is therefore often important to understand the type of storms in PFHA investigations.

2.2.1 Probable Maximum Precipitation

The Probable Maximum Precipitation (PMP), defined as “theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year” [21], is the most common deterministic approach of estimating extreme rainfall. PMP estimates are based on extreme storm data within a meteorologically homogeneous region and transposed to the area of interest, and calculated by multiplying the storm efficiency by the maximized precipitable water [22]. Storms can be transposed and applying only minor modifications to observed rainfall volumes in areas with similar climatic and topographic characteristics [21]. The traditional approach for calculating PMPs in the U.S. is using methods published in the National Weather Service’s Hydrometeorological Reports (HMRs) to develop enveloped depth-area-duration curves [23]. Modernized technologies and meteorological understanding to improve HMR methods are now commonly used in updating or developing PMPs [24]. Although the PMP is defined as an absolute upper bound, PMP estimates have a small probability of being exceeded [25], and uncertainties are associated with PMP estimates assigned for site and regional PMF estimates [26-28].

2.2.2 Statistical Approaches for Precipitation Frequency

Several statistical techniques are used to estimate extreme rainfall, most of which use an index-flood approach based on local annual point precipitation maxima and regional growth curve derived using L-moments [10]. Regional rainfall observations are combined with at-site data as many stations have relatively short periods of record with respect to recurrence interval(s) of interest. Data are fit to different statistical distributions (e.g. Generalized Extreme Value (GEV), Log-Pearson Type III (LP-III), Generalized Pareto, Generalized Logistic, and Kappa) such that they best represent data [10, 29].

Stochastic rainfall models are statistical models fitted directly to observed point data, and do not generally include explicit modeling of meteorological processes [30]. Most research in stochastic rainfall models have focused on cluster processes because they better represent the discrete nature of rain cells within storms. Multi-station models typically use Markov chains or nonparametric techniques to simulate data at several sites, preserving correlations between sites or variables [30]. Stochastic storm transposition (SST) is an alternative to station-based rainfall analyses used to derive depth-duration-frequency relationships. [14, 22, 30].

Extreme rainfall frequency can also be derived using a Bayesian approach [31]. Coles et al. described a fully probabilistic approach to extreme rainfall modeling, arguing the Bayesian approach is the most natural approach for taking into account all uncertainties [32]. Using a Bayesian approach, probabilistic distributions of parameter values can be developed [32]. The Bayesian framework can also be used to account for seasonality, heterogeneity, and non-stationarity.

Multifractal approaches can be used to simulate extreme rainfall as multifractals are statistically homogeneous random fields which are useful for modeling natural patterns with a high degree of variability [12]. A limitation with the multifractal approach is that spatial trends are not accounted for, regulating its use to smaller homogenous basins and areas devoid of orographic influences [33].

2.2.3 Numerical Simulation of Precipitation

Mesoscale numerical weather models are more recently being used to simulate atmospheric phenomena. These models simulate extreme rainfall directly and can be used to better understand governing metrological variables and generate storm templates that can be used in stochastic flood modeling simulations [13]. Reclamation has used the Weather Research and Forecasting (WRF) modeling system [13.5] for higher level flood hazard studies to develop storm templates for application in stochastic rainfall-runoff models. WRF solves governing equations (e.g., conservation of mass, conservation of momentum, conservation of energy) based on initial conditions and transient conditions provided at domain boundaries.

2.3 Extreme Flood Flow Estimation

The hydrological response to metrological drivers is governed by basin characteristics including topography, soils, vegetation, and underlying geology, which influence hydrologic processes. Additionally, antecedent soil moisture conditions, land use, and the network of drainage channels affect runoff rates and volumes. In estimating extreme flood flows, it is important to characterize these basin attributes for hydrologic simulation.

Many kinds of historical and paleoflood data can be used for flood frequency analysis to extend record to better estimate less frequent events. Investigations, techniques, and analyses for collecting and using paleoflood data are discussed in House et al. [34]. Historical flood data are typically extreme floods that have occurred and were described in some qualitative or quantitative fashion before establishing a stream gaging station. Paleoflood hydrology is the study of past or ancient floods that occurred before the time of human observation or direct measurement by modern hydrologic procedures. The basic types of paleoflood indicators that are useful for flood frequency analysis are paleostage indicators and botanical evidence. Fluvial geomorphic evidence includes erosional and/or depositional features that are used to infer paleostages or non-inundation levels [1]. Flow computation is based on the stage determination from the field data and corresponding discharge via hydraulic modeling. This data can be incorporated in the graphical approach, Expected Moments Algorithm (EMA), and Bayesian Maximum Likelihood estimates [1].

For estimating very low AEPs, different types of data and methods of analysis are generally combined, and information can be expanded temporally, spatially and causally [35]. Following this approach in a Bayesian analysis using a GEV distribution, Viglione et al. demonstrated incorporation of this additional information significantly improved the confidence of flood frequency estimates, and recommended a Bayesian approach and incorporation of temporal, spatial, and causal information in extreme flood frequency estimation [36].

2.3.1 Hydrologic Models

A physically-based hydrologic model is used to transform the hydrometeorological inputs into flood characteristics at specified locations and times [12]. The primary components of simulation model include rainfall input (including the spatial and temporal distribution), runoff, and routing to produce flow characteristics. In many basins, it is also important to characterize antecedent snowpack, snowmelt attributes, and flood mitigation structures, and understand the temporal response of flows to runoff and snowmelt.

The complexity of the hydrologic model is differentiated by the extent of spatial and temporal aggregation and simplification of physical processes [12]. Hydrologic models can be lumped (homogeneous basin with aggregated physical parameters); semi-distributed (meteorological and physical parameters aggregated to sub-basins); and fully distributed (spatially gridded distribution of input variables including meteorological conditions and physical parameters) [3]. Model simulations can be discrete independent events, or continuous or semi-continuous simulations (antecedent conditions continuously accounted for, but extreme events sampled separately), and performed at different temporal resolutions as necessary.

2.3.2 Probable Maximum Flood

Approaches based upon the deterministic PMF are commonly used to estimate extreme flood flow, derived from the most severe combination of critical meteorological (i.e. PMP) and hydrologic conditions (i.e. conservative hydrologic antecedent conditions) [26]. In routing the resulting flows to develop a PMF inflow hydrograph in dam regulated systems, it is necessary to account for initial reservoir level, spillway discharge capacity, and reservoir storage characteristics [12]. If used as the design flood, the results of a PMF calculation can have considerable implications including expensive facility design features or modifications. However, if a facility does not have a hydrologic safety deficiency using the PMF as the hydrologic loading condition, no further hydrologic studies may be warranted [1]. When a flood frequency analysis produces peak flows or volumes that exceed the PMF, then it should be used as the practical upper limit to statistical extrapolations [3].

2.3.3 Flood Frequency with Historical and Paleoflood Data

A peak flow frequency curve can be developed using either a graphical or numerical approach. Reclamation primarily uses three methods to develop such curves: one graphical method and two numerical methods. All the methods use a time series of annual maximum flows developed from systematic stream gage records, historical data, and paleoflood information [3, 38]. A graphical method is performed by drawing a “best fit” curve using visual inspection of the plotted time series. Traditionally, this was done using log-normal plotting paper and drafting tools. Currently, the method Reclamation considers “graphical,” fits a log-normal distribution using only the 100-year flow and the paleoflood information. These curves are linear when transformed to log-normal plots and can easily be interpreted on paper with a straight edge. Reclamation only uses this method for extrapolating frequency flow rarer than a 100-year probability [4].

The two numerical approaches currently used by Reclamation both estimate the statistical distribution parameters of the time series along with its confidence. The first, and primary approach, is a frequentist method that estimates the statistical parameters using an expected moments algorithm or EMA [3]. EMA has the capability to estimate peak flow distribution parameters with confidence using interval data derived from the time series as well as incorporating an independently developed regional skew coefficient. EMA is also capable of identifying both low and high data outliers [40, 41]. EMA is the underlying computational method described in USGS Bulletin 17c guidelines for determining peak flow frequency [107]. Bulletin 17c, however, assumes that all peak flow distributions can be described by a log-Pearson Type III (LPIII) distribution. A second method Reclamation uses for estimating a peak-flow distribution is a Bayesian maximum likelihood approach. Unlike the EMA approach, this approach assumes a prior distribution for the time series to develop a model distribution conditional to the given data. When a prior distribution is selected for the data, the Bayesian method for computing the model distribution (also known as posterior distribution) and its associated confidence is well established and computationally straightforward. Reclamation currently uses the FLDFRQ3 program for a

Bayesian approach to estimate a peak flow distribution. FLDFRQ3 provides several prior distributions to choose from thus offering more flexibility than EMA [42].

2.3.4 Hybrid and Coupled Statistical and Process-Based Models

Hybrid coupled statistical and physical process models are increasingly being used when spatial interactions and the temporal sequencing of events are important, and typically use statistical information on rainfall storms to drive physically based hydrological models [12]. Coupled whole system models, representing both rainfall and rainfall runoff, are also used offering a better understanding of the hydrological system but often requiring more computational effort [12]. Some approaches provide a long time series of synthetic rainfall with prescribed hydrologic and operational conditions. Other approaches use stochastic sampling of single storm events and antecedent conditions and derive extreme distribution of flows from results of independent events.

One approach that Reclamation uses developed by the Australian Institution of Engineers is the Australian Rainfall and Runoff (ARR) method for estimating large to extreme floods [6]. A rainfall distribution is estimated and AEP of PMP is assigned, and subsequently runoff is modeled with AEP neutral parameters (i.e., flood frequency AEP is assumed to be equivalent to precipitation frequency AEP) to develop flood frequency curve).

One of the more sophisticated ways Reclamation estimates extreme flood frequencies is through stochastic event-based rainfall-runoff modeling using the Stochastic Event Flood Model (SEFM) [3]. The basic concept of the SEFM is to employ a deterministic flood computation model and treat the input parameters as uncertain variables instead of fixed values [20]. The SEFM provides magnitude-frequency estimates for flood peak flow, runoff volume and maximum reservoir level resulting from different storm types including long-duration synoptic-scale storms and shorter duration mesoscale convective and local storms [20]. Monte Carlo sampling procedures for uncertain hydrometeorological variables is employed while preserving natural dependencies that exist between some climatic and hydrologic parameters [3]. SEFM requires that a distributed approach be used in modeling the rainfall-runoff process so that the spatial variability of storm patterns, soil moisture storage characteristics, and soil infiltration rate is accounted for [37]. Multi-thousand years of extreme storm and flood events are generated through computer simulation of the watershed model and routing of the inflow floods to provide a corresponding multi-thousand year series of annual maxima flood characteristics used to assign flood frequency [3, 20].

In regulated reservoir systems, like the Tennessee River system TVA manages, flood frequencies are largely dictated by reservoir operations and flood policy especially for more frequent floods. The Tennessee Valley Authority (TVA) is conducting an extensive analysis of hydrologic hazards for the reservoirs in their system. To account for this, a TVA RiverWare model, with defined rules representing TVA's flood policy, is being included in the stochastic simulations. In the TVA system, the "deterministic watershed model" consists of multiple models. The Sacramento Soil Moisture Accounting (SAC-SMA), Unit Hydrograph, and Lag/K hydrologic models are used to generate runoff and inflows into the TVA reservoir system. A RiverWare reservoir operations model is used to simulate reservoir operations based on the defined operating policy, including joint operations between multiple projects.

An approach integrating hydrometeorology, flood hydrology, and paleoflood information can also be applied to physically-based extreme flood hazard estimation [38]. This approach includes rainfall frequency analysis and storm modeling with stochastic storm transposition; extreme storm data and analyses for storm probability modeling supplemented by radar data; two-dimensional rainfall–runoff modeling to estimate flood frequency; and streamflow and paleoflood data with frequency analysis utilized for independently testing and calibrating runoff model predictions [38].

A continuous simulation methodology can also be used for flood frequency estimation, and can incorporate quantification of modeling uncertainties [39]. Using a continuous simulation approach, time series of meteorological variables are transferred into an output time series of stream flow, and the flood events of interest are extracted from the simulated stream flow record and analyzed by conventional frequency analysis [12]. Rainfall inputs can come from observed data or generated through a stochastic rainfall model, incorporating more frequently occurring and extreme events in the time series. A primary advantage of continuous simulation is that hydrologic conditions that change through time are accounted in the rainfall-runoff model [39].

2.3.5 Multifractal Approach

A multifractal approach can also be applied to discharge series to estimate flood frequency [33], as discharge data are highly irregular and difficult to measure and model [40]. Using the universal multifractal model for hydrological applications, values associated with AEPs can be estimated from data with significant statistical dependence [12]. The multifractal approach, which is still in the developmental stage, may prove a powerful approach to flood frequency estimation [40].

2.3.6 Quantifying Uncertainty

The basic concept behind an uncertainty analysis is the recognition that there are numerous plausible variations of the watershed model that is being used to generate flood hydrographs and develop the hydrologic hazard curves [41]. This occurs because of uncertainties and inaccuracies in hydrometeorological inputs to the watershed model; imperfect understanding of the physical processes and the adequacy of the sub-models, algorithms and model parameters used to mimic these processes; and uncertainties and inaccuracies in the streamflow and flood hydrographs used to calibrate the watershed model [41, 42]. The basin-average precipitation-frequency is usually a major contributor to the magnitude of flood outputs, and should be included in an uncertainty analysis [20]. The flood frequency curve and uncertainty bounds can be developed by ranking flood outputs (i.e non-parametric approach) from stochastic simulations sampling distributions of critical watershed model variables in a Monte Carlo framework [6].

2.4 Reclamation Case Studies Summaries

As the owner of over 350 high- or significant-hazard storage dams in the Western U.S., the Reclamation is committed to providing the public and the environment with adequate protection from inherent risks associated with large dams. The Reclamation has extensive experience in developing tools and data for extreme storms and rainfall-runoff modeling for AEPs in the range of $1x10^{-4}$ to $1x10^{-7}$. Historically, dam design and analysis methods have focused on selecting a level of protection based on a specified probability or flood event, generally based on the PMF; however, risk-informed decision-making is currently used to assess the safety of dams, recommend safety improvements, and prioritize expenditures. 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 water surface profiles, and hydrologic hazard curves can be used to assess potential hydrologic-related failure modes, such as overtopping, seepage at various levels, erosion in earth spillways, and overstressing structural components, as well as the risk associated with these failure modes. AEP estimates are made to cover the range of values needed for risk-based dam safety decision-making at a specific facility or across a portfolio of projects. For detailed Issue Evaluations, Corrective Action Studies, and design studies, Reclamation uses multiple methods. Methods today typically include peak-flow frequency using EMA or FLDFRQ3 with detailed paleoflood data [43]; and SEFM or equivalent stochastic rainfall-runoff model. Such studies ensure rainfall-runoff model is consistent with field observations, causal information, and streamflow and paleoflood data. Often results from one method will be used to validate the results from another; and, in some cases, justify parameters and parameter values used in other methods.

The following section describes hydrologic hazard estimation for Issue Evaluation Studies or Corrective Action Studies conducted by Reclamation.

East Park Dam Issue Evaluation, Hydrologic Report (2011)

Reclamation conducted a detailed hydrologic hazard analysis for East Park Dam to evaluate multi-day storm sequences and develop inflow flood hydrographs associated with peak flow and volume frequency relationships to better quantify the hydrologic risk at this facility [44]. Two methods were used to estimate the flood frequency at East Park Dam. The first approach was an EMA frequency analysis incorporating at-site detailed paleoflood information. Paleoflood exceedance and non-exceedance data were collected downstream of East Park Dam and dated using radiocarbon age analysis. Estimates of discharge associated with paleoflood stages were made using SRH2D, a two-dimensional depth-averaged hydraulic model. Streamflow gage data and paleoflood results were included in EMA analysis performed using EMFREQ. The second approach combined L-moments precipitation frequency analysis with rainfall-runoff modeling. The SAC-SMA was used as the hydrologic model. The two methods yielded comparable results and confidence intervals from both approaches were consistent with paleoflood data. Runoff from the East Park Dam basin has a snowmelt component, however, the discharge for the portion of the frequency curve for low AEPs was assumed to be rainfall dominated. Therefore, the recommended hydrologic hazard curve was a combination of the two methods. The final recommended hydrologic hazard curve utilized the EMA curve to represent AEPs greater than 5.0×10^{-5} and the L-moments/SAC-SMA curve AEPs less than 5.0×10^{-5} and used confidence limits from EMA analysis. Frequency hydrographs were developed directly from the SAC-SMA model results.

Trapped Rock Dam and Tufa Stone Dam Hydrologic Hazard Studies (2011)

The Trapped Rock Dam Hydrologic Hazard [45] and Tufa Stone Dam Hydrologic Hazard [46] studies were initiated to support the Bureau of Indian Affairs (BIA) and local tribes with Issue Evaluations of these respective dams. Similar approaches were applied in each of these studies. The ARR method was used in developing frequency flood hydrographs using NOAA Atlas 14 precipitation frequency estimates for up to a 1,000-year event (6-hour duration considered controlling), and assigning a probability to the PMP (HMR 49) using the CRC-FORGE approach [6]. Frequency hydrographs were computed using calibrated Hydrologic Engineering Center’s Hydrologic Modeling System (HEC-HMS) rainfall-runoff models. Paleoflood studies were conducted, and discharge estimates were made for paleofloods and non-exceedance bounds. Additionally, USGS regional regressions of discharge frequency based on basin characteristics were conducted and regional peak discharge envelope curves were developed using proximal USGS gaging stations [108]. The paleoflood information, and regional estimates were used for comparison to ARR results. Frequency hydrographs were developed to depict hydrologic hazard loadings for the purpose of aiding in risk-based decisions associated with these two dams.

Hydrologic Hazard Analysis, Anderson Ranch Dam (2012)

To support an Issue Evaluation Study for Anderson Ranch Dam, an HHA was conducted to provide flood loading information to improve risk estimates associated with the dam [47]. This included paleoflood data collection, stochastic rainfall-runoff modeling, reservoir elevation frequency analysis, and updated flood routings. Two methods were used to estimate the hydrologic hazard. The first method calculated peak-flow frequency using the EMA approach and incorporating detailed, site-specific paleoflood data. The second method included estimation of peak-flow frequency, hydrographs, and volumes from a calibrated rainfall-runoff model (HEC-HMS), with storm rainfall inputs based on regional precipitation frequency analysis with L-Moments and ARR concepts. Historic storms were analyzed with respect to seasonality, and spatial and temporal distribution. A regional peak discharge envelope curve was developed using proximal USGS gaging stations. A single hydrologic hazard relationship for Anderson Ranch Dam was developed based on combining results from the data and methods [47].

Altus Dam Hydrologic Hazard and Reservoir Routing for Corrective Action Study (2012)

An HHA was completed to provide flood loading and reservoir elevation information as part of a Corrective Action Study investigating reduction of static and hydrologic risks associated with Altus Dam [48]. Detailed at-site paleostage data was collected and dated, and associated discharges were estimated using hydraulic modeling (SRH-2D). A peak flood frequency curve was developed using the EMA incorporating gaging station and paleoflood data. Meteorological data was collected to estimate precipitation frequency as well as develop applicable temporal and spatial rainfall patterns to incorporate in hydrologic model. Flood frequency relationships and inflow hydrographs were developed using calibrated SEFM. The recommended hydrologic hazard curves for risk analysis included the SEFM curves using the lower and median precipitation frequency curves, which were assumed to have an equal probability of occurrence. It was recommended further uncertainty analysis should be conducted to better characterize the uncertainty associated with model parameters, data reliability, and climate reliability, as the full uncertainty of the hydrologic hazard was assumed to be greater than what was assigned to the two curves. Thousands of SEFM hydrographs were routed through Altus Dam to provide reservoir water surface elevation frequency curves (to AEP of 10^{-5}) to use in risk analysis.

Hyrum Dam Hydrologic Hazard for Corrective Action Study (2012)

Reclamation performed an HHA to evaluate multi-day storms with low probability of occurrence and their effects on the hydrologic hazard at Hyrum Dam [49]. This included collecting site-specific, detailed level paleoflood data with stratigraphy, radiocarbon dating, and hydraulic modeling, and developing inflow flood hydrographs associated with peak-flow frequency and volume frequency relationships to evaluate the hydrologic risk. A flood frequency at Hyrum Dam was estimated using the EMA, incorporating annual peak discharge records and paleoflood and non-exceedance information. Additionally, stream and rain gage analyses were performed to identify actual rain-on-snow hydrographs that occurred during extreme storm events. Reservoir elevation exceedance curves were developed for daily reservoir elevations for seasonal and monthly spring rain-on-snow storms and local storms for Hyrum Dam.

3 DATA SOURCES AND FLOOD MODEL INPUTS

3.1 Streamflow

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

If gage data are not available for a particular site, another gage at a nearby site can be used to estimate streamflow. Ideally, the nearby gage will be in the same watershed, however, nearby watersheds having similar basin characteristics can be used if none are available. The most common technique for extending flood data in time from a gage at a nearby site is the Maintenance of Variation Extension (MOVE) technique as described by Hirsch [50]. The MOVE procedures are based on only one independent variable and the assumption that there is a linear relationship between the dependent and independent variables. The MOVE technique was further refined by Vogel and Stedinger by suggesting the MOVE.3 and MOVE.4 methods [51]. The MOVE.3 method insures the mean and variance of the lengthened flood data (observed plus extended record) will be equal to the Matalas-Jacobs estimators [52]. The MOVE.3 method is preferred in the proposed Guidelines for Determining Flood Frequency (Bulletin 17-C; [53]). The MOVE.4 method is often used by Reclamation because of its simplicity. The MOVE.4 method utilizes the observed data for the short-term record for parameter estimation and maintains the variance and the mean of the estimated data using all of the long record time series data and produces the lowest mean square error for both of these parameters.

The U.S. Geological Society (USGS) has produced numerous publications via their National Streamflow Statistics (NSS) Program that contain specific methods for extending streamflow records at un-gaged locations. These methods are specific by state. Reclamation commonly uses a transposition method when the streamflow data do not overlap, and no other method is suggested. This is easily done using the following equation [54]:

$$Q_{\text{peak, site}} = Q_{\text{gage}} \left(\frac{\text{Area}_{\text{site}}}{\text{Area}_{\text{gage}}} \right)^{0.5} \qquad (1)$$

Where $Q_{peak,site}$ is the peak discharge at the desired location, $Q_{peak,gage}$ is the peak discharge at the gage location, $Area_{site}$ is the contributing area to the desired location, and $Area_{gage}$ is the contributing area at the gage location.

Many gaged sites in the U.S. have, to some degree, been affected by regulation due to dams and diversions. The USGS notes these effects in their datasets. Careful investigation needs to occur to determine if the streamflow record adequately represents the flood potential at a particular site.

Flood frequency curves are developed very differently for unregulated flows and regulated flows, which are affected by reservoir operations, hydraulic structures, operable weirs and diversions, and the effects of levees. The shape of the regulated flood frequency curve varies with at-site storage characteristics of the reservoir, the frequency of inflow peak, volumes, and storm durations, and the reservoir's operating policies. The regional information used to increase record lengths statistically is only useful for determining the reservoir inflow frequency curve. The duration of flood volumes critical to determining peak annual outflow, operational contingencies, and the relationship between regulated and unregulated flow values must be considered when converting the inflow frequency curve to a regulated frequency curve [55]. The critical duration for inflows to a reservoir depends upon the reservoir's storage capacity, its outlet capacity, operating rules, and the uncontrolled area between the dam and downstream locations of interest. The frequency of instantaneous peak inflows to reservoirs is rarely critical to determining the frequency of regulated outflows. Inflow volumes and durations are usually more important.

The U.S. Army Corps of Engineers' (USACE) Engineer Manual 1110-2-1415 suggests "it is usually possible to use one or more large hypothetical floods (whose frequency can be estimated from the frequency curve of unregulated flows) to establish the corresponding magnitude of regulated flows. These floods can be multiples of the largest observed floods or of floods computed from rainfall; but it is best not to multiply any one flood by a factor greater than two or three" [56]. The assumption is made either that the initial reservoir elevation is at the bottom of the flood control pool or higher because of some special knowledge about the relationship between antecedent storms and major floods. Goldman suggests that the "simplest and most defensible approach is to assume the initial water surface elevation is at the bottom of the flood control pool and use a historical or design event of sufficient or critical duration that brings the reservoir elevation to an appropriate level prior to the peak inflow" [55]. An unregulated-regulated peak flow transform is constructed using peak inflows (unregulated) and outflows (regulated) for a range of scaled hydrographs.

HEC's Reservoir Simulation program (HEC-ResSim) is used to route gage data through the system to develop the unregulated and regulated flow time series. It is used to model reservoir operations at one or more reservoirs whose operations are defined by a variety of operational goals and constraints. While unregulated frequency curves can be developed using statistical models, such as those described in Bulletin 17-B [9], the operated nature of regulated flows makes these methods insufficient to develop the regulated frequency curves. The shape of the regulated flood frequency curve varies with at-site storage characteristics of the reservoir, the frequency of inflow peak, volumes, and storm durations, and the reservoir's operating policies. The regional information used to increase record lengths is only useful for determining the reservoir inflow frequency curve. The duration of flood volumes critical to determining peak annual outflow, operational contingencies, and the relationship between regulated and unregulated flow values must be considered when converting the inflow frequency curve to a regulated frequency curve [55]. A regulated frequency curve must be developed from the unregulated frequency curve and a corresponding peak flow transform. A peak flow transform translates an unregulated flow of a given quantile to the corresponding regulated flow for that same quantile. The final regulated flow frequency curve is sensitive to the shape of this curve.

Peak-flow measurement errors exist particularly when measuring the largest flood discharges. The measured discharge from very large floods can be substantially in error because of uncertainty in both stage and stage-discharge relationships. Very large discharges are often estimated by extending the stage-discharge regression curve beyond the limit of measured discharge. Such extensions are subject to greater uncertainty unless the data are transformed such that the regressed errors remain independent. In other words, the physical relationship between stage and discharge must be maintained and accommodated. can seriously degrade flood quantile estimates in some situations; therefore estimation errors in the largest floods should be investigated [9].

3.2 Regional Streamflow

To estimate the flood potential at a site, a regional analysis can be used to extend the flood frequency estimates to a reasonable limit. If streamflow data does not exist in the watershed, a regional regression equation from NSS can be used to estimate the flood potential at a particular location. However, caution should be taken when using the NSS equations because they are derived using large regions that might not best represent the watershed of interest. A smaller, more suitable region can provide more accurate flood estimates using statistically derived moments from streamflow measurements inside the smaller region.

A regional envelope curve is often used to estimate the flood potential at a location based on regional floods that have occurred (see Figure 3-1). This is commonly done by selecting peak discharge gages in a homogeneous region and developing a plot of the peak discharges versus the contributing area. The selection of the homogeneous region is very important when developing regional envelope curves and should accurately reflect the flood potential for the watershed of interest. The USGS NSS documentation for each state provides valuable information and offers insight on selecting a region. Additionally, it is important to ensure that controlling peak discharges should be from natural flood events not influenced by dam failures, spillway debris plugging, or other anthropogenically-influenced factors.

The envelope curve is plotted to encompass all the regional peak discharges as illustrated in Figure 3-1. In this figure, two curves were plotted to estimate a range of peak discharge; the lower curve excludes one of the controlling stations because the estimated peak historic discharge was extrapolated beyond limits of established stage-discharge relationship.

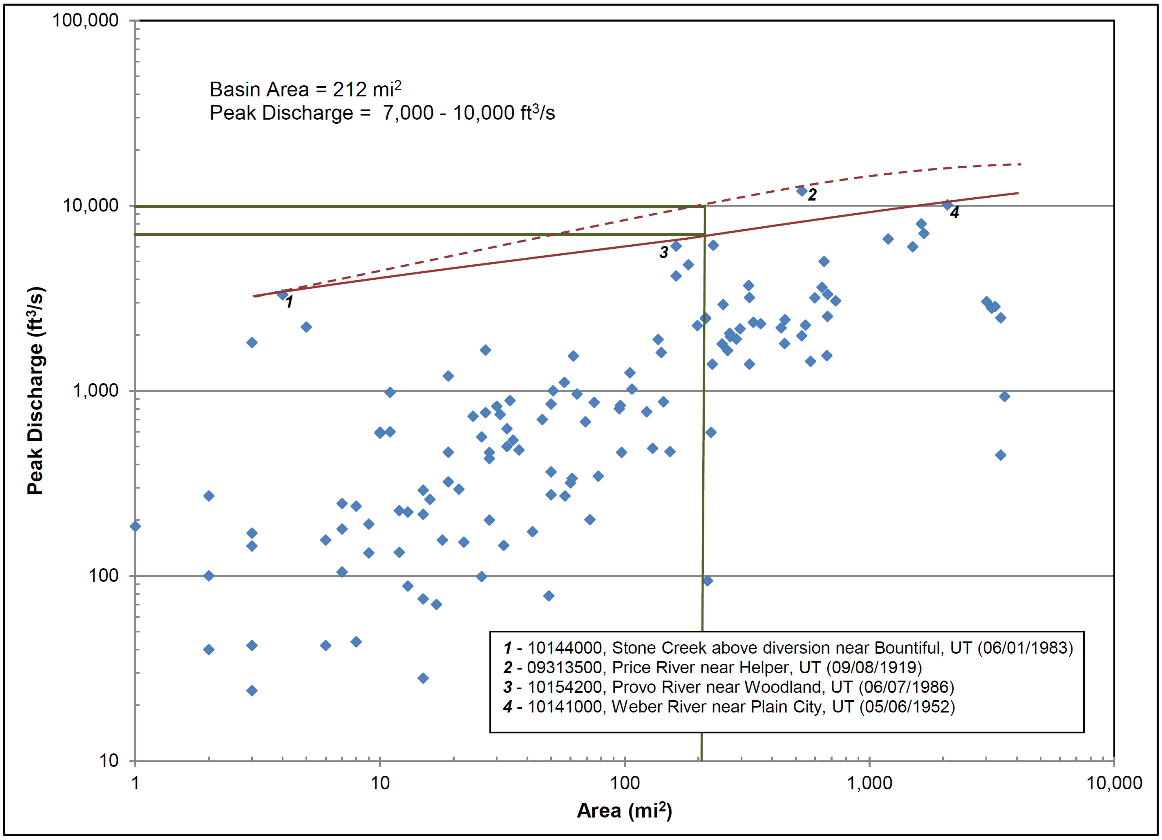

Figure 3-1 Regional envelope curve derived for Reclamation facility in northern Utah.

3.3 Paleoflood Data

Information about paleofloods, flood events which occurred before the time human observation or direct measurement by modern hydrologic methods [57], is a critical component used in assessing the flood hazard for risk assessment. The primary advantage of paleoflood data is the ability to extend streamflow records up to 2 orders of magnitude longer than conventional or systematic streamflow records. The addition of paleoflood data to a more traditional flood frequency analysis based solely on the historic record allows for an extension of that record and can lead to a more accurate estimate of the flood hazard [58].

The two basic elements of paleoflood data for flood hazard analysis include 1) the age of either a specific paleoflood or non-exceedance bound, and 2) associated estimate of peak discharge. Whereas a paleoflood is an actual flood with preserved evidence, a non-exceedance bound is not a flood, rather a discharge of a specific magnitude that has not been exceeded over a certain time period [59]. Evidence of past floods are often found in the fluvial stratigraphy on river terraces and can be found in the form of erosion and/or deposition (Figure 3-2). Unlike paleoflood events, a non-exceedance estimate is made by observing evidence of long-term landscape stability. Geomorphic, stratigraphic, and geochronologic information is developed from the geologic record to establish the extent of flooding, the nature of the flood record and character of the deposits in which it is preserved, and the age of non-exceedance bounds or timing of paleofloods that can be input directly into a flood frequency analysis [60].

The age (both relative and absolute) of paleofloods and non-exceedance bounds are critical to understanding the flood history for flood frequency and flood hazard in risk assessment [60]. The relative age of the deposits can be assessed on the basis of geomorphic characteristics (soil development, surface morphology, vegetation, weathering features, topographic position) and forms the basis for establishing landscape stability (Figure 3-2). In paleoflood studies, numerical ages are typically based on the radiocarbon analysis of detrital charcoal, shell, wood, bone, or other organic (carbon-bearing) material recovered from flood sediment or stable soils. Other methods of developing numerical ages may include pollen analysis, optically stimulated luminescence (OSL), dendrochronology, and tephrachronology.

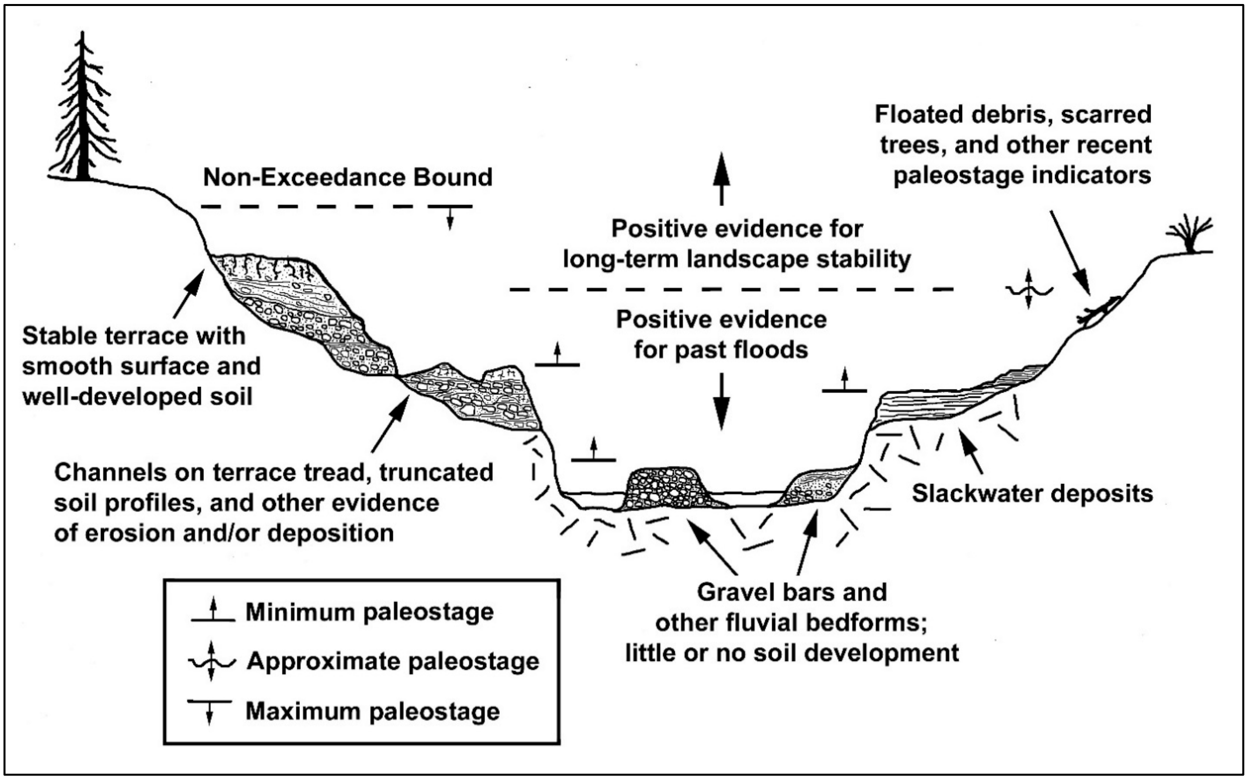

Figure 3-2 Channel cross-section illustrating fluvial landforms important to paleoflood information.

Typically, paleoflood peak discharge estimates are developed using one of several different methods or hydraulic models with the most widely applied being a one-dimensional step-backwater model [61]. Three different methods have been used at Reclamation to estimate the peak discharges of paleofloods in hydrologic hazard studies: 1) a simple single cross-section slope-conveyance calculation based on Manning's equation, 2) a one-dimensional step-backwater model utilizing multiple cross-sections with varying reach lengths (e.g. HEC-RAS (River Analysis System)), and 3) a two-dimensional depth-averaged hydraulic model through a high-resolution topographic mesh (SRH-2D; [62]). Method selection depends on study scope and objectives, and perceived need to improve paleoflood peak discharge estimates relative to the detail of the topographic data required and the computational sophistication of the model used. Currently, Reclamation primarily uses two-dimensional modeling to estimate paleoflood discharge because the incremental cost increase is far outweighed by the reduction in the uncertainty associated with the peak discharge estimate [60].

3.4 Climate Data

Precipitation and weather data used in hydrologic models can include rainfall, snowfall, snow water equivalent, temperature, freezing elevations, solar radiation, and wind speed and direction. In the U.S., these data are available from various sources and vary greatly in record length and quality. Some of these types of data (i.e., snowfall, snow water equivalent, solar radiation, and wind) are limited to record lengths of less than about 30 years; rainfall and temperature data are available for some stations for up to 150 years, but in most cases are limited to less than 100 years.

Detailed information about precipitation and weather data is further documented in the NRC Phase II Research to Develop Guidance on Extreme Precipitation Frequency Estimates for the Tennessee Valley [63].

3.4.1 Precipitation

Historical data from precipitation gages near or in the watershed of interest are often available from the National Oceanic and Atmospheric Administration (NOAA). These data can be found online through the National Centers for Environmental Information (NCEI; see ncdc.noaa.gov/cdo-web). The NCEI has a gage-based dataset known as the Global Historical Climatology Network (GHCN). These data have monthly, daily, and hourly precipitation amounts that can be used to determine seasonality or certain storm patterns or can be used to develop single event storm patterns. Several states such as California (see cdec.water.ca.gov) maintain a state-level data repository that may include additional precipitation data.

The estimation of extreme precipitation events can be approached with regional frequency analysis, which includes information from stations with similar statistical behavior to obtain more reliable estimates [64]. The cornerstone of a regional analysis is that data from sites within a homogeneous region (based on similarity of physical and/or meteorological characteristics) can be pooled together to improve the reliability of the magnitude-frequency estimates. Commonly, the L-Moments approach is used to estimate the average, variability and skewness of pooled regional data to develop a regional growth curve [10]. Within a homogeneous region, a probability distribution can be selected based on L-moment statistics of dimensionless values of pooled at-site annual precipitation maxima (dividing annual maxima by at-site means) to develop dimensionless regional frequency curves for durations of interest. Regional extreme precipitation frequency estimates can also be derived using a Bayesian approach (see [63]; [65]), which more appropriately accounts for uncertainties as well as seasonality, heterogeneity, and non-stationarity [32].

NOAA provides estimated precipitation volume frequencies throughout the U.S. and affiliated territories through its Precipitation Frequency Data Server (see hdsc.nws.noaa.gov/hdsc/pfds). The current precipitation frequency estimates for Washington, Oregon, Idaho, Montana, and Wyoming are contained in NOAA Atlas 2 [66]. NOAA Atlas 2 contains precipitation volume estimates for 50% and 1% AEPs of 6- and 24-hour duration events. NOAA Atlas 14 [67] contains the most recent precipitation frequency estimates with associated 90% confidence intervals for all U.S. states except Texas and five states in the Northwestern U.S., and provides a significant improvement from NOAA Atlas 2 because a regionalized L-moments approach is used to develop frequency estimates. NOAA Atlas 14 is divided into volumes based on geographic sections of the country and provides estimates on 5-minute to 60-day durations for recurrence intervals of 1 year to 1,000 years. Supplementary information includes cartographic maps, temporal distributions, seasonality analysis, time series data, and interpolated estimates in geographic information system (GIS) format. Additionally, pertinent information on development methodologies and intermediate results are included. Precipitation frequency data is being updated for Texas, which currently uses frequency information from Technical Memorandum NWS Hydro 35 [68] and Technical Papers 40 [69] and 49 [70].

3.4.2 Spatial and Temporal Characteristics of Extreme Storms

A critical component to rainfall-runoff modeling in estimating probabilistic floods includes characterizing the spatial and temporal characteristics of extreme storm events [63]. Probabilistic characteristics of storm events applicable to a homogenous region are used to develop input parameters in determinate and stochastic rainfall-runoff models. Spatial characterization generally involves defining i) areal coverage and physical shape; ii) depth-area relationships for different duration storms; iii) storm directional pattern; and iv) topographic influences including orographic uplift [71]. Probabilistic information about the temporal distribution of extreme storms includes macro storm patterns, depth-duration relationships, and the time of occurrence of storms.

Temporal characterization of extreme storms in the most basic form is time series of precipitation, traditionally represented by discretized or continuous hyetographs of either incremental or cumulative mass precipitation or intensities [72]. The temporal distribution is often derived from hourly precipitation gages; but can also be a synthetic distribution such as a Reclamation two-thirds PMP distribution [54], NOAA's Atlas 14 temporal distributions, or the National Resources Conservation Service (NRCS (SCS)) storm type distribution [73]. The frequency characteristics of storms with respect to the time of year they occur (seasonality) is an additional temporal component that is important for probabilistic hydrologic hazard analysis. The primary use of seasonality information is in the selection of climatological and hydrologic conditions associated with extreme storms [71]. In combination with climate and streamflow data, seasonality information can inform the selection of antecedent conditions including soil moisture, snowpack, runoff characteristics, and initial reservoir levels and volumetric flow rates.

Often there is more than one type of storm (e.g., mid-latitude cyclones, tropical cyclones (and remnants), local storms) that can produce an extreme flood in any given watershed. Different storm types, with unique spatial, temporal, and seasonal characteristics, have traditionally been included as a mixed population in precipitation frequency analyses, introducing additional uncertainty to frequency estimates. A recent approach, classifies storm events by type through statistical characterization and performs regional precipitation frequency analysis for each storm type [74]. This provides a direct connection between precipitation frequency estimates and storm spatial and temporal characteristics.

High-resolution gridded meteorological datasets, which capture the spatiotemporal attributes of extreme events, can be used to better simulate the basin response from various observed or synthetic storms [75]. Such data require rainfall-runoff models that allow sub-basins to be further discretized. Through storm transposition, historic storms can be moved (and scaled) to the watershed of interest in hydrologic simulation [75]. When these storms are moved, the precipitation volumes can be i) scaled based upon precipitation frequency of watershed, and ii) adjusted to account for orographic differences and moisture availability between the source and target location. Stochastic models can be used to randomly center a storm within a watershed to simulate the variability of storm locations and patterns. Applicable storm templates can be sampled, scaled, and transposed stochastically in a watershed to better define a probability mass curve of the flood response from various storms with respect to the variabilities associated with spatiotemporal storm patterns and precipitation frequency relationships [38].

3.4.3 Snowpack

The National Snow and Ice Data Center (National Oceanic and Atmospheric Administration, National Weather Service, National Operational Hydrologic Remote Sensing Center (NOHRSC)) collects and publishes snow data: The Snow Data Assimilation System (SNODAS) dataset contains snowpack properties including snow depth and snow water equivalent (SWE) to provide the best possible estimates of snow cover and associated parameters to support hydrologic modeling and analysis. These data can be accessed through NOAA FTP site maintained with the University of Colorado: ftp://sidads.colorado.edu/DATASETS/NOAA/G02158/.

Snowfall quantity and accumulation (snow cover), and their spatial distributions are critical data necessary for snowmelt runoff modeling [76]. Measured parameters include snow depth, snow water equivalent (SWE), snow density, and extent of snow cover. In addition to snow measurements, other hydrometeorological data required for snowmelt simulation include air temperature and precipitation; and if energy budget methods are employed, parameters including wind speed, dew point, and solar radiation are also necessary.

Snowfall is measured at a point using a snow ruler or snow board, limited-capacity non-recording snow gauges, recording-weighing-type precipitation gauges, or high-capacity precipitation-storage gauges [72]. Snow depth is often measured using graduated snow rulers affixed to the ground surface and can be measured with acoustic snow depth sensors interfaced with remote data collection systems. SWE is commonly measured by weighing a vertical core taken through the snowpack. Non-recording snow gauges have also been used extensively to measure SWE. The snow pillow is a non-destructive technique for measuring SWE, in which the pressure of the fluid in the pillow is measured with a manometer or pressure transducer. Snow density is obtained by dividing the SWE by the depth of snow. The location and extent of snow cover is usually estimated using remotely sensed data, generally expressed as an areal percentage of a basin area in elevation zones. Aircraft measurements have been used historically to define the spatial distribution of snowpack; however, airborne gamma survey technology and satellite observations are now often used.

The Snow Telemetry (SNOTEL) system, an automated snow data collection system managed by the NRCS in the Western U.S., was introduced 1977. SNOTEL has grown into an extensive network of over 800 data collection sites, often located in remote, high-elevation mountain basins. A basic SNOTEL site provides snowpack water content data via a pressure-sensing snow pillow. It also collects data on snow depth, all-season precipitation accumulation, and air temperature with daily maximums, minimums, and averages. Data collected and transmitted by SNOTEL stations and manual collection sites are available at www.wcc.nrcs.usda.gov.

NRCS also maintains over 1,100 snow course sampling stations to provide representative manual snow measurements of depth, density, and SWE. Snow courses are located with the objective of obtaining data representative of a given area – the number of samples depending largely upon the terrain and meteorological characteristics of the area. In addition, snow courses are located to adequately sample elevation ranges, and to be representative of average basin snow accumulation and melt conditions. All the data collected at snow courses are available at www.wcc.nrcs.usda.gov.

4 PROBABILISTIC HYDROLOGIC HAZARD METHODS

Hydrologic hazard curves provide magnitudes and probabilities for the entire ranges of peak flow, flood volume, and reservoir elevations, and do not focus on a single event [19]. Reservoir elevation curves are used to assess the probability of overtopping, while hydrograph information can be used to provide peaks, volumes, and durations of loading. For Reclamation dam safety risk assessments, HHCs of high hazard dams need to extend beyond AEPs of 1×10^{-4}, and the flood hydrologist that performed the analysis is an integral team member in the assessment.

Discharge frequency curves are developed from annual peak inflow data over the period of record. Additional extreme flood data points (historical estimated peak flows and paleoflood information) are combined with gage data when available to better define the extrapolation beyond the historical data. HHCs are extrapolated based on the fitted probability distribution to provide AEP estimates in the range of interest for dam safety [1]. Uncertainty estimates for HHCs are a function of the data and method used and should be included with discharge frequency results [42]. Peak flow frequency curves are typically the primary hydrologic loading estimates necessary to assess dams with limited storage volumes such that the relationship between peak flow and peak stage remains consistent during large flood events.

When structures require more than a peak inflow HHC, additional methods can include reservoir routing and/or a volume frequency analysis coupled with patterned hydrographs, balanced hydrographs, or rainfall-runoff model-based hydrographs [19]. A volume frequency analysis is performed on the daily average inflows for the period of record. For regulated systems, inflows can be transformed into unregulated flows. A range of hydrologic load scenarios can be created by combining durations and estimated volume frequency with patterned hydrographs that represent regional extreme storm runoff response [19]. A simplified method of scaling PMF or 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.

4.1 Statistical Methods

Statistical methods rely on the observation of historic events that are assumed to have occurred in an infinite sample space. The data are mostly events taken from streamflow, historic and paleo floods, and precipitation. Reclamation uses several statistical techniques in estimating probabilistic precipitation, which are described in detail in Guidance on Extreme Precipitation Frequency Estimates for the Tennessee Valley [63]. Reclamation currently uses four statistical methods listed below to estimate probabilistic floods. These methods are described in this section.

1. Graphical Mixed-Population Approach
2. Expected Moments Algorithm
3. Bayesian Maximum Likelihood Method
4. Gradient of Extreme (GRADEX) Approach

4.1.1 Graphical Mixed-Population Approach

A mixed-population graphical frequency approach was developed by Reclamation to provide estimates of peak-discharge frequencies utilizing minimal effort [77]. The frequency curve is developed using i) standard hydrologic statistical methods up to the 100-year return period (see [9, 78]), and ii) graphical methods for estimates greater than the 100-year return period. Peak discharge estimates derived from fitting the LP-III distribution to at-site gaging data are used to define the first part of the curve. The second portion of the frequency curve is defined between the 100-year and the available paleoflood data return period(s). It is estimated by drawing a straight line between the 100-year LP-III discharge estimate and the average time and discharge from paleoflood estimate on a graphical plot with probability-log scaled axes [1]. By connecting these points linearly in probability-log space, it is implied that the extension of the flood frequency curve (i.e. second part of curve) follows a 2-parameter log-Normal (LN-2) distribution.

The mixed-population graphical approach, estimating extreme flood frequency curves using existing streamflow data and site-specific paleoflood data, has two primary assumptions: i) the upper portion of the frequency curve is appropriately defined by the 100-year peak discharge and paleoflood data, and ii) the extrapolation of this portion of the curve using a LN-2 model is appropriate [1]. In reviewing the approach, Kuczera noted that estimating the upper confidence limit for the second part of the curve using information from regional envelope curve was a weakness of this approach; recommended that regional growth curves be used to compliment the use of envelope curves [79]. An example peak-flow frequency curve using the graphical approach is shown in Figure 4-1.

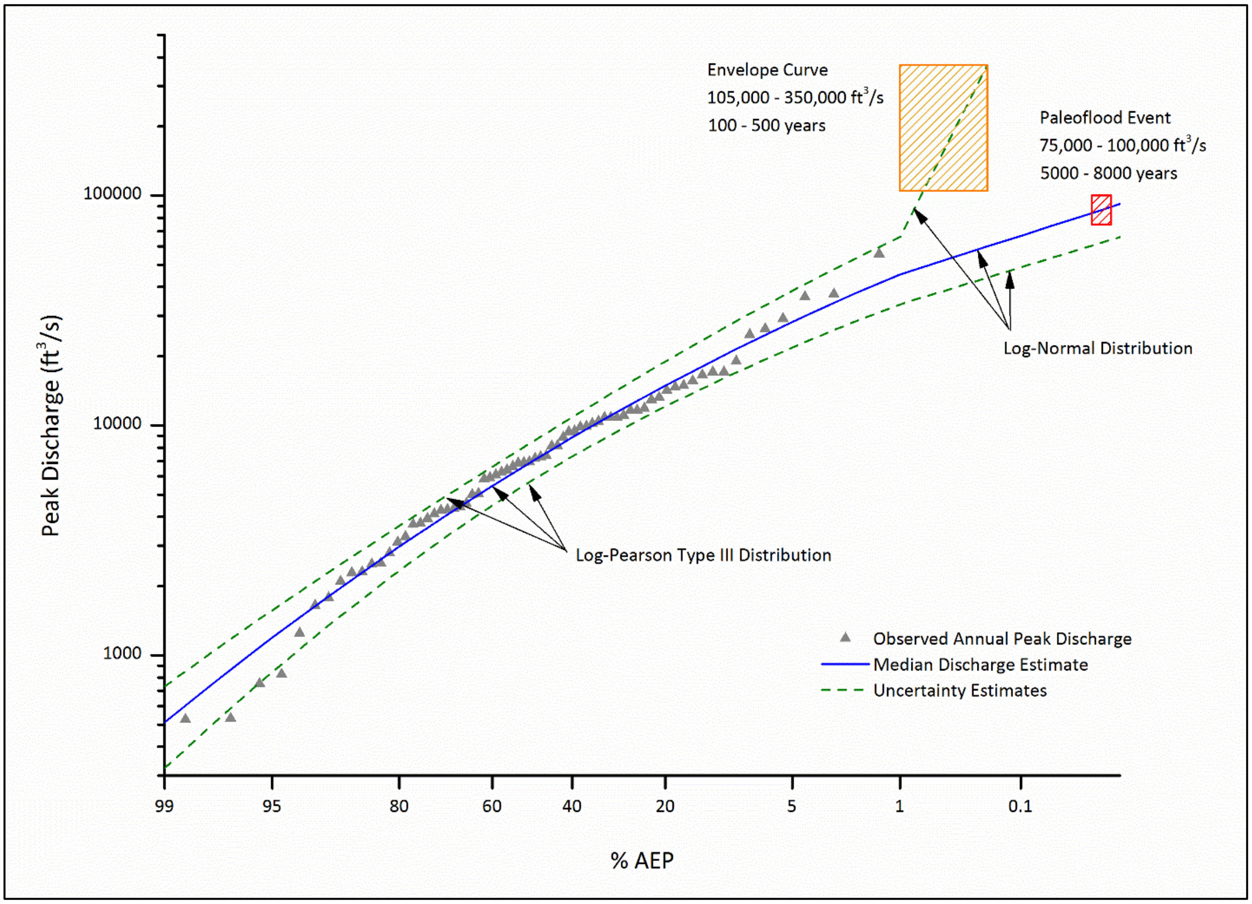

Figure 4-1 Example application of mixed-population graphical flood frequency curve using peak discharges, paleoflood data, and region envelope curve information.

4.1.2 Expected Moments Algorithm

The EMA is a moments-based parameter estimation procedure that was designed to incorporate many different types of systematic, historical, and paleoflood data into flood frequency analysis [80-82]. EMA assumes the LP-III distribution is the true distribution for floods. EMA was designed to handle the four different classes of historical and paleoflood data beyond the applicability of the Bulletin 17B historical weighting procedure [9]. As noted by Cohn et al. [81, 82] and in Bulletin 17C [53], EMA is philosophically consistent with, and is an improvement to, the Bulletin 17B method of moments procedure when historical or paleoflood information can be incorporated in the analysis. EMA is specifically designed to use historical and paleoflood data, in addition to annual peak flows from gaging stations, in a manner similar to Maximum Likelihood Estimators [81]. It is a more logical and efficient way to use historical and paleoflood data than the current Bulletin 17B historical method, and it is a natural extension to the moments-based framework of Bulletin 17B.

The five basic steps of EMA (equations stated in [80-82]) include:

1. An initial set of the three sample statistics $(\hat{\mu}, \hat{\sigma}^2, \hat{\gamma})$ are estimated from annual peak flows from gaging station records, and historic and prehistoric flood information if available.
2. An initial set of the LP-III distribution parameters are estimated from initial sample statistics.
3. From the initial set of LP-III parameters, a new set of sample moments are estimated based on the complete data set (annual peak observations, floods less than defined thresholds, floods that exceed defined thresholds, and floods within a range).
4. From this new set of moments, a new set of LP-III parameters are estimated.
5. Steps 3 and 4 are iteratively performed until there is convergence between initial and subsequent estimates of LP-III distribution parameters.

EMA has been rigorously peer reviewed in the literature [81, 82] and provides a suitable flood frequency model. EMA has been applied at many sites for peak-flow frequency (England et al., 2003b). The National Research Council applied EMA for 3-day annual maximum mean flood flows on the American River (NRC, 1999). An example peak-flow frequency curve with EMA is shown in figure 4-3. There are several limitations with the current version of EMA: (1) the program assumes that the distribution is LP-III, (2) software has not been fully developed to implement the confidence interval technique of Cohn et al.[82], and (3) low outlier and regional skew methods with EMA have been recently developed [83], but not tested with actual data.

4.1.3 Bayesian Flood Frequency

FLDFRQ3 [84, 85] uses a Bayesian maximum likelihood procedure to estimate parameters of various distributions. The Bayesian approach includes measurement uncertainty in the parameter estimation procedure. FLDFRQ3 uses a "global" parameter integration grid to identify ranges of probability distributions that are consistent with the data [84]. Two measurement error sources are included: peak discharge measurement errors and errors in paleohydrologic bound ages. Bayesian methods [86] and likelihood functions modified from Stedinger and Cohn [87] are used to incorporate data and parameter uncertainties. Two options can be used to find the "global" maximum likelihood estimate in FLDFRQ3 [84]: simulated annealing and the downhill simplex method. In FLDFRQ3, one can choose among five main three-parameter probability distributions to assume a peak discharge parent distribution. These distributions are the Generalized Extreme Value, Generalized Logistic, Generalized Normal, Generalized Pareto, and Pearson Type III (P-III)

[10]. These distributions include two logarithmic transform options for P-III models to include the LP-III. O'Connell [84] provides details of the numerical approach used for estimating distribution parameters and uncertainty using grid integration.

There are generally three main steps in running FLDFRQ3 [84]: input and data check, parameter estimation for a particular distribution, and generating parameter uncertainties for a particular model (e.g., LP-III) using grid integration. The data are grouped into two broad classes: data with normal uncertainties, such as peak discharge, and values in a range with potentially variable probability density and skew within the range, such as paleohydrologic bound discharges and ages and discrete paleofloods. After entering and checking data, the parameter estimates are obtained from the data and assumed model. The user then checks the appropriateness of the model and estimated parameters. There can be several steps here to determine the "best models" (there can be more than one) that fit the data and the model parameters. Finally, the user estimates the parameter uncertainty given the chosen model and parameter combination. O'Connell et al. [85] demonstrate how to combine results of several models and their parameter uncertainties using a likelihood criterion.

FLDFRQ3 has been rigorously peer reviewed in the literature [85] and contains suitable flood frequency models for all levels of analysis. It has been used at many sites for peak-flow frequency, such as Folsom Dam [88], Seminoe and Glendo Dams [89], and Pathfinder Dam [90]. An example peak- discharge frequency curve using FLDFRQ3 is shown in figure 4-4.

4.1.4 GRADEX- Estimating Upper Tail of Flood- Frequency Volume Distribution

Much of this description of the GRADEX Method is paraphrased from the Ph.D. dissertation, "Methodology for Estimating the Upper Tail of Flood-Peak Frequency Distributions Using Hydrometeorological Information," by Mauro Da Chunha Naghettini, completed in partial fulfillment of the requirements for the Ph.D. degree at the University of Colorado [91]. Naghettini, Potter, and Illangasekare later described the same method in the Water Resources Research publication in 1996 [92]. Some additional comments related to Reclamation dam safety needs are inserted when appropriate.

In its 1988 report, the National Research Council Committee on Estimating the Probabilities of Extreme Floods identified principles for improving the estimation of floods with AEPs on the order of 10^{-3} or smaller. These principles are: "(1) 'substitution of space for time'; (2) introduction of more 'structure' into the models; and (3) focus on extremes or 'tails' as opposed to or even to the exclusion of central characteristics" [14]. The methodology proposed in Naghettini's Ph.D. dissertation [91] presents techniques for the estimation of extreme flood peaks and volumes that make strong use of these principles. The main objective is to develop a peak-flow frequency curve for the extremely rare probabilities. To do so, the method involves a peak to volume relationship and the derivation of a frequency curve of extreme flood volumes based on extreme regional rainfall statistics. The method is useful to Reclamation dam safety needs in that it provides a means to produce frequency curves for rare flood volumes and some apparatus to define peak flows for the extreme flood volumes. It can also be used to create hydrographs based on the flood volumes and peaks, if needed.

The method relies on extrapolating a conventionally estimated probability distribution of flood volumes. To strengthen this step, the GRADEX Method, originally developed by Guillot and Duband [93, 94], is incorporated. The GRADEX Method has been used extensively in France since about 1967 for various improvements and hydrologic safety investigations and spillway renovations at numerous hydroelectric dams and facilities. The French Committee on Large

Dams has prepared the publication, *Small Dams* (undated), which outlines the very basic steps that can be used to perform such calculations in France. The main GRADEX Method is based on two assumptions:

(1) That, asymptotically, the upper tail of the flood volume distribution is exponential with the same scale parameter as that which describes the upper tail of the distribution of rainfall volumes for the basin. Figure 4-2 graphically displays this assumption.

(2) That any increase in total precipitation during a severe rain event, falling on already saturated ground, will produce a corresponding increase in volume of the resulting flood.

The estimation of the rainfall scale parameter has been enhanced in this application from the original French methodology by incorporating the work of Smith [95], who developed a regional model for estimating the upper tail of a frequency distribution based on extreme order statistics. Figure 4-2 depicts the GRADEX Method.

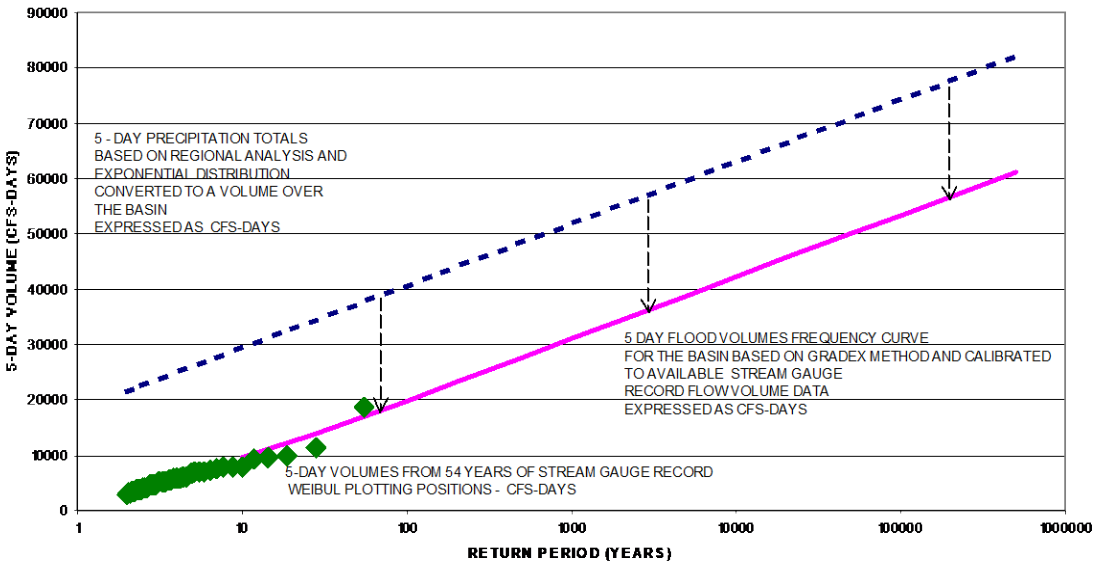

Figure 4-2 GRADEX Method of Volume Curve Calculation.

The location where the extrapolated flood volume curve takes over from a more conventional analysis of stream gage volume data, such as using LP-III, is not fixed, but must be assumed. In the literature from France, this return period ranges from about 10 years, for very impermeable basins, to 50 years for very permeable basins.

The first assumption of the GRADEX Method given above refers to the upper tail of the rainfall volume distribution, which is assumed to be a generalized Pareto density function of the form:

$$g_p(p|s,K) = 1/a\,[1- ((Kp)/a)]^{1/K - 1} \quad \text{if } K \neq 0$$

$$g_p(p|s,K) = (1/a)\exp(-p/a) \quad \text{if } K = 0 \qquad (2)$$

Where the positive constants K and *a* are the location and scale parameters, respectively. The scale parameter a is a function of various physical components of the available rain gage data sets such as elevation and mean annual precipitation (MAP). If K > 0 then the distribution of rainfall for all sites has an upper bound; if K < 0 it is unbounded. If K = 0 the upper tail of the distribution is exponential with a scale parameter *a*. The parameter estimates are found by fitting a distribution that asymptotically exhibits an exponential upper tail (e.g., Exponential, Gumbel, Gamma, or log-Normal) to rainfall maxima. Combining the two GRADEX assumptions causes the upper tail of the flood volume distribution to also be exponential with the same scale parameter *a* (the GRADEX parameter) as the one estimated for the upper tail of the distribution of rainfall volumes, except for a necessary conversion to units of volume instead of precipitation depth.

The first step in the GRADEX Method involves selecting a critical duration. This begins with an examination of the time series of unregulated daily flows for a stream gage record deemed to be hydrologically like the basin being studied or a record of reservoir daily inflows. What is required is a series of independent flood events (hydrographs) that have occurred over the entire length of the unregulated streamflow record. These flood events should be rain-generated, as opposed to floods derived from snowmelt. Also, the rain-generated flood events should all be of the same storm type. For these reasons, the stream gage record analysis should be limited to a “season” when the rain floods of the same type are most likely to occur based on historic experience. Once the season is selected, the daily streamflows for each year within that season are examined. A threshold discharge, Q threshold, is set. The number of daily flows above this threshold value is observed. Multi-day events with several days of flow above the threshold are observed. The number of and the duration of each of these multi-day events are then calculated. It is desired to obtain a set of independent flood events with nearly the same number of events as the number of years in the length of record. If the number of events calculated is too large or small, then the threshold Q value is raised or lowered until approximately the number of events equals the number of years in the stream gage record. The average duration for the entire set of events is then calculated. This average duration, generally raised to the next highest number of days, will become the critical duration d used for the rest of the study. Once the critical duration *d* is determined, the average flow discharge of all these events can be calculated. A second flow value, termed the reference discharge, is also determined such that 90 percent of the selected flood events will have average *d*-day flow values less than this discharge value. An approximate return period is also placed on this reference discharge value by the inverse of the Gringorten plotting position formula.

$$Reference\ Return\ Period = 1/((i - 0.44)/(N + 0.12)) \qquad (3)$$

Where N is the total number of years of record and *i* is the rank of the selected reference discharge. This part of the analysis can require much hydrologic judgment. Often, a set of daily flows will show a pattern that is above the selected threshold Q for 1, 2, or 3 or more days, then drop just below the threshold for 1, 2, or 3 days, and then continue for a few more days above the threshold. Decisions have to be made as to whether this should all be considered one flood event or separated into two or more events. Rainfall records from the area may help with this decision, but, generally, it is left to the analyst to make the decision. Independence of the events is generally assumed if the time from the end of the first event to the beginning of the next event is longer than the critical duration that is calculated for this set of events.

In hydrology, this process is often referred to as a marked point process. Much literature is available dealing with statistical assumptions related to events derived by the marked point process. By its nature, the set of floods derived by this process may include several events in any one year, and no events for several years. This is what is desired because the data will be used to help calibrate the GRADEX-derived flood volume information from rainfall totals for the critical duration. It is often the case that several large rainfall events can occur in any one year. Cautions that are given for the selection of the critical duration are: (1) that selection of too short a duration might result in non-exponential, probably heavier-than-exponential, upper tails for the rainfall volumes and (2) adoption of too long a duration might result in poor peak-volume relationships. Since the goal of the application of the GRADEX Method to Reclamation dam safety investigations is to create a good volume relationship, it is advised to raise the computed critical duration value to the next higher full day.

In conventional applications of the GRADEX Method, the parameter *a* can be estimated by fitting an exponentially tailed distribution to seasonal or annual rainfall maxima. The simplest estimation procedure of the GRADEX parameter is to fit a Gumbel distribution to a series of annual maximum rainfall events for a duration *d* that is equal to the watershed critical duration, or some other measure based on time of concentration calculations. However, the most frequently used estimation procedure is to fit an exponentially tailed distribution to seasonal (sometimes monthly) rainfall maxima and then combine the seasonal (monthly) distributions to obtain the annual distribution. What can be shown is that the annual frequency curve, which would no longer be a strictly exponential curve, will tend to have the same shape or slope (GRADEX) as that of the month that produces the largest rainfall amounts, especially at the extreme upper end. A slightly more conservative approach is to use smaller durations of seasonal maxima rainfall totals for even smaller durations, even 24 or 48 hours.

Estimation of the GRADEX parameter of flood volumes requires that different units for expressing the rainfall be used. If the drainage area and critical duration *d* are expressed as mi^2 and days, respectively, and the GRADEX parameters are to be expressed in English units, then:

$$\text{Flood Volume GRADEX} = [(26.89 * DA)/d] * \text{Rainfall GRADEX} \qquad (4)$$

Where the units of the flood volume GRADEX is ft^3/s-days. Usually, following the French examples, the extrapolation of the flood volume distribution according to the GRADEX parameter starts at the 10-year flood for small and relatively impervious basins, or at the 20-year flood for larger basins, or possibly the 50-year flood for watersheds showing very little topographical relief or high infiltration capacity.

The current application of the GRADEX Method applies a new methodology to estimate the slope of the rainfall durations for a critical duration d within a specified season. This new approach combines deterministic constraints with contemporary statistical techniques, extracting the maximum information from the available data. The regional rainfall frequency model described in this section is based on the premise that meteorological processes affecting large rainfall events may be different from those affecting smaller rainfall events. The model is an adaptation of a regional flood frequency model developed by Smith [95] and is based on results from extreme value theory. In this model, the parameters *a* and *K* in the Pareto or exponential distribution functions (equations 2 or 3) are determined based on a regional analysis of the largest *d*-day rainfall totals for several daily rainfall stations that are shown to be or believed to be homogeneous and to represent the meteorological conditions of the basin under study. The parameter *a* is further allowed to be a function of the basin mean annual precipitation and the basin mean elevation.

$$a = S_i = exp(c + b_1 W_{i1} + b2W_{i2}) \qquad (5)$$

Where W_{i1} and W_{i2} are the natural logarithms of the set of rain gage elevations and mean annual precipitation values for each gage site i, respectively. The constants b_1, b_2, and c are determined as part of the parameter estimation process. This is an improvement over the French general cases where only one rain gage or set of regional information reduced to one point for any basin may be used. Further, no consideration of elevation or mean annual precipitation is given in the standard GRADEX analysis.

The mathematical process to estimate the parameters K, c, b_1, and b_2 from the data set of rainfall totals proceeds as a maximum likelihood parameter estimation process. A log-likelihood function is then formed.

$$L_n(K, b_1, b_2, c) = \sum \sum ln[\, g_p(Zg/K, b_1, b_2, c)] + C \tag{6}$$

Zg is the set of random variables of *d*-day rainfall totals above the threshold precipitation value at each gage site. The double sum is for all of precipitation values above the threshold value at each site and then summed over all sites.

Partial derivatives of the log-likelihood function with respect to the four parameters to be estimated (K, b_1, b_2, and c) are derived. In taking the partial derivatives, the additional constant C in the log-likelihood function is eliminated. These partial derivative functions are then set equal to zero, and a series of four non-linear equations with four unknowns (if $K \neq 0$) or three non-linear equations with three unknowns (if K = 0 is assumed) are formed. As part of the parameter estimation process, statistical tests are performed to see if the three-parameter exponential distribution form is equally valid for the data set as is the four-parameter Pareto distribution. In almost all cases, this is true. The assumption that the extreme rainfall totals can follow an exponential distribution is validated, and the rest of the GRADEX Method follows. The three parameters are then used to form the single scale parameter, a for a single parameter exponential distribution form. In cases where the statistical test does not prove the validity of the three-parameter exponential distribution form, the rainfall total data sets need to be further investigated as to homogeneity.

Software to solve the complex sets of non-linear equations was adopted from the MINPACK software package originally developed in 1980 at the Argonne National Laboratory. This software is now free and in the public domain. Only the most extreme rainfall totals for the critical durations *d* at each daily rainfall stations are used as data. Once the equations are solved, the scale parameter *a* is estimated. Readers who are interested in the complete theoretical and mathematical background are referred to Naghettini [91]. The remainder of this discussion deals with the hydrological and meteorological details of this method.

The method requires that all stations selected have a common period of record that is as long as possible. Daily rainfall totals for all official rainfall gage stations in the United States are available online from the National Climatic Data Center [96]. Several stations near the basin being studied need to be selected and their periods of record noted. These rain gage records should represent climate and meteorological conditions like conditions in the basin being studied. Stations too far from the study area or too high or low in elevation should not be used. The same continuous period of record should be available for each rain gage selected. It is also advisable to avoid selecting too many stations in any one area, which would then overly weight the climate and rainfall records in that localized area compared to the rest of the surrounding areas for the basin being studied.

The method relies on data from the rainfall gage records that cover the same continuous period for each gage. If large gaps in the gage record are found (even though the beginning and ending dates may cover the continuous period needed), the record should be discarded. Recorded rainfall data is subject to many errors, omissions, and other anomalies. Within each rain gage record, missing days, days with accumulated rainfall from several previous days, and days with only a trace of precipitation or other notations are noted. Analyzing the daily rainfall totals involves summing the total rainfalls for the number of days previously defined as the critical duration d for this basin based on analysis of the appropriate stream gage records. The process is complicated by the need to eliminate all the days with missing data or with special notes, such as when the recorded value was already an accumulated value. Any multi-day total rainfall that includes such data is then set to zero and eliminated from further consideration. Trace values are set to zero for the day that they were reported and then they are allowed in the summation process. Any extremely large daily rainfall totals need to be further checked against official hardcopy records, and the correct daily values for these dates are inserted in the analysis if changes are needed. In the process, independence of the rainfall total events also needs to be ensured. The start dates of any two multi-day events must be more than the critical duration *d* apart.

The method requires selection of several multi-day total rain events at each gage equal to the number of common years of record for all selected gages. A threshold *d*-day total rainfall for each gage is selected such that exactly the same number of independent *d*-day rain totals is above this value as are in the continuous period of record covered by all the rain gages in the analysis. Further, a reference total precipitation value for each rain gage is also selected such that 90 percent of the previously selected events are below this reference precipitation value. The threshold and reference precipitation values are used later in the statistical analysis. Only the top 10 percent of the *d*-day rainfall totals are used in the regional analysis. This amounts to a form of top-end fitting for the precipitation totals.

To further facilitate the computations, the rainfall multi-day totals are reduced by subtraction of the reference precipitation amount for each rain gage. This step is necessary to eliminate very large numbers in the calculations that follow. This is a form of "indexing" and is common in many regional flood methodologies.

The upper order statistical method calculates the slope (or GRADEX parameter) of the best-fit decaying exponential distribution of the top 10 percent of the *d*-day total indexed precipitation amounts for each selected rain gage site. The selected station elevations and mean annual precipitations help weight the slope parameter. Knowing the basin's mean elevation and MAP, a GRADEX parameter fit specifically to the drainage basin being studied can be calculated. The result is the slope of the decaying exponential distribution of the most extreme precipitation amounts that the selected precipitation data suggest can occur over the drainage basin. The distribution of *d*-day total index precipitation values can then be used with knowledge of the contributing drainage area for the basin to create associated *d*-day volumes as shown in equation 5, above. This distribution of *d*-day volumes now has a slope, but it must also be fit to the actual reservoir *d*-day inflow volumes at the lower return periods. This is done through a statistical procedure. The fitted curve will match the experienced stream gage *d*-day volumes near the computed reference Q value previously computed. The resulting curve can be extended to very high return periods based on the second basic assumption of the method, that all large flood volumes will occur from rain falling on already thoroughly saturated conditions in the contributing areas of the basin, and any increase in a *d*-day rainfall will result in a corresponding increase in *d*-day inflow volume to the reservoir.

Because the GRADEX parameter *a* is calculated using a maximum likelihood estimate, it is further possible to place a confidence bound on this parameter. Note that for one-parameter distributions such as the exponential, the natural logarithm ratio between the estimated likelihood function and a true likelihood function for the one parameter can be proportional to a chi-square distribution with one degree of freedom. This process is displayed on the Web page,

<http://www.weibull.com.LifeDataWeb/likelihood_ratio_confidence *bounds*exp.htm>.

By a trial-and-error process, the upper and lower confidence bounds associated with parameter estimate can be determined for some set confidence level.

Once the slope and location of the flood volume curve for the *d*-day durations have been established, the question of what is the probability that a particular volume of flooding will be equaled or exceeded in any year can be answered. The more common question is what is the volume of flooding that will be exceeded on average only once in a stated return period, T_c = number of years. To answer that question, the calculated exponential distribution and associated confidence bounds, need to be inversed. The inverse of the distribution has the form:

$$\hat{X}(T_c) = \hat{\beta}_1 + \hat{a} ln\left(T_c + \hat{\beta}_2\right) \qquad (7)$$

Where $\hat{x}(T_c)$ is the d-day flow value for any return period, in ft^3/s-days, T_c is the return period (in years) for which a d-day flow estimate is required, $\hat{a}$ is the previously estimated GRADEX slope factors converted to volume units, $\hat{\beta}_1$, and $\hat{\beta}_2$ are constants that can be estimated from a system of simultaneous equations that are formed knowing the mean of the sample d-day flood discharge and the reference d-day discharge with an approximate return period. Both discharge values and the reference discharge return periods are previously computed from the daily inflow record for the study. The $\hat{x}(T_c)$ value can then be further converted to more common units (such as acre-feet) for a specified number of days.

The original goal of the method, as presented in Naghettini (1994), was to produce a peak-flow frequency curve. In this procedure, a known set of peak flows associated with *d*-day volumes can be determined from the stream or reservoir inflows, assuming peak flows have been recorded. This set of paired data for the period of the streamflow record can be further extended using various rainfall-runoff models. Calibrated rainfall-runoff models can be created for some of the largest events in the stream gage record if appropriate rainfall data are also available.

In the original presentation of the method, it is suggested that several large storms, all the same type and from meteorologically similar areas, could be transposed into the basin. For each of these large storms, the calibrated rainfall-runoff models can then be rerun with the transposed storm precipitation data and a new peak flow and hydrograph can be generated. Additional sensitivity analysis runs can be made by varying certain parameters in the rainfall-runoff model that affect the peak, such as the lag time or other parameters related to unit hydrograph development. The peaks and *d*-day volumes from all the additional transposed storms can then be added to the original set of peak and volume data. Regressions on this extended set of peaks and volumes can provide the necessary information to help determine a peak flow for a selected volume at some rare return period that has been calculated by the GRADEX Method.
In both the French and American literature for the GRADEX Method, it is suggested that the regression between volume and peak data should not be linear. The French literature states that the ratio of peaks to a *d*-day volume will increase with increasing return periods. A regression

procedure known as LOWESS (Locally Weighted Regression and Smoothing of Scatter Plots) [97] can be used to perform the non-linear curve fitting required for this procedure.

Reclamation's practice with the method has not involved multiple storm transpositions. For each application, some attempt has been made to create a calibrated rainfall-runoff model using HEC-HMS [98]. The largest one or two floods from the stream gage record and the best available rainfall data are used to create the calibrated runoff model. The model is calibrated to match as nearly as possible the peak and the entire volume of flooding, which may be longer than the *d*-day critical duration determined earlier. Once the calibrated rainfall-runoff model is completed, the historic rainfall information, with both temporal and spatial distribution, is increased by a constant ratio at each time period. The resulting peak and *d*-day volume of the hydrograph is recorded. Additional runs are made, and the lag times are reduced by 10 or 20 percent to account for the fact that the historic flood may not have resulted from such intense rainfall as the desired higher return period floods might produce. With more intense rainfalls, it may be that the basin lag times should be reduced to allow for quicker formation of the flood peaks. The extended peak and *d*-day volume set is then fit with the LOWESS procedure. Using this non-linear regression, peak flows associated with the various volumes for different return periods by the GRADEX Method can be estimated. This method will also allow for production of the entire hydrograph with exactly the required *d*-day volume estimated by the GRADEX Method. Examples of the results of this computation can be seen in the Fresno Dam example at the end of this report.

In the publication, *Small Dams*, (French Committee on Large Dams, undated), an empirical equation is given that will produce an entire hydrograph with a specified peak, time to peak, and the desired time step. One of the parameters in that equation can be varied by trial and error until the desired volume of the hydrograph over any period, such as *d*-days, is achieved [99]. This represents another strictly empirical method to derive a hydrograph once a peak and volume for the desired return period are known.

Some other concerns have become apparent in the application of the GRADEX Method to some dams in the Reclamation inventory. The first concern is with the possible additional volume of flooding that may result from snowmelt that may not be explicitly considered in the GRADEX Method. The available literature indicates that a separate snowmelt volume analysis should be undertaken. For each year of stream gage record, the maximum snowmelt volume for some time period larger than *d*-days should be estimated. A separate LP-III (or any other distribution) analysis of the snowmelt volumes can be constructed and extrapolated to rare return periods. This frequency curve of snowmelt flood volumes can be used with a combined probability analysis of the rain flood GRADEX *d*-day volumes. The resulting frequency curve will display the probability of getting a flood volume composed of both snowmelt and rain flood volumes. What becomes apparent for the large return periods is that the GRADEX rain flood curve will dominate the combined probability volumes. The combined probability curve is almost identical to the GRADEX curve at the large return periods. For a large return period, the probability of getting a flood with X acre-feet composed of Y acre-feet of snowmelt, plus Z acre-feet of rain generated flood volume ($X = Y + Z$), is nearly identical to getting the rain flood alone with X acre-feet of volume.

A second concern is with drainage area size. The GRADEX Method is based on assumed basin average rainfall. Because of this, there is a clear question as to its applicability to large basins. The original French literature limits the size of the drainage basins where the GRADEX Method can be applied to about 10^4 square kilometers, or about 3,800 square miles. It is noted that few storms with greater aerial coverage exist in the rain gage data. The application of the method to such larger drainage sizes would not produce defendable results. To approach this problem, the suggestion is that the larger basin be broken into smaller parts along logical lines, such as at major tributary confluences, such that each part is no larger than 3,000 square miles. The GRADEX Method could be applied to each separate part, and a combined probability analysis could then be performed with the resulting curves for each part. The resulting frequency curve would show the volume of flooding that could occur resulting from contributions from each separate part of the basin. This approach has not yet been tried for any Reclamation dams.

For the full application of the method for a detailed hydrologic study, additional effort should be made to determine a homogeneous set of rain gages for use in the GRADEX Method. Naghettini [91] provides some useful suggestions and examples along these lines. Due to time and money constraints, this has not been done in any Reclamation studies to date.

4.2 Physically based modeling 1-dimensional lumped models

Throughout the years, 1-dimensional rainfall-runoff models have proven adequate for flood modeling. Only in rare exceptions, a 2-dimensional model needs to be used to resolve complex hydraulics on the surface. A 1-dimensional rainfall-runoff model assumes uniform parameters throughout each sub-basin such as loss rates, rainfall, etc. Arriving at such uniform parameters involves spatial averaging and calibration.

All 1-dimensional rainfall-runoff models perform the same basic calculation: convolution-de-convolution. In other words, the models transform a unit hydrograph into a watershed flood response from the excess precipitation. This is done independently for each sub-basin within the watershed and routed through a channel network defined by the watershed. The excess precipitation or runoff for each sub-basin can be determined using a variety of surface-subsurface models intrinsic to HMS.

4.2.1 HEC-HMS/HEC-lumped synthetic hydrograph approach

The most common rainfall-runoff model used in the United States is the US Army Corps of Engineers Hydrologic Modeling System (HEC-HMS) developed by the hydrologic engineering center. HMS simulates rainfall-runoff processes of dendritic watersheds. It allows for simulations that can be used in both flood modeling and forecasting. It uses many algorithms developed throughout the HEC history used in many of its predecessors (such as HEC-1).

The Snyder's synthetic hydrograph is most used for flood modeling within the HMS program. Described in 1938, Snyder's method uses a lag time, a peak flow, and a total time base as the critical characteristics of a unit hydrograph. The lag time can be further refined into a period of rise (T_p), which is the time from the center of mass of the excess rainfall hyetograph to the peak flow of the watershed's response. The period of rise can be related to the duration of the precipitation event (Tr) in the following way:

$$T_p = 5.5T_r \qquad (8)$$

Commonly, the period of rise is calculated using the following formula:

$$T_p = CC_t\left(\frac{LL_c}{\sqrt{s}}\right)^{.33} \tag{9}$$

Where C is an adjustment factor converting lag to time to peak (typically 0.75), C_t is a basin coefficient, L is the longest length along the basin's watercourse to its pour point, L_c is the length from the basin's pour point along the watercourse to a point nearest the basin's centroid, and s is the average slope of the watercourse.

The unit hydrograph peak, Q_p, is defined using the watershed's area (A), period of rise (T_p), and a calibrated peaking coefficient (C_p) as follows:

$$Q_p = C_p\left(\frac{A}{T_p}\right) \tag{10}$$

The Snyder's synthetic unit hydrograph is often used in models that require dynamic adjustment to the unit hydrograph by varying the basin's lag response. Because HMS dynamically calculates the synthetic unit hydrograph, this allows a flood modeler to adjust the lag response without the need of developing an entirely new unit hydrograph.

Another popular synthetic unit hydrograph was developed by the Soil Conservation Service (SCS) in their Technical Report No. 55 [100] for use in determining flood response in agricultural areas. The SCS (or TR-55) method is widely used throughout the United States for determining a design flood response for events as rare as 1,000 years. It assumes a 24-hour rainfall event with a temporal distribution as a function of location within the United States.

4.2.2 AEP neutral approach

An AEP neutral approach offers a pragmatic method of extrapolating the hydrologic hazard curve beyond the current consensus. This method assumes the probability of the flood event is equal to the probability of the precipitation event. This method is commonly used in engineering design of municipal and rural drainage facilities for events as rare as 500-years.

This approach does not directly account for other factors contributing to the flood event such as snowmelt or antecedent moisture conditions. In areas that exhibit floods due to mixed population effects, a common practice used by Reclamation is to assume a concurrent 100-year snowmelt flood during extreme (greater than 100-years) precipitation events. This produces an upper bound to the hydrologic hazard at a desired frequency that can be used as a preliminary analysis for both appraisal and design level efforts. Other conditions can be accounted for with conservative adjustments that vary with probability.

4.2.3 Strengths and limitations of 1-D lumped models

Event-based deterministic rainfall-runoff modeling has a long track record in the engineering and hydrologic community and is a proven technique for generating design hydrographs. Reclamation uses deterministic precipitation-runoff modeling. From a technical standpoint, the approach is flexible and requires less effort than most of the more complex approaches. Model choice should be a function of the hydrometeorological and physical data available. For example, a distributed model could be applied in cases where detailed information was available; however, a simplified lumped-parameter model would be appropriate in less data-rich locations. Output from either model would be similar.

Limitations to this method arise from the need to calibrate model results to known historical flood events or to flood frequency analyses so that the AEP of the storm is the same as the resulting flood. Calibration can be difficult if the model is sensitive to many input parameters. A lack of good meteorological data can prove troublesome in developing design storms with appropriate temporal and special characteristics. Rainfall-runoff modeling in data-sparse locations may require a high level of regional data gathering and analyses to obtain the necessary hydrometeorological inputs.

4.3 Australian Rainfall and Runoff

The Australian Rainfall and Runoff (ARR) method is a pragmatic approach of extrapolating precipitation beyond a credible limit of extrapolation. The method assumes the Probable Maximum Precipitation (PMP) results in a Probable Maximum Flood (PMF) and the PMF is the physical upper limit of the flood potential. The PMF, however, is a design limit that cannot be assigned a probability. To overcome this limitation, the ARR method assigns a probability to the PMP. Doing so, allows interpolation of precipitation between credible extrapolated values having an AEP as rare as 0.1% (1000-year return period) and the PMP. The ARR method adopts an AEP-neutral approach. This means a rainfall-runoff model uses model parameters and inputs such that the AEP of the precipitation is equal to the AEP of the corresponding flood.

The Australian Institution of Engineers developed and published an approach for estimating large to extreme floods in 1999 and revised the method in 2016 [7]. The focus of this work is on estimating floods with very low probabilities of occurrence. The floods developed using this technique usually have AEPs ranging between 1 in 50 and 1 in 10 million. Uncertainties involved in estimating floods increase with increasing sizes of floods. The following discussion describes Reclamation’s experience with estimating rare and extreme floods using the Australian approach.

Three categories of floods are considered – large, rare, and extreme. Large floods typically have probabilities of occurrence ranging from 1 in 50 to 1 in 100. Rare floods include floods with AEPs extending from 1 in 100 to the credible limit of extrapolation, generally around 1 in 2,000. Extreme floods involve estimating floods for the AEPs beyond the limit of credible extrapolation. For risk analysis purposes, rare and extreme floods are of most interest.

Rare floods include events between the largest observed flood and the credible limit of extrapolation. The creditable limit of extrapolation depends on the type and amount of data used for flood frequency analysis. Generally, regional flood and precipitation data, and the inclusion of paleoflood data, allow extrapolation out to around 1 in 2,000 or 1 in 5,000. It is important to note that floods in this category contain considerable uncertainty because estimates are outside the range of observations.

Extreme floods extend beyond the credible limit of extrapolation from the data to AEPs out to 1 in 10 million. Estimating these floods requires prescriptive measures, which do not allow the hydrologist to quantify the uncertainty of the estimates even though it is known to be very large. Extreme floods determined by these methods are intended to be consistent and as reasonable as possible given the state of current knowledge.

4.3.1 Extrapolating frequency precipitation using NOAA rainfall atlas and PMP estimate

The procedures involved in the Australian Rainfall and Runoff Method are based on flood frequency analysis and rainfall-runoff modeling. Any of the flood frequency analysis techniques previously discussed in previous sections of this report are applicable to the Australian Rainfall-Runoff Method. The unique concept in this approach is the use of “AEP-neutral” parameters in the rainfall-runoff modeling process. This involves selecting model parameters such that the AEP of the 1 in Y rainfall amount produces a flood with a 1 in Y AEP.

Reclamation has used an event-based deterministic rainfall-runoff model to convert a 1 in Y AEP design rainfall into a 1 in Y AEP flood. A single set of hydrometeorological parameters and watershed characteristics are used to produce a flood event. No soil moisture or surface storage recovery is provided. Therefore, the deterministic model always produces the same output.

The major inputs to the deterministic rainfall-runoff model are: (1) precipitation (rainfall and snowfall), (2) losses (infiltration/interception), (3) physical watershed characteristics for runoff and routing simulations (drainage areas, watershed and channel slopes, lag times, antecedent moisture, etc.), (4) precipitation-runoff transformation function, and (5) runoff conveyance and routing mechanisms. Model output includes runoff hydrographs at user-specified locations, maximum peak discharges, and total runoff volumes.

Deterministic event-based precipitation-runoff modeling applies design rainfall distributions and volumes to watersheds for which runoff response is characterized by unit hydrographs and generalized loss-rate functions. Calculations proceed from upstream to downstream in the watershed. Subbasin hydrographs are routed and combined at the points of interest.

A design storm (rainfall and basin snow cover) is the primary model input. Typically, a time series of basin-average rainfall for a preselected duration and frequency is input to the model. A 1-hour to 72-hour duration storm event is typically simulated. Appropriate duration storm events should be derived from local and regional rainfall records. In the process of developing extreme floods, the Australian Rainfall and Runoff Method assigns an AEP to the PMP and is solely a function of drainage area size. Reclamation assigns an AEP to the PMP on an as-needed basis and does not endorse the drainage area relationship used by the Australians. Reclamation considers the proximity to moisture sources, areal coverage of the storm, and other factors in assigning an AEP to the PMP.

Excess precipitation is estimated by subtracting losses typically due to infiltration and interception. A variety of infiltration models are available and range from constant uniform loss rates to approximate theory-based functions (Green and Ampt, Philips equation). Antecedent storm assumptions can have a severe impact on basin infiltration estimates. Since the deterministic rainfall-runoff model is based on a single event, soil moisture storage and recovery during and between storms is not considered.

The amount of watershed information required is a function of the type of precipitation-runoff model used. Two classes of models are currently used—lumped and distributed parameter models. Lumped parameter models consider the system as being spatially averaged. In contrast, a distributed system considers hydrologic processes at various points in space and defines model variables as functions of the space dimensions. Some lumped parameter models that are widely in use are HEC-1 [101], FHAR [102], and RORB [103]. Some distributed models that can handle single events include DR3M [104], PRMS [105], HEC-HMS, and WMS. Additional surface water models are discussed in DeVries and Hromadka [106].

Transformation of rainfall excess to a direct runoff hydrograph is completed via a convolution integral using (1) unit hydrograph techniques or (2) kinematic wave routing for overland flow. The unit hydrograph has been used extensively for flood runoff estimation. Kinematic wave and distributed modeling approaches may be more appropriate for modeling non-linear systems. A good discussion about rainfall-runoff processes and floods, including practical issues comparing design floods and actual storms, is presented in Pilgrim and Cordery [107]. Beard [108] presents a methodology for simulating floods of a given probability from hypothetical design storms derived from point rainfall.

Streamflow routing may be classified as either lumped/hydrologic (linear reservoirs, level-pool, Muskingum, etc.) or distributed/hydraulic (diffusive wave, kinematic wave, etc.). In lumped flow routing, streamflows are computed as a function of time at one location; however, in distributed flow routing, streamflows are computed as a function of time at several locations along the stream. Most precipitation-runoff models have adequate routing mechanisms. A detailed discussion of routing options is presented in Chow et al. [109].

For risk-based dam safety studies, it is necessary to adopt an AEP-neutral approach, where the objective is to derive a 1 in Y AEP flood with an AEP equivalent to its 1 in Y rainfall. The factors that influence the transfer between rainfall and runoff can be characterized by probability distributions. Thus, ideally, the design hydrograph should be determined by considering the joint probabilities of all the input factors. Stochastic methods are ideally suited to the AEP-neutral objective because they accommodate the observed variability of the inputs while still preserving the interdependencies between parameters. However, for the least important parameters, it may be appropriate to adopt a single representative value instead of the full distribution. Since the relationship between rainfall and runoff is non-linear, it is important to note that adoption of a single representative value for the major inputs will introduce bias into the rainfall-runoff transformation. Therefore, more important model inputs may require use of a joint probability approach.

The simplest approach to deriving AEP-neutral inputs is to use the correlation relationship between the two variables. For example, if it is necessary to derive a temporal relationship to use with the design rainfall magnitude, an appropriate relationship may be derived from the correlation between the largest observed storms and their temporal characteristics during the largest storms on record. When applying relationships based on a limited historical sample to large flood events, the inputs should be conditioned by physical reasoning. For instance, large snowmelt events may require large snowpacks and high temperatures, but the meteorological conditions required to sustain an extreme rainfall event may preclude the joint occurrence of extreme wind speeds. The concurrent wind speeds used in the transformation of snow into runoff must be bounded by a reasonable upper limit.

The selection loss parameters are required inputs common to all event-based rainfall-runoff models. With loss rates, there is evidence to suggest that loss rates are independent of flood magnitude for design floods up to 1 in 100 AEP, though, for more extreme events, it is possible that the loss rates depend on both the AEP and the duration of the design rainfall. When considering snowmelt design floods, it may be necessary to vary loss rates with snowpack extent [110].

The most appropriate approach required to achieve AEP-neutrality depends on the complexity of the system being modelled, the nature of the available data, and the requirements of the flood model. In many cases, it may be expedient to adopt model input parameters derived using regional data, and it will be necessary to supplement empirical evidence by physical reasoning.

Calibration of the design flood estimates to flood frequency quantiles will help reduce the uncertainty in extreme flood estimates.

Calibration of a flood event model for application to design flood estimation is traditionally restricted to the selection of model parameters to achieve a fit between observed and estimated hydrographs. Attention is focused on collecting streamflow and rainfall data corresponding to the largest events on record. Considerable effort is required to ensure that the temporal and spatial distribution of the rainfall data is representative of the actual event. The ability of a model to reproduce historic events certainly gives some confidence to the validity of subsequent flood estimates. However, the available historic information for floods is usually much smaller than the extreme floods of interest. In most watersheds, the AEPs of the calibration floods are likely to range between 1 in 10 and 1 in 25. While it would be expected that floods of this magnitude would activate some floodplain storage, the non-linear nature of the out-of-bank flood response is such that the streamflow routing characteristics of larger events may be considerably different. Therefore, while calibration of the model provides valuable information on the flood routing parameters for small floods, caution is needed when using the model to estimate extreme floods of much larger magnitude.

Calibration of rainfall-runoff model results to flood frequency quantiles can provide important information on flood response characteristics for extreme flood events. With this approach, rainfall data are prepared for a specified AEP and then used with a given set of model parameters and input assumptions to derive a flood hydrograph. The peak (or volume) of the flood hydrograph can then be compared to the corresponding quantile obtained from flood frequency analyses. The model inputs associated with the greatest uncertainty can be varied within appropriate limits to ensure agreement between the selected flood quantiles. It is recommended that model calibration be undertaken for a range of exceedance probabilities to ensure a consistent variation of parameters with flood magnitude. The approach is suited to ungaged watersheds using regional flood frequency methods as well as sites with limited information. The approach is particularly useful when combined with flood frequency information that uses paleoflood data.

4.3.2 Determining how to model AEP neutral parameters

Although an AEP-neutral approach assumes the flood frequency is equal to the precipitation frequency, some measures can be taken to vary other parameters with probability. Doing this recognizes that the probability of the flood event may not be attributed to only the probability of the precipitation. Other factors can be involved. Such factors might include model runoff parameters, subbasin routing parameters, and channel routing parameters.

Reclamation often varies the runoff parameters with the probability of the event. In its simplest form, the basin's loss rate can be adjusted such that the 100-year event will have an approximate peak discharge equal to a regressed stream gage 100-year event and the rarer events adjust log-normally until the recommended PMF loss rate value is met. The same can be done for the initial abstraction. The Trapped Rock Dam Hydrologic Hazard, presented in Section 6.3, offers a good example of adjusting the runoff parameters with the probability of the flood event. In practice, this accounts for the variability that might be present in the near-soil and sub-soil conditions that lead to more extreme flood events. The general practice used by Reclamation is to decrease the soil losses with probability. This often yields floods that become more conservative with rarity.

Some watersheds justify adjusting the initial abstraction as a function of the probability. This accounts for the variability that occurs in the antecedent events leading up to the flood. Like the constant loss rate, the initial abstraction is often adjusted as a function of probability decreasing until it reaches zero – recommended for the PMF due to all of the watershed voids being satisfied.

Subbasin routing parameters are more difficult to justify when changing as a function of probability. Reclamation commonly uses a lag time expressed as a function of its basin factor and Manning's *n*. Because the basin factor is a physically measured parameter that does not change with probability, Manning's *n* is the only variable that can be adjusted. Factors that might justify adjusting Manning's *n* might include frozen or charred ground, and/or ponded water. Reclamation will often not change a subbasin's lag time with flood probability because of the difficulty of justifying doing so.

The extreme events modeled by Reclamation often do not alter the stream channel properties with probability because all the flood flow is assumed flowing outside of the channels normal capacity to begin with. The channel capacity might display flows that vary with the magnitude of the flood event, making it seem as though the stream characteristics vary with probability, however, they do not. The variation is often the result of the stream flow rating curve changing with stage as the inundated area grows. Incorporating a dynamic routing routine in a hydrologic model will account for streamflow changes with flow magnitude and thus physically account for the changes with probability. If incorporating such a dynamic model into the hydrologic model is beyond the scope and budget of the analysis, an alternative might be using a simple lagged channel routing method that increases the lag as a function of probability. This method requires justification through the physical characteristics of the stream channel.

4.4 Stochastic Event Flood Model (SEFM) approach

SEFM is a unique rainfall-runoff model that utilizes methods to provide greater confidence in magnitude-frequency estimates (e.g., peak discharge-, inflow volume-, maximum reservoir elevation-, etc.) with very rare annual exceedance probabilities (AEPs) as rare as 1-in-100,000,000-years. Traditional methods used by the Flood Hydrology and Meteorology Group, such as the Expected Moments Algorithm (EMA), can provide confidence in magnitude-frequency estimates with return periods only as rare as twice the length of the period of record. With only 100 years of systematic data, confidence deteriorates at around the 1-in-200-year event. However, EMA can handle historic and paleo-reconstructed flood data, such as paleoflood events or non-exceedance bounds (i.e., the knowledge that floods have not exceeded a certain threshold in a certain length of time). Paleo information such as this can significantly extend the confidence in peak discharge-frequency estimates, generally to the 1-in-10,000-year or rarer threshold. Development of SEFM involves detailed meteorological preparation (section 4) to drive the rainfall portion of the rainfall-runoff model, as well as hydraulic and hydrologic preparation (section 5) to drive the runoff portion of the rainfall-runoff model.

4.4.1 Building a stochastic model using HRU approach

A basin-average precipitation-frequency curve was developed using the regional L-moments methodology, which fits a four-parameter Kappa distribution to regional precipitation data [111]. Generalized extreme value (GEV) and generalized normal (GNO) distributions were also identified as suitable distributions for 72-hour precipitation in the Unity Dam homogeneous region, but the Stochastic Event Flood Model (SEFM) requires the four-parameter Kappa distribution parameters as input. A sensitivity study identified no significant differences in the precipitation-frequency estimates produced from the GEV, GNO, and four-parameter Kappa distributions.

4.4.2 Generalized Least Uncertainty Estimate (GLUE) event calibration

The uncertainty for SEFM was estimated using a Latin Hypercube Sampling (LHS) approach [112]. LHS is a method of generating a sample of plausible collections of parameter values from a multidimensional distribution. The ranges of potential parameter values were inferred through (i) bootstrap resampling procedure for the precipitation-frequency distribution parameters, and (ii) expert knowledge on the realistic range of parameter values for the Holtan loss parameters. Eleven LHS models were produced, with distinct parameter values for each. For each of the eleven LHS models, 20,000 simulations were performed. The range of the 220,000 LHS simulations provides confidence intervals for the peak discharge, volume, and maximum water surface elevation magnitude-frequency relationships.

5 MULTIPLE METHODS & OTHER CONSIDERATIONS

Due to the complex nature of rainfall-runoff processes, it is rare that the 1-in-1,000-year precipitation depth translates to the 1-in-1,000-year peak discharge, inflow volume, or other magnitude-frequency process. The assumption that the 1-in-1,000-year precipitation depth corresponds to the 1-in-1,000-year peak discharge has been termed to be an “AEP neutral” assumption. For higher level studies, such as the Unity Dam IE, this is an inappropriate assumption. Thankfully, SEFM incorporates the complexities between precipitation depths, soil infiltration rates, antecedent conditions, and countless other physical properties that govern rainfall-runoff behavior.

Another important distinction of stochastic modeling, such as SEFM, as compared to deterministic modeling, such as HEC-HMS, is that in stochastic modeling there are many different hydrograph shapes and volumes that could produce the 1-in-1,000-year peak discharge. In deterministic modeling it is common practice to scale a unit hydrograph by the 1-in-1,000-year peak discharge magnitude to obtain the 1-in-1,000-year frequency hydrograph. However, numerous factors come into play when quantifying the impact of the unit hydrograph method, perhaps most importantly being the shape of the hydrograph itself. No single hydrograph shape will always occur in a watershed, as the shape of the hydrograph depends on the antecedent conditions of the watershed, the meteorological conditions governing the flood event, and the antecedent hydrologic conditions.

Traditional design and analysis methods focused on selecting a level of protection based on spillway evaluation flood loadings, which were usually based on the PMF [4]. Since 1995, Reclamation has used a risk assessment process to determine an appropriate level of public protection by evaluating a full range of loading conditions and possible dam failure consequences. This contrasts with the traditional approach of using upper bound events without regard to their likelihood of occurrence and without assessment of their incremental consequences.

Reclamation uses the PMF as the upper limit of flood potential at a site for storm durations defined by the PMP. If peak flows or volumes calculated using probability or statistically based hydrology methods exceed those of the PMF, then the PMF is used in evaluating the hydrologic risk and as a theoretical and practical upper limit to statistical extrapolations. 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” [54]. If the PMF has been properly developed, it represents the upper limit to runoff that can physically occur at a particular site. Various storm types, sequences, and durations are taken together with the most severe hydrologic parameters in its development. Extrapolation of statistical analyses can become unbounded for flood distributions that exhibit positive skewness;

therefore, Reclamation uses the PMF to limit extrapolation to flood discharges that are physically possible.

5.1 Mixed Population Systems

A watershed response that can be described by multiple processes is termed a mixed-population system. Such processes included various meteorological precipitation events (storm types) and snowmelt processes.

The most common method of determining hydrologic risk from a mixed population system is to create multiple models depicting the hydrologic events that can lead to failure of a dam. If enough data are available, a Log-Pearson III statistical fit can be made that might be considered reliable for events as rare as having an annual exceedance probability of 1/40,000. With a large sample size, using systematic, historic, and paleoflood data is assumed to capture all the various processes that effect floods into consideration. The problem, however, arises when one must consider risks rarer than an AEP of 1/40,000. Processes causing such extreme events may not have occurred during the recent (Holocene) life of the watershed. These events can only be theorized using probabilistic rainfall-runoff models such as ARR. Such models can be used to estimate the hydrologic risk for the extremely rare events, as such, it is not uncommon to have a sharp break in a flood distribution curve (Figure 5-1).

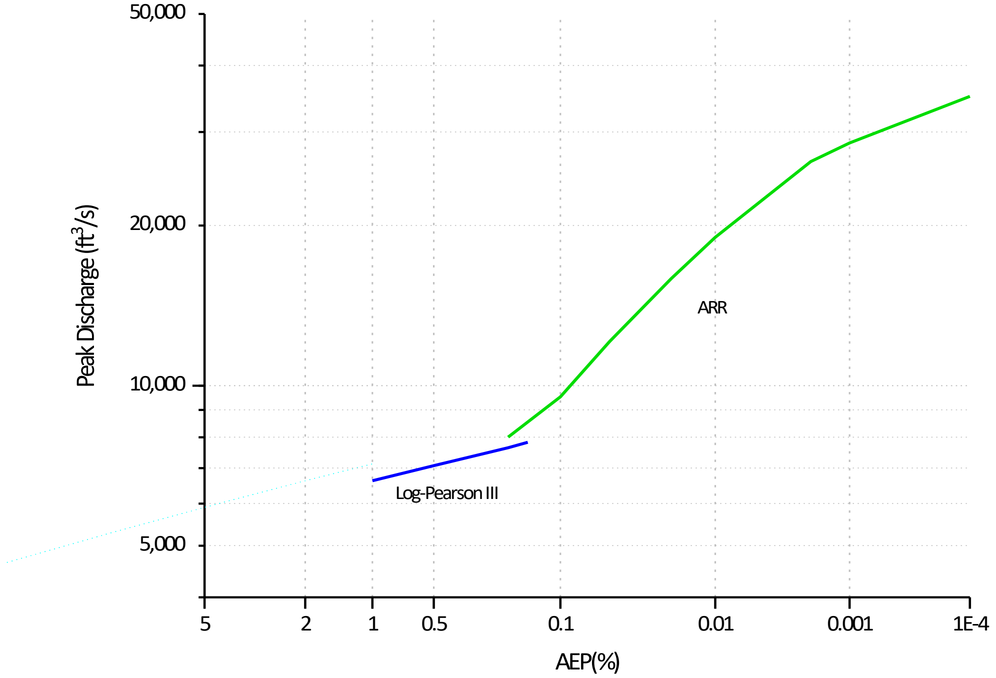

Figure 5-1 Distribution Curve Example showing break distribution types.

There are methods that can be used to determine the hydrologic hazard from a mixed population including Reclamation's mixed-population graphical approach [77]. Other methods include weighting schemes between two statistical distributions, as well as combining the probabilities of the separated events to create a single distribution. A well-developed stochastic model is a good method for combining the various events into a single distribution.

5.2 Incorporating a Probable Maximum Flood into an Analysis

Reclamation uses the PMF as the upper limit of flood potential at a site for storm durations defined by the PMP. If peak flows or volumes calculated using probability or statistically based hydrology methods exceed those of the PMF, then the PMF is used in evaluating the hydrologic risk and as a theoretical and practical upper limit to statistical extrapolations. 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" [54]. If the PMF has been properly developed, it represents the upper limit to runoff that can physically occur at a particular site. Various storm types, sequences, and durations are taken together with the most severe hydrologic parameters in its development. Extrapolation of statistical analyses can become unbounded for flood distributions that exhibit positive skewness; therefore, Reclamation uses the PMF to limit extrapolation to flood discharges that are physically possible.

5.3 Envelope curves and how to best use them

A regional envelope curve estimates a flood potential using observed flood maximums within a larger region having similar hydrometeorologic characteristics. Typically, the estimate depends on the area of the study watershed. The envelope flood value can be used in two ways: qualitative or quantitative. Qualitatively, the value can be used as an upper limit of flood potential based on scientific judgment of the watershed and the larger region. Scientific judgment, however, needs to be justified with valid arguments, for example:

The Big Thompson Creek has experienced very large floods in excess of 20,000 ft^3/s during the past 50 years of systematic record. Boulder Creek, located two drainages to the south, has not experienced floods of similar magnitude. Boulder Creek is likely to not have such large floods in comparison to the Big Thompson Creek because it has less travel distance from the alpine headwaters until it reaches the eastern plain. Although a storm can track along both drainages from west to east, the Big Thompson drainage allows much more concentration of rainfall due to its' longer distance.

To use an envelope curve quantitatively, one must assign a probability to the flood estimate. One way to do this is to observe where the envelope curve intersects multiple peak discharge distributions within the region. Ideally, the curve will intersect near the same probability. Another method is to examine the controlling floods and intersect them with their respective peak discharge distribution. Knowing the probability of the envelope curve allows one to use it as a historic flood event in an EMA analysis. It can also be used to calibrate or validate rainfall-runoff models.

Care should be taken to develop an envelope curve such that data used comes from regional watersheds having similar hydrometeorological characteristics. The USGS National Streamflow Statistics (NSS) program has underlying documentation for regions throughout the United States [113]. The documentation, commonly in the form of Scientific Investigation Reports (SIRs), offers insight on similar hydrometeorological regions and should thus be consulted when determining an envelope region. Each controlling flood should also be investigated to determine if it is the result of natural phenomena. Floods that result from dam breaks, debris plugging, etc., should be eliminated. Floods that result from events such as ice dam failure should be justified using scientific judgment when used in an envelope curve. Some envelope curves might be controlled by a single event such as the example in Figure 5-2. If the event is determined to be extremely rare, a second, lower curve can be developed without the event. This can be used to estimate an envelope range.

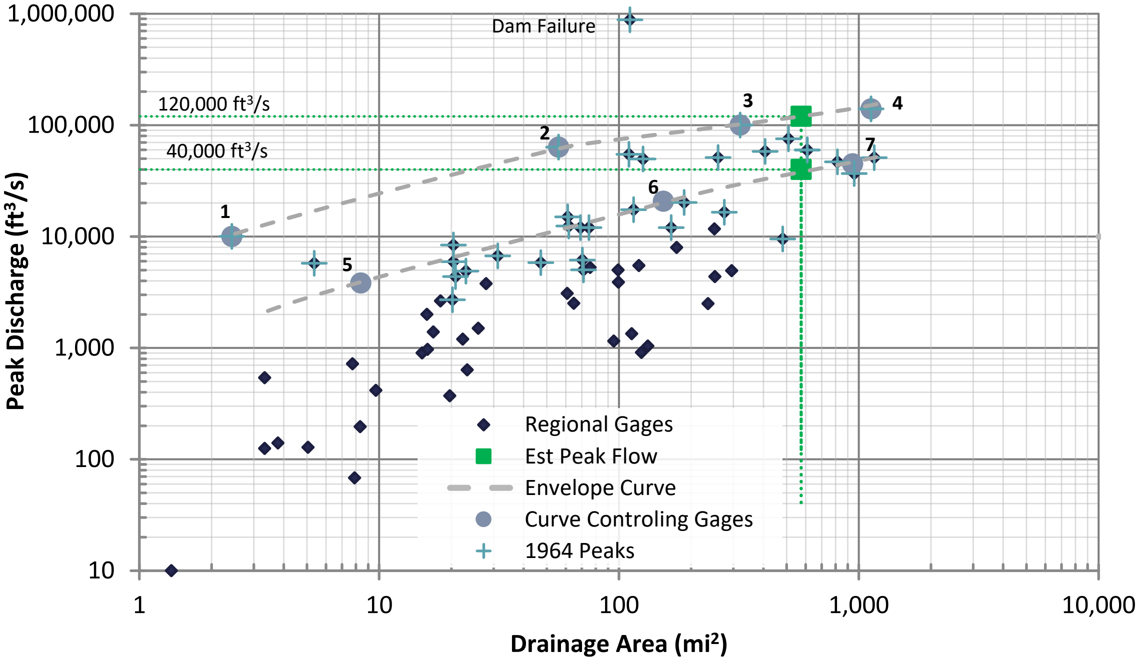

Figure 5-2 Regional envelope curve estimating a peak discharge flood potential between 40,000 and 120,000 ft^3/s for a drainage area of 575 mi^2

5.4 <u>Hydrograph Scaling</u>

Probabilistic hydrographs can be constructed based on streamflow estimates from gaging stations, historical data, and paleoflood data. Four components are used: (1) a peak discharge-probability relationship, (2) an extreme storm duration probability relationship, (3) relationships between peak discharge and maximum mean daily flow volumes, and (4) observed hourly flow hydrographs that have regulation effects removed. The key idea is calibration or scaling of hydrographs to match peak discharge for a given probability. The approach relies completely on the specification of a peak-flow frequency curve that describes the probabilities of interest, based on paleoflood data.

There are four major assumptions for developing the hydrographs: (1) the probability of peak discharge represents a probability of the composite hydrograph, (2) unit hydrograph assumptions apply to the basin, (3) direct runoff volumes can be estimated from daily flow hydrographs, and (4) the recorded streamflow observations, historical information, and paleoflood data in the river basin of interest provide an adequate sample so one can extrapolate peak discharge probabilities, peak-volume relationships, and hydrographs for extreme floods. Maximum mean discharge (*Qd*) for n-day periods is related to peak discharge (*Qp*) by a power function:

$$log(Qd) = a + b\ logQ_p \tag{11}$$

The assumed known variable is peak discharge (*Qp*), with an associated exceedance probability estimate from the frequency curve. The quality of the regression relationship expressed in equation (1) depends principally on the data from the site of interest and the flow duration (n). Mixed-population flood data (e.g., from thunderstorms, snowmelt, or rain-on-snow) can lead to difficulties in obtaining statistically significant relationships. Good regression fits are typically found for shorter duration (1- to 7-day) flow volumes; the relationships become progressively worse for longer durations. The maximum n-day hydrograph ordinates are linearly scaled, based on the selected n-day volume.

An alternate approach to using streamflow data is to use hydrographs from rainfall-runoff models as a basis for scaling. In these cases, there are typically no flood hydrograph data at the site of interest. A design flood hydrograph, a PMF hydrograph, or another suitable hydrograph for the basin is obtained. The hydrograph can then be scaled in some linear fashion to match peak flows from a peak-flow frequency curve. The analyst needs to be careful to ensure that flood volumes do not exceed physical limits when applying this scaling procedure.

Probabilistic hydrographs, developed from scaling streamflow observations or from rainfall- runoff models, are combined with recommendations for initial reservoir levels for hydrograph routing. Reservoir routing issues and selection of varying initial levels are discussed in [30]. One can then determine a maximum reservoir level by routing the given hydrograph and initial reservoir level. Initial reservoir levels can sometimes have a large effect on maximum reservoir level estimates for extreme floods. Maximum reservoir elevation probability estimates depend on the inflow hydrograph peak, volume, shape, and probability estimate. The initial reservoir level can also be a major factor. The selection of an appropriate initial reservoir level is of considerable importance in determination of spillway adequacy [7]. For estimating maximum reservoir levels for design floods such as the PMF, Reclamation uses a fixed initial reservoir level. This initial reservoir level is usually set at the top of active conservation or bottom of the flood control pool. This assumption has been criticized as being unduly conservative. Current practice for most agencies is to assume conservatively high initial pool levels for routing PMFs. Instead of using a fixed initial reservoir level for routing hydrographs, variable initial reservoir levels are needed for risk analysis. Initial reservoir levels and associated exceedance probabilities should be estimated from daily reservoir elevation estimates for the period of record at the site of interest.

Practical tools have been developed for estimating probabilistic hydrographs that can be used in risk analyses for dam safety. These tools are presented in Reclamation's Stochastic Modeling Methods [30] and are summarized below. The key feature of the approach is to use peak-discharge frequency curves that include paleoflood data as a basis to develop hydrographs and volume frequency curves. The methods are relatively flexible and can be tailored to different types of investigations. The methods need to be adjusted depending on the available data at the site and region of interest. For example, if a peak-discharge frequency curve developed using the graphical approach is available, one could use less detailed methods to develop hydrographs because the data might not warrant sophisticated techniques. In contrast, if detailed, high-quality peak discharge and paleoflood data are available, one could use more refined methods such as the SEFM [20] discussed below.

Probabilistic hydrographs can be constructed based on streamflow estimates from gaging stations, historical data, and paleoflood data. Four components are used: (1) a peak discharge-probability relationship, (2) an extreme storm duration probability relationship, (3) relationships between peak discharge and maximum mean daily flow volumes, and (4) observed hourly flow hydrographs that have regulation effects removed. The key idea is calibration or scaling of hydrographs to match peak discharge for a given probability. The approach relies completely on the specification of a peak-flow frequency curve that describes the probabilities of interest, based on paleoflood data.

5.5 Combining Statistical and Physical Based Modeling Approaches

Best practices suggest that both statistical and physical based models should be used to estimate the hydrologic loading for extreme events. Statistical models are limited because of the lack of data and can predict floods for events only as rare as having an AEP of 1/40,000. Rainfall-runoff models should be used for events rarer than AEP 1/40,000, however, they should overlap the statistical model. Any differences in the overlap need to be explained and justified.

Larger projects involving stochastic event flood models (SEFM) are often calibrated using the statistical model. This is done after the physical model has been calibrated for the runoff using individual storm events. Once the proper behavior of the runoff model has been established, sampling parameters can be adjusted to give a better fit in the right tail of the statistical distribution.

5.6 Uncertainty

All methods used to describe hydrologic flood probability have uncertainty. Quantifying the uncertainty can be a difficult task for the hydrologic engineer because of the many factors that contribute to the uncertainty. Such factors might include errors in peak discharge measurement, errors in paleoflood discharge estimates, errors in paleoflood age estimates, and errors in fitting a statistical distribution. When using a physical-based rainfall runoff model, errors can arise in selecting sub-basins, parameterizing runoff characteristics, and distributing rainfall. Reclamation has observed that quantifying the uncertainty is directly related to the amount of effort applied to a flood frequency study.

Statistical models can better quantify uncertainties associated with the statistics of the data used and their fit to a statistical distribution. Such estimates can be made numerically using a variety of statistical methods that measure the confidence of the parameters making a distribution. Software programs such as EMA allow individual data uncertainties to be accounted in the overall confidence of the model. Such uncertainties can be expressed as measurement error in both time and space. For example, a paleoflood might have a discharge range as well as an age range. A systematic record might have error in the peak discharge measurement, often because the flood exceeds the established rating curve for the gage location. Care should be taken when gathering data for statistical models such as EMA. Systematic data that exceed the established peak discharge rating curve should be adjusted such that more statistics surrounding a particular datum are used, such as maximum and minimum. Historic and paleoflood data almost always have a range in discharge measurement. Paleoflood data will almost always have a range in time.

Physical models present more difficulty quantifying the uncertainty because they lack the mathematical dogma that surrounds statistical distributions. Much more judgment is used developing rainfall-runoff models in terms of parameterization. Models also introduce epistemic uncertainty because they often simplify or lump parameters by sub-regions, eliminating the spatial diversity that may occur. Often, an AEP-neutral approach will assume the uncertainty estimated in the rainfall statistics is directly translated into the uncertainty of the flood response. Adjusting the runoff parameters can also be done to estimate a range of flood responses from a singular event, however, this usually results in maximizing a modeled flood response. Such models may be suitable for design; but might be too conservative for risk analysis. A stochastic model is a better solution for quantifying uncertainty.

Stochastic models account for the variation in hydrometeorological parameters that cause extreme floods, however, error may still exist in the calibrated stationary model parameters. Such parameters include soil characteristics, snowmelt properties, streamflow properties, frequency rainfall parameters, etc. A stochastic simulation with a fixed set of stationary parameters is known as a realization. To quantify uncertainty, multiple stochastic simulations can be made for multiple realizations. Reclamation currently practices establishing eleven realizations using Latin Hypercube Sampling [114]. By using eleven simulations, each simulation can be ranked for each probability and the 90% quantiles are simply the 2nd and 10th ranked values and the median is the 6th.

The hydrologic engineer needs to actively participate in the overall risk analysis to effectively communicate how the uncertainty should be used. The risk analysis should be performed for the entire range of uncertainty. If the upper estimate or median estimate results in an un-favorable risk analysis, using a lower estimate will need to be justified by the hydrologic engineer. Often, uncertainty will be carried through the entire risk analysis to account for the uncertainty in other failure mode events related to the flood. Such uncertainties can be related to the flood magnitude; however, they can be difficult to quantify. An example might be the ability to close a gate or mobilize equipment during a large flood. The hydrologic engineer who performed the flood study for the risk analysis can offer valuable insight on the flood mechanics that can be used for quantifying uncertainties in other failure mode events.

6 RECLAMATION CASE STUDIES[1]

6.1 Hyrum Dam Hydrologic Hazard for Corrective Action Study (2012)

The Hyrum Dam Hydrologic Hazard for Corrective Action Study [49] provided a detailed hydrologic hazard analysis to support an analysis to evaluate risk reduction actions alternatives for hydrologically-induced spillway failure modes [115]. A summary of the study [49] is documented below (modified from its executive summary).

The primary objective of this study was to provide a detailed hydrologic hazard analysis to complement the results of the frequency hydrograph assessment for Corrective Action Study for Hyrum Dam [116]. The primary objectives of the study included: 1) evaluating multi-day storms with low probability of occurrence and their effects on the hydrologic hazard at Hyrum Dam; 2) collecting site-specific, detailed-level paleoflood data with stratigraphy, radiocarbon dating, and hydraulic modeling; and 3) developing inflow flood hydrographs associated with peak-flow frequency and volume frequency relationships for use in the hydrologic risk evaluation of Hyrum Dam.

The flood frequency at Hyrum Dam was estimated using the Expected Moments Algorithm (EMA). A comprehensive stream gage analysis was completed to ensure that all the appropriate and available data were used as input into the EMA model. Similarly, a stream and rain gage analysis were performed to identify actual rain-on-snow hydrographs that occurred during extreme storm events. Paleoflood and non-exceedance data were derived from field studies, detailed chronological analyses, and two-dimensional hydraulic modeling through a river reach downstream of Hyrum Dam on the Little Bear River.

The peak flow frequency upstream of Hyrum Reservoir on the Little Bear River (USGS gages #10106000 and #10105900) were estimated using EMA. The hydrologic hazard analysis used 68 annual peak discharge records from the Little Bear River upstream of Hyrum Reservoir. Site specific paleoflood non-exceedance data and one historic paleoflood were used as input into the EMA models. The results were consistent with both the annual peak discharge and paleoflood data. The upper estimate was determined by using a modified Australian rainfall-runoff model adopted from the 2009 study. The final hydrologic hazard curves for the best estimate and upper estimate were both recommended for use in the corrective action for Hyrum Dam and are summarized in Table 6-1 and illustrated in Figure 6-1.

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[1] The full USBR technical reports referenced here are typically not publicly available because they contain Critical Energy Infrastructure Information (CEII). Summaries are provided here instead.

Table 6-1 Summary of frequency flood hydrographs for Hyrum Dam [49].

Return Period (year)	Rain-on-snow Hydrographs*		Local Storm Hydrographs†	
	Peak Discharge (ft^3/s)	15-Day Volume (ac-ft)	Peak Discharge (ft^3/s)	1-Day Volume (ac-ft)
100	3,210	33,080		
200	3,830	33,950		
500	4,760	35,000	5,240	1,560
1,000	5,550	35,850	7,190	2,190
5,000	7,740	38,070	12,980	4,080
10,000	8,840	39,160	16,100	5,110
20,000	10,060	40,340	19,380	6,190
50,000	11,850	42,050	23,960	7,690
100,000	13,360	43,480	27,760	8,970

* *Best estimate (median EMA results)*

† *Upper estimate (95% confidence EMA results)*

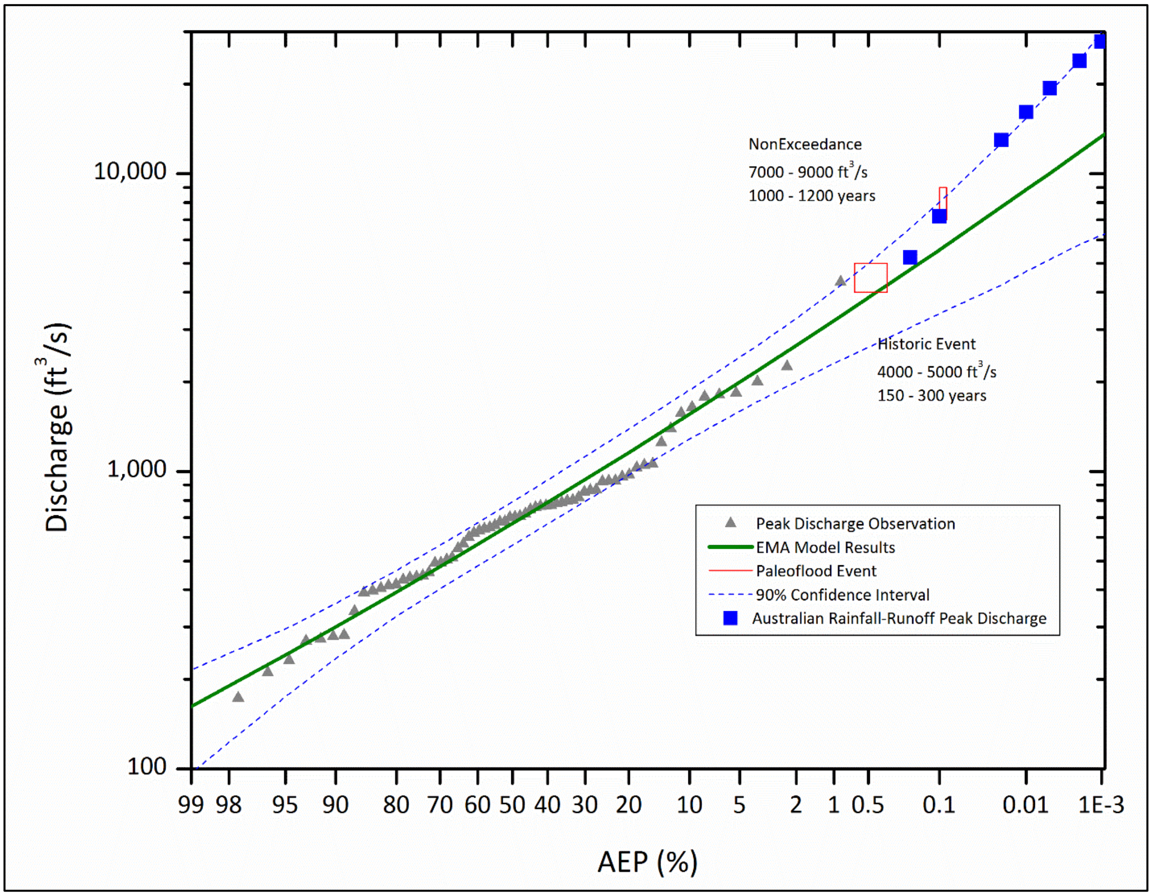


Figure 6-1 Flood frequency curve for Hyrum Dam [49].

Reservoir elevation exceedance curves were developed for daily reservoir elevations for seasonal and monthly spring rain-on-snow storms and local storms for Hyrum Dam. For routing the inflow hydrographs through Hyrum Dam, it was recommended that the initial reservoir water surface elevations vary in accordance with the reservoir exceedance curves for the appropriate storm season.

6.2 Hydrologic Hazard – Red Willow Dam (2010)

The Hydrologic Hazard for Red Willow Dam Study [117] provided a detailed hydrologic hazard analysis to support an analysis evaluate potential alternatives to mitigate potential risks associated with a hydrologic overtopping failure at Red Willow Dam [118]. This included revising hydrographs and estimating overtopping hazard. A summary of the study [117] is documented below.

The most recent flood frequency analysis for Red Willow Dam consisted of site-specific paleoflood data collection analysis, an updated flood frequency analysis, and reservoir routing of flood frequency hydrographs. Detailed paleoflood data were collected immediately downstream of Red Willow Dam and adjacent watersheds; updated paleoflood flow estimates were significantly lower than the previous regionalized estimates. Data from three USGS gaging stations were used to develop annual peak flow time series for Red Willow Dam. The flood frequency was developed using annual peak flow and paleoflood data (Figure 6-2) using a Bayesian, Maximum Likelihood Estimator (MLE) approach. The flood frequency program FLDFRQ3 was utilized because it readily incorporates peak discharge and age data uncertainties [85]. The maximum likelihood frequency model was run using the log base 10 Pearson Type III (LP3) distribution, with parameters μ, σ, and γ (mean, standard deviation, and skew). The calculated peak discharge estimates are shown in Table 6-2. The revised peak-flow frequency curve shown in Figure 6-3 was based on new, detailed paleoflood data collected within the Red Willow basin.

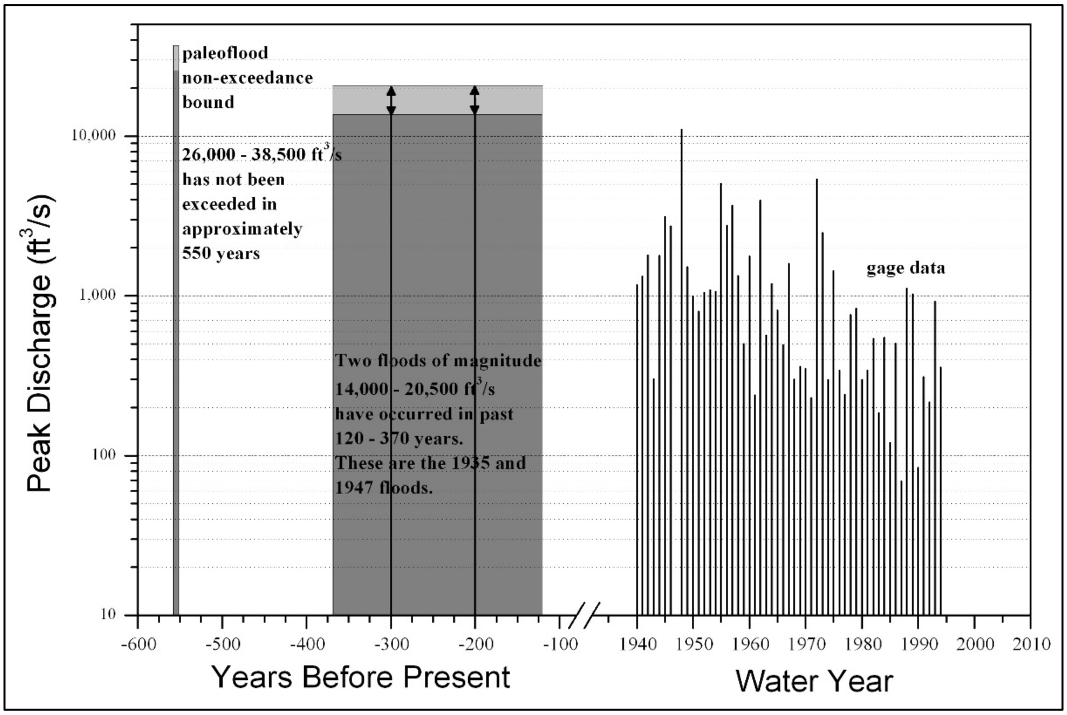


Figure 6-2 Red Willow annual peak discharge estimates (gage and paleoflood data).

Table 6-2 Red Willow peak discharge frequency estimates.

Return Period (yr)	5% Confidence Limit	Median (50%)	95% Confidence Limit
100	7,600	10,800	15,800
1,000	16,500	28,000	54,400
5,000	24,900	50,500	125,000
10,000	29,300	64,300	177,000
20,000	33,900	81,300	249,000
50,000	40,800	110,000	278,000*
100,000	46,500	138,000	*
200,000	52,700	171,000	*

**Discharges limited to the 278,00 ft^3/s peak-critical PMF peak*

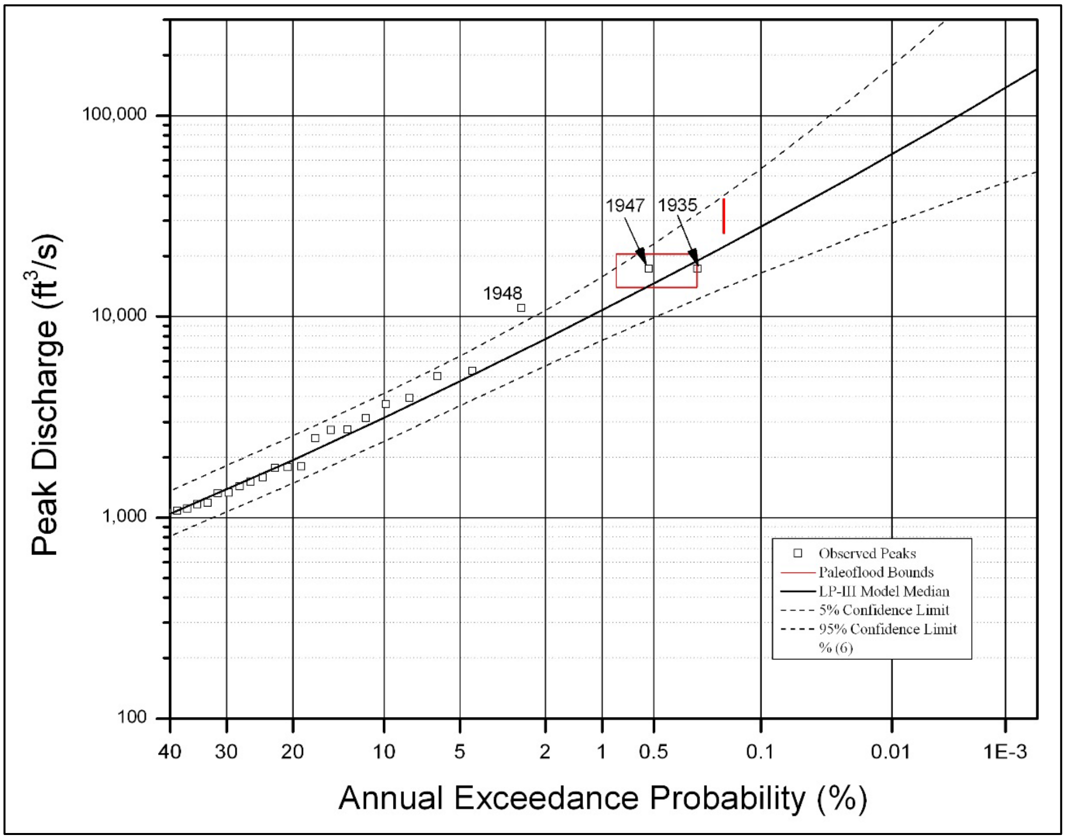


Figure 6-3 Red Willow Dam peak discharge frequency curve.

A sensitivity analysis was conducted to determine the potential effects of changing various paleoflood data on the revised peak-flow frequency curve and included the removal of the late Holocene non-exceedance bound and the addition of a late Holocene flood event (Table 6-3). Figure 6-4 shows the results of the sensitivity and comparison with previous estimates. The skew coefficient of the revised peak-flow frequency curve decreased by a factor of 1.8 compared to the 2000 frequency curve (Table 6-3). This decrease resulted in a substantial lowering of the frequency curve, especially the upper tail, for AEPs < 0.1%. The 10,000-year median flow estimate decreased by a factor of 2.6. The 2000 frequency curve generally follows the 95% confidence limit of the revised frequency curve. The paleoflood data sensitivity analyses indicate that estimates from variations in paleoflood data fall within the 90% confidence interval of the updated peak-flow frequency curve.

Table 6-3 Red Willow peak flow frequency results (including paleoflood data sensitivity).

LP-III Model	log-10 skew coefficient	10,000 yr median flow (ft^3/s)
2000 Study	0.610	168,000
2010 Study	0.342	64,300
2010 Study without late Holocene non exceedance bound	0.477	94,200
2010 Study with late Holocene paleo event	0.446	90,500

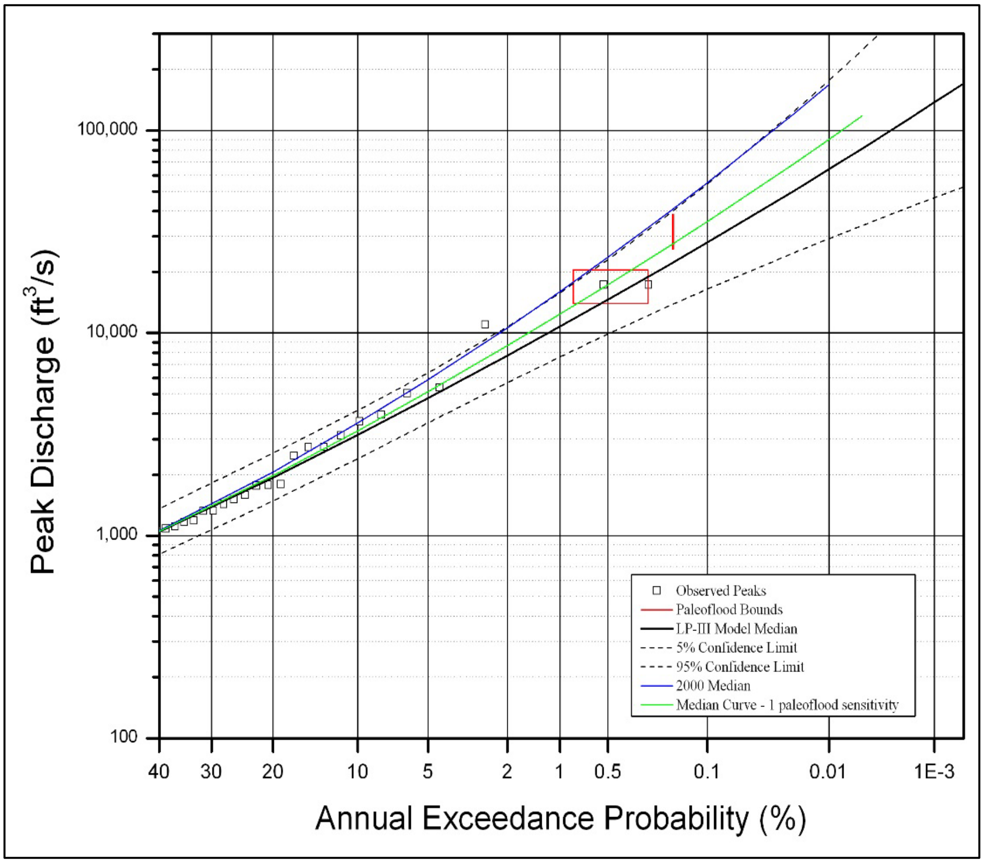
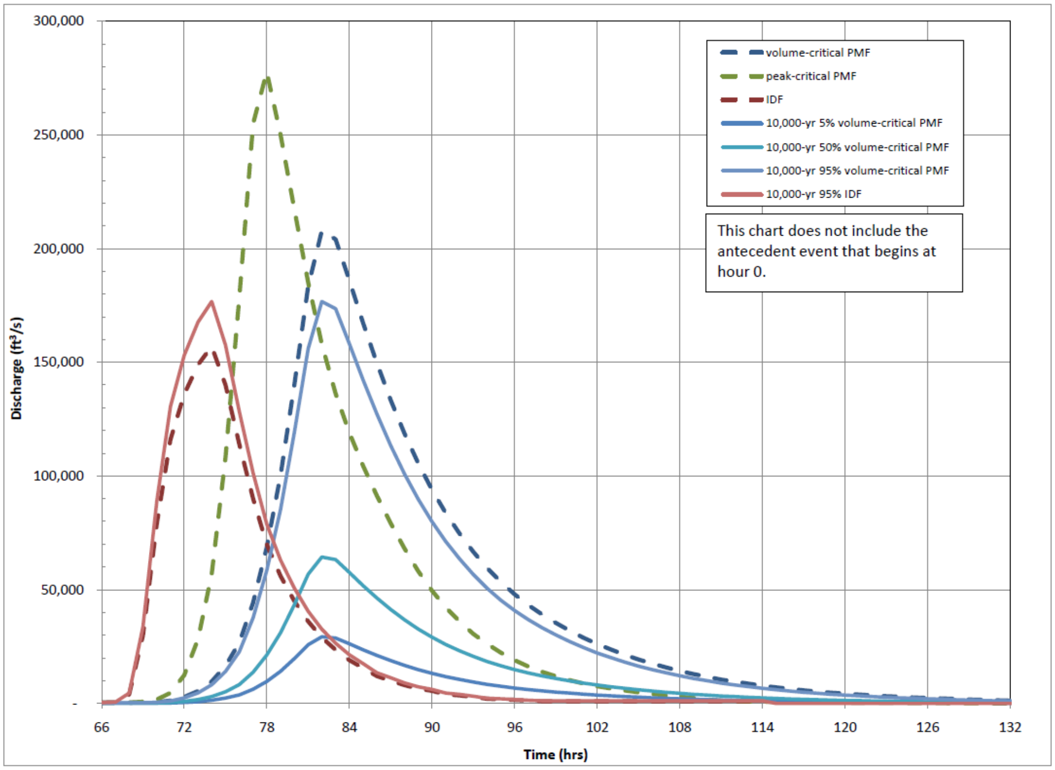


Figure 6-4 Flood frequency curves including current estimate, previous estimate, and sensitivity estimate.

The 1955 and 1984 hydrographs [119, 120] were scaled to the peak discharge estimates from the frequency analysis (see Table 6-2). The volume-critical PMF was used instead of the peak-critical PMF for conservatism since the hydrographs are all scaled to the same peak discharge. The volume-critical PMF and IDF hydrographs were scaled by the 100-, 1,000-, 5000-, 10,000-, 20,000-, 50,000-, 100,000-, and 200,000-year return period median, 5%, and 95% confidence limit event peak discharge estimates (Table 6-4). Figure 6-5 contrasts the 10,000-year scaled hydrographs with the IDF and volume-and peak-critical PMFs. The antecedent event (hours 0 to 24) was excluded from the hydrographs and the flow volume calculations to focus on the main flood runoff.

Table 6-4 Flood hydrograph volume (acre-ft) frequencies (excluding 100-year antecedent flood).

Return Period (yr)	PMF Hydrograph (74 hr)			IDF Hydrograph (48 hr)		
	5% Confidence Limit	Median (50%)	95% Confidence Limit	5% Confidence Limit	Median (50%)	95% Confidence Limit
100	8,500	12,000	17,500	5,600	7,800	11,500
1,000	18,300	31,100	60,600	12,000	20,400	39,700
5,000	27,800	56,200	139,000	18,200	36,900	90,900
10,000	32,600	71,600	197,000	21,300	46,900	129,000
20,000	37,700	90,500	278,000	24,700	59,300	182,000
50,000	45,400	122,000	-	29,800	80,200	-
100,000	51,700	153,000	-	33,900	100,000	-
200,000	58,600	190,000	-	38,400	125,000	-



This chart does not include the antecedent event that begins at hour 0.

Figure 6-5 Red Willow Dam scaled frequency hydrographs.

The 2010 hydrographs were routed through Hugh Butler Lake and Red Willow Dam using the Reclamation program Flood Route Version 1.6 [11] [121] The initial reservoir water surface elevation was set equal to the top of active conservation pool at 2581.8 ft. Hydrographs including the antecedent event were routed to provide conservative estimates of maximum reservoir levels. Additionally, it was demonstrated that routing hydrographs with and without the antecedent storm provided negligible differences in results. For the 95% confidence limit, the results from both the scaled PMF hydrograph and the scaled IDF hydrograph were averaged to define the best estimate of the upper confidence limit for the maximum water surface elevation at Red Willow Dam.

6.3 Trapped Rock Dam Hydrologic Hazard (2011)

The Trapped Rock Dam Hydrologic Hazard Study [45] was initiated as part of the ongoing Safety of Dams Program by Reclamation on behalf of the Bureau of Indian Affairs and the Zuni Tribe. The purpose of this study was to develop flood frequencies and associated flood hydrographs for an Issue Evaluation for Trapped Rock Dam. A paleoflood study was conducted to examine the history of large floods in the Trapped Rock Dam watershed and the Australian Rainfall Runoff method was used in developing frequency flood hydrographs. Frequency hydrographs were presented depicting hydrologic hazard loadings for Trapped Rock Dam for the purpose of aiding in risk-based decisions, and not considered for corrective action or final design. A summary of the study [45] is documented below.

In this hydrologic hazard study, the primary approach to flood frequency estimation included applying developed precipitation frequency volumes and temporal storm pattern in a rainfall-runoff model of the Trapped Rock Dam basin. Additionally, this study used a regional envelope curve, USGS regional regression estimates, and paleoflood information to inform flood potential in the region.

A regional peak discharge envelope curve was developed using 57 USGS gaging stations located nearby Trapped Rock Dam (Figure 6-6). The gages used were selected based on similar Hydrologic Unit Codes (HUCs). The regional envelope curve suggests that the 2.88 mi^2 Trapped Rock Dam basin could see a peak discharge of 2,100 ft^3/s (Figure 6-7). All of the controlling gages have similar watershed land cover to Trapped Rock with the exception of Dead Wash Tributary near Holbrook, AZ (09396400), which has less than 30% vegetation cover.

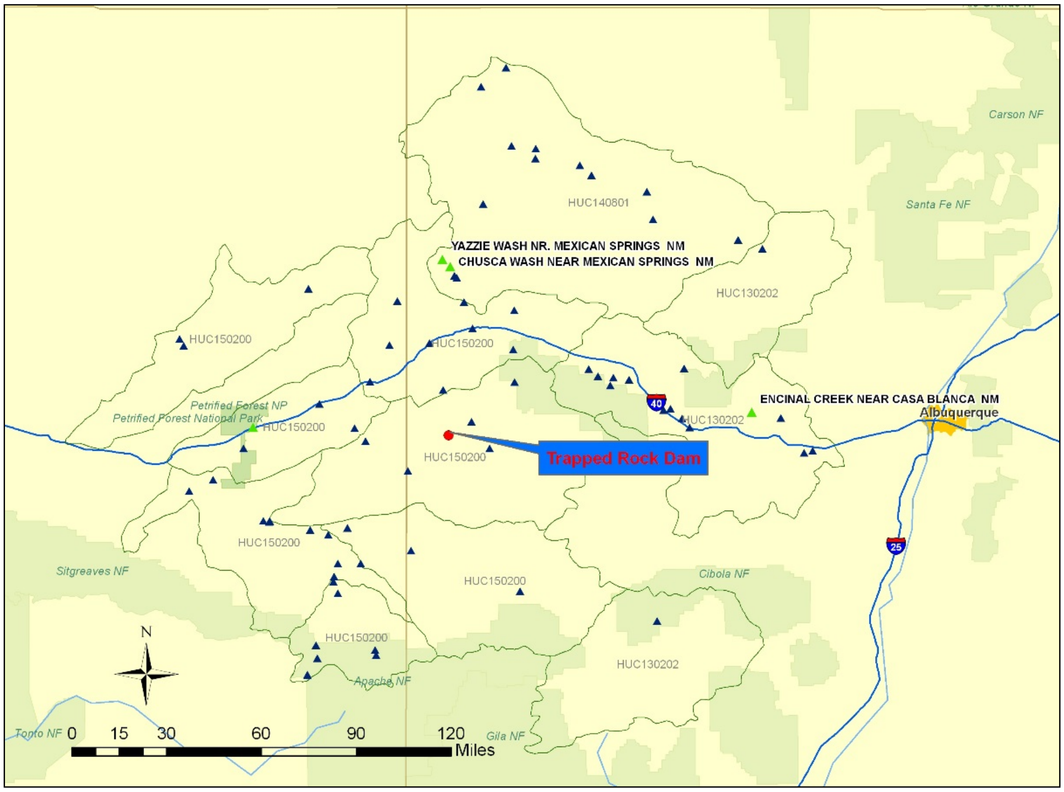


Figure 6-6 Location of gages used in Trapped Rock Dam envelope curve development.

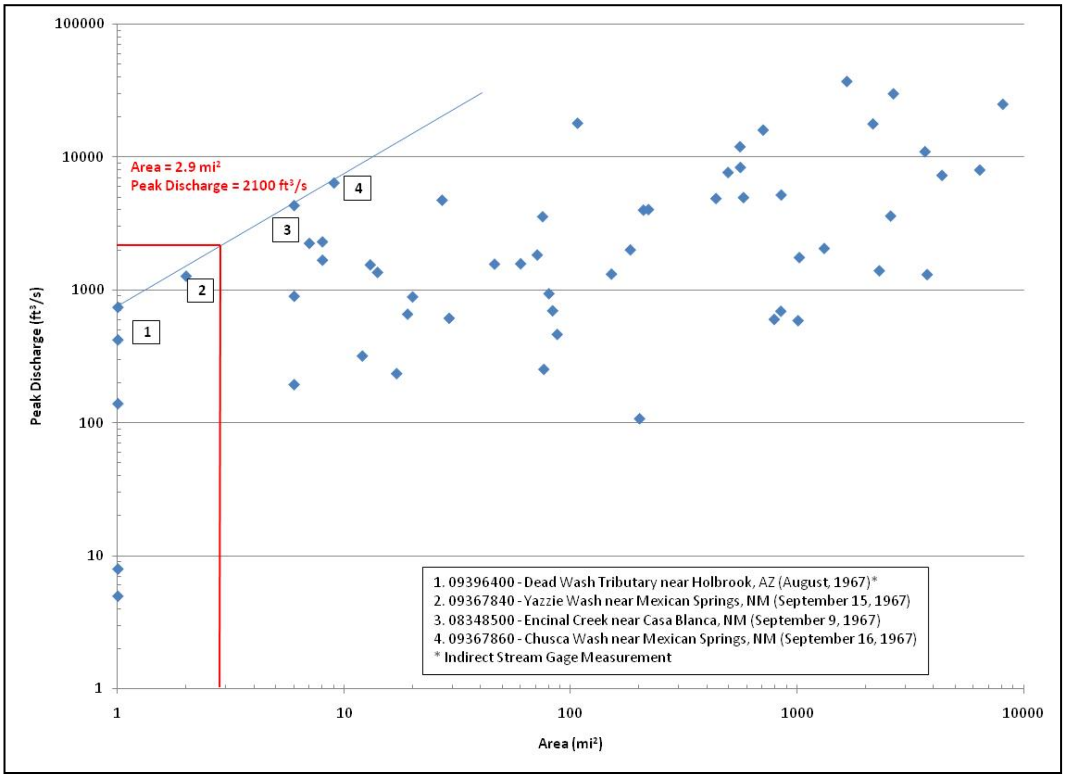


Figure 6-7 Regional envelope curve for Trapped Rock Dam.

The USGS National Streamflow Statistics (NSS) method was used to determine frequency peak discharge estimates to compare to rainfall-runoff modeling results. Specifically, the method for determining the magnitude and frequency of peak discharge for Trapped Rock Dam is outlined in “Analysis of the Magnitude and Frequency of Peak Discharges for the Navajo Nation in Arizona, Utah, Colorado, and New Mexico” [122].

Reconnaissance-level paleoflood data were collected along Trapped Rock Draw immediately downstream of Trapped Rock Dam [123]. Estimates for one paleoflood and a non-exceedance bound were developed on deposits preserved in two terraces along the arroyo. Age estimates for the deposits were based on stratigraphic correlations to dated stratigraphic sequences in the region (Table 6-5). The peak discharge estimates for the paleoflood and non-exceedance bound were based on the results of a one-dimensional hydraulic model (Table 6-5). The range in peak discharges for the paleoflood were estimated based on the depth of water needed to just inundate the terrace surface at site TR1 over a range of roughness values. The range of peak discharge estimates for the non-exceedance bound at site TR2 were based on a water depth needed to just inundate the terrace surface up to a depth of 2 feet.

Table 6-5 Paleoflood information for Trapped Rock Dam.

Event	Site	Age (yr B.P.)	Peak Discharge (ft^3/s)
Paleoflood	TR1	<500	700-900
NEB[1]	TR2	2000-4000	1,200-2,600

[1] *Non-Exceedance Bound*

Rainfall-runoff modeling was used to develop frequency hydrographs for Trapped Rock Dam. NOAA Atlas 14 was used to define 6-hour point precipitation frequency estimates up to the 1,000-year event. For events rarer than the 1000-yr event, the precipitation frequency curve was created using the CRC-FORGE approach of the ARR method [7]. An AEP of 10^{-7} was used for defined PMP [124], as suggested for basin with areas less than 100 km^2 [7]. An areal reduction factor of 0.88 was applied to all of the NOAA Atlas 14 precipitation estimates up to the 1000-yr event. Storm temporal patterns from 13 storms measured at nearby McKinley station were normalized to produce final unit hyetograph.

The runoff was calculated by using a constant infiltration rate and was transformed into a hydrograph using methods outlined by the National Resources Conservation Service [73]. This included estimating constant loss rates based on hydrologic soils classification. For events rarer than the 100 year event, the loss rate was adjusted by fitting a normal distribution between the 100-year loss rate and the 10,000,000 year loss rate or PMF loss rate. This allowed the model to maintain AEP neutrality with the assumption that a frequency rainfall event yields a flood of the same frequency. The SCS method was used for developing the unit hydrograph [73] for Trapped Rock Dam.

Frequency hydrographs were computed for Trapped Rock Dam using the U.S. Army Corps of Engineer’s HEC-HMS rainfall-runoff model. Table 6-6 summarizes the results and Figure 6-8 presents the frequency hydrographs.

Table 6-6 Hydrologic loadings summary for Trapped Rock Dam.

Return Period (yr)	Peak Discharge (ft^3/s)			1-Day Volume (ac-ft)		
	Best Estimate	Low Estimate	High Estimate	Best Estimate	Low Estimate	High Estimate
2	28	24	32	8	7	9
5	35	30	40	10	8	11
10	41	36	89	11	10	22
25	130	40	240	30	12	56
50	240	120	400	56	28	92
100	390	210	560	90	47	131
500	910	620	1170	212	145	271
1000	1170	830	1470	272	193	340
2000	1450	1040	1800	336	242	417
5000	1830	1340	2310	423	311	542
10,000	2130	1560	2780	502	361	678

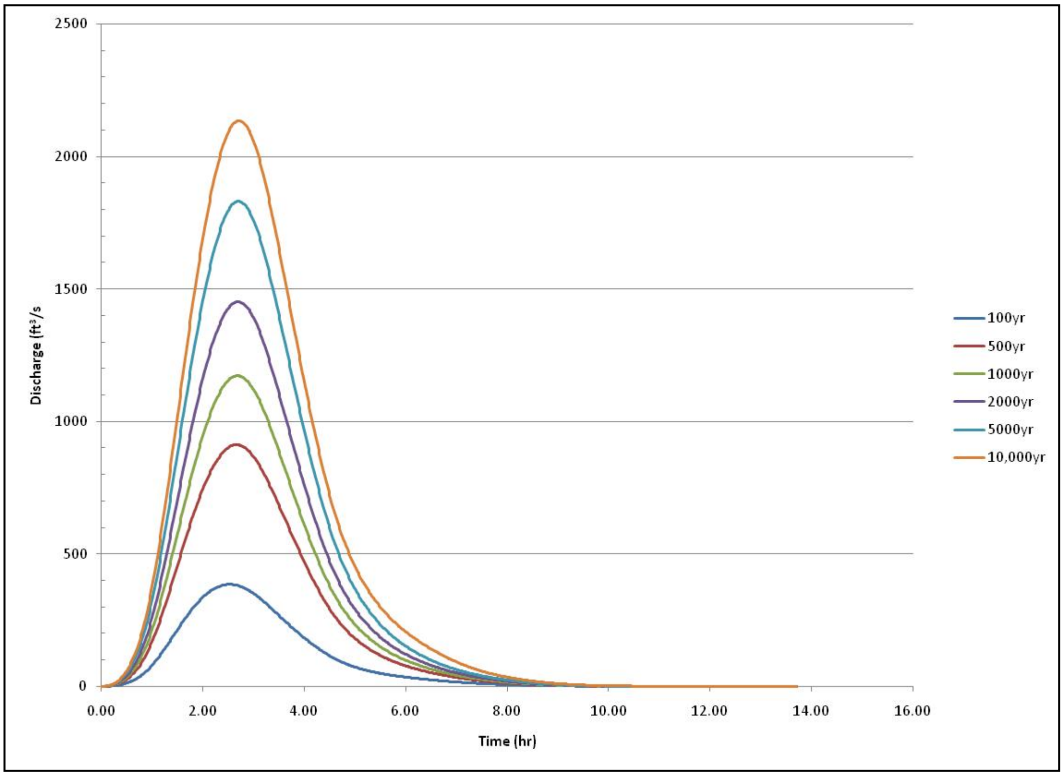


Figure 6-8 Flood frequency hydrographs for Trapped Rock Dam.

Peak discharge frequencies were compared to USGS regional regression estimates and paleoflood data (Figure 6-9).

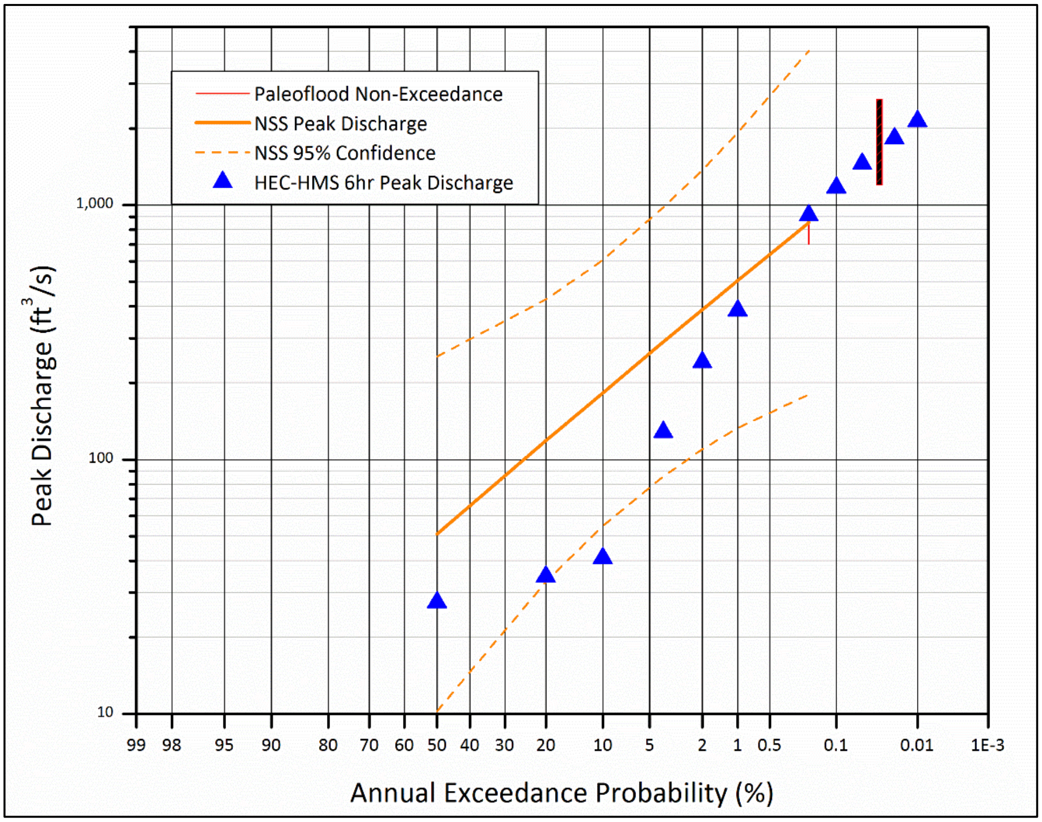


Figure 6-9 Peak discharge frequency estimates with USGS regional regression and paleoflood results.

6.4 Friant Dam Hydrologic Hazard for Issue Evaluation (2013)

The Hydrologic Hazard for Friant Dam [125] provided a detailed probabilistic flood loading analysis as part of an Issue Evaluation Study to address a 2003 Safety of Dams recommendation to better quantify risks associated with overtopping failure modes [126]. This was accomplished by developing flood frequency hydrographs through stochastic rainfall-runoff modeling using the Stochastic Event Flood Model (SEFM) [20], and updating reservoir routings of new flood frequency hydrographs. A summary of the study [125] is documented below (modified from its executive summary).

This study provided hydrologic hazard estimates for Friant Dam near Fresno, California, and included probabilistic flood loadings and reservoir elevations to be used in a risk assessment for evaluating overtopping risks. The main objectives of this hydrologic hazard study were to:

1. evaluate multi-day extreme storm sequences and their effects on the hydrologic hazard at Friant Dam.
2. collect at-site, detailed paleoflood data with stratigraphy, radiocarbon ages, and hydraulic modeling within the basin, to supersede preliminary estimates used in the 2009 CFR [126].
3. develop reservoir elevation-exceedance probability relationships, reservoir inflow hydrographs, and peak-flow frequency and volume relationships to assess the overtopping risk of Friant Dam.

A basin-average precipitation-frequency curve was developed by fitting a 4-parameter Kappa distribution to regional precipitation data and a basin-average regression relationship and is shown in Figure 6-10. The controlling precipitation events that lead to flooding at Friant Dam occur during the winter months between November and March. Spatial and temporal patterns were developed for 17 unique precipitation events of 10-day duration with maximum 72-hour precipitation volumes occurring in the middle of these events.

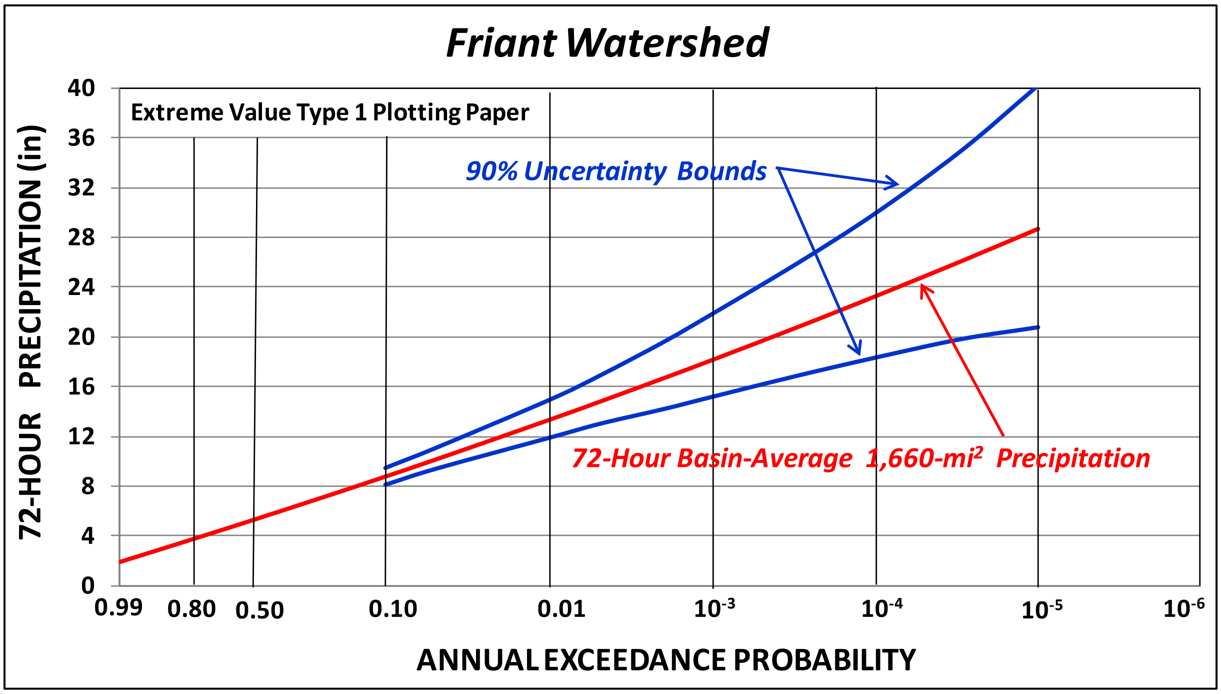


Figure 6-10 Derived 72-hour basin-average precipitation-frequency relationship and 90% uncertainty bounds for Friant watershed.

The largest flood recorded on the San Joaquin River near Friant occurred on December 24, 1867, and was estimated to have a peak discharge ranging from 84,000 to 110,000 ft^3/s. The largest flood occurring with the existing regulating facilities on the San Joaquin River occurred on January 3, 1997, having a peak discharge of 86,500 ft^3/s. Other significant floods occurred on January 11, 1862, January 25, 1914, December 11, 1937, and December 23, 1955.

Paleoflood data were collected on the San Joaquin River near Friant Dam to be incorporate in the flood frequency analysis. These data included positive evidence of floods (paleofloods) and non-exceedance information. The paleoflood data suggested that floods having a peak discharge magnitude of 44,000 to 110,000 ft^3/s may have occurred at least 6 times during the past 350 to 550 years. Paleoflood non-exceedance data suggested that there have been no floods having a peak discharge between 105,000 and 140,000 ft^3/s in the past 1,040 to 2,400 years.

A peak flood frequency curve was developed for upstream Redinger Dam from stream gage data and paleoflood data using the Expected Moments Algorithm (EMA). The results of the EMA analysis are presented in Figure 6-11.

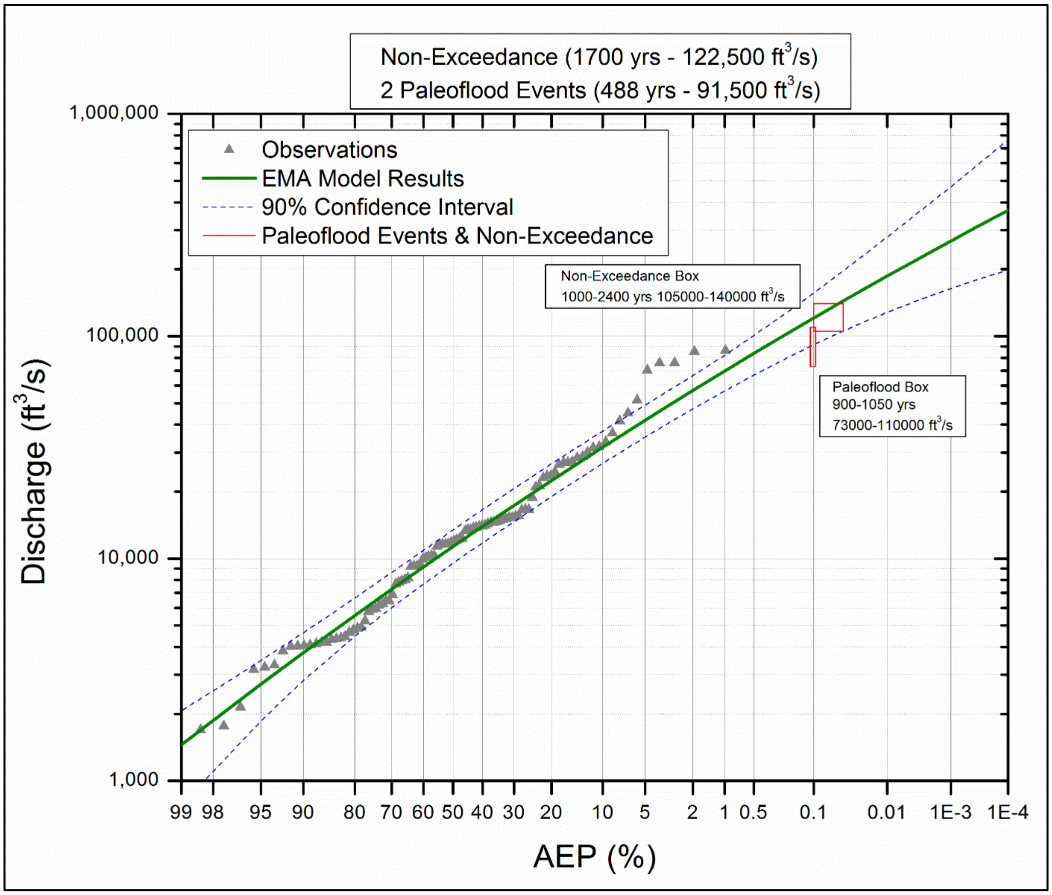


Figure 6-11 EMA flood frequency curve for Redinger Dam, CA.

A Stochastic Event Flood Model (SEFM) was developed for the Friant Dam watershed. Developed magnitude-frequency rainfall estimates, snowpack estimates, and rainfall storm spatial and temporal patterns were used as input into the model. The model was calibrated to observed events and estimates of hydrographs for the 2% to 0.001% annual exceedance probability events were developed from calibrated model. An initial reservoir water surface elevation was also stochastically developed and associated with each SEFM-generated hydrograph for incorporation into reservoir routing of these hydrographs to develop maximum reservoir water surface frequency relationship.

The uncertainty for SEFM was estimated using a Latin Hypercube Sampling (LHS) approach. LHS is a method of generating a sample of plausible collections of parameter values from a multidimensional distribution [112]. This analysis resulted in a total of 710,160 individual hydrographs generated within 4 probability zones with their associated initial reservoir elevations.

The median peak discharge for the 1,000- and 10,000-year return periods were determined to be 164,500 ft^3/s and 278,700 ft^3/s respectively. Figure 6-12 and Figure 6-13 present the peak discharge and volume frequency relationship with uncertainty at Friant Dam.

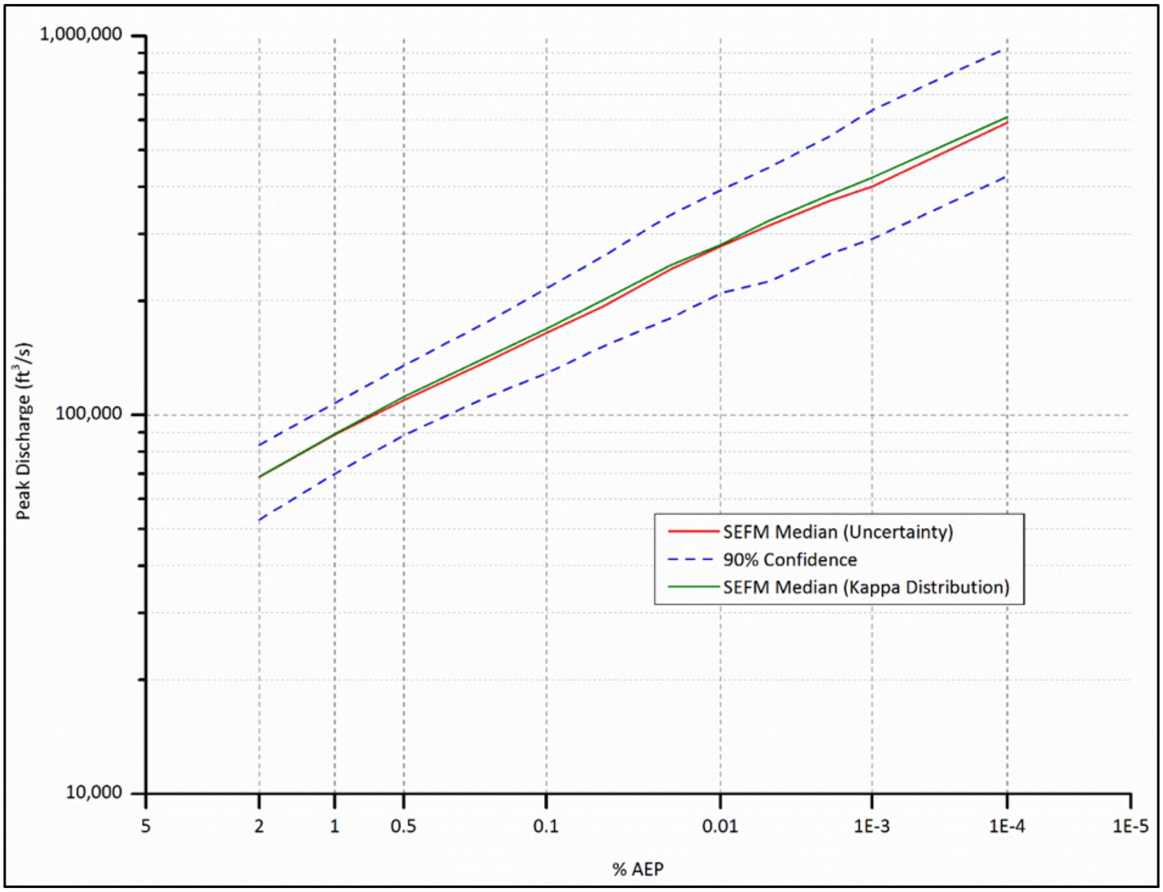


Figure 6-12 SEFM frequency peak discharge for Friant Dam, CA.

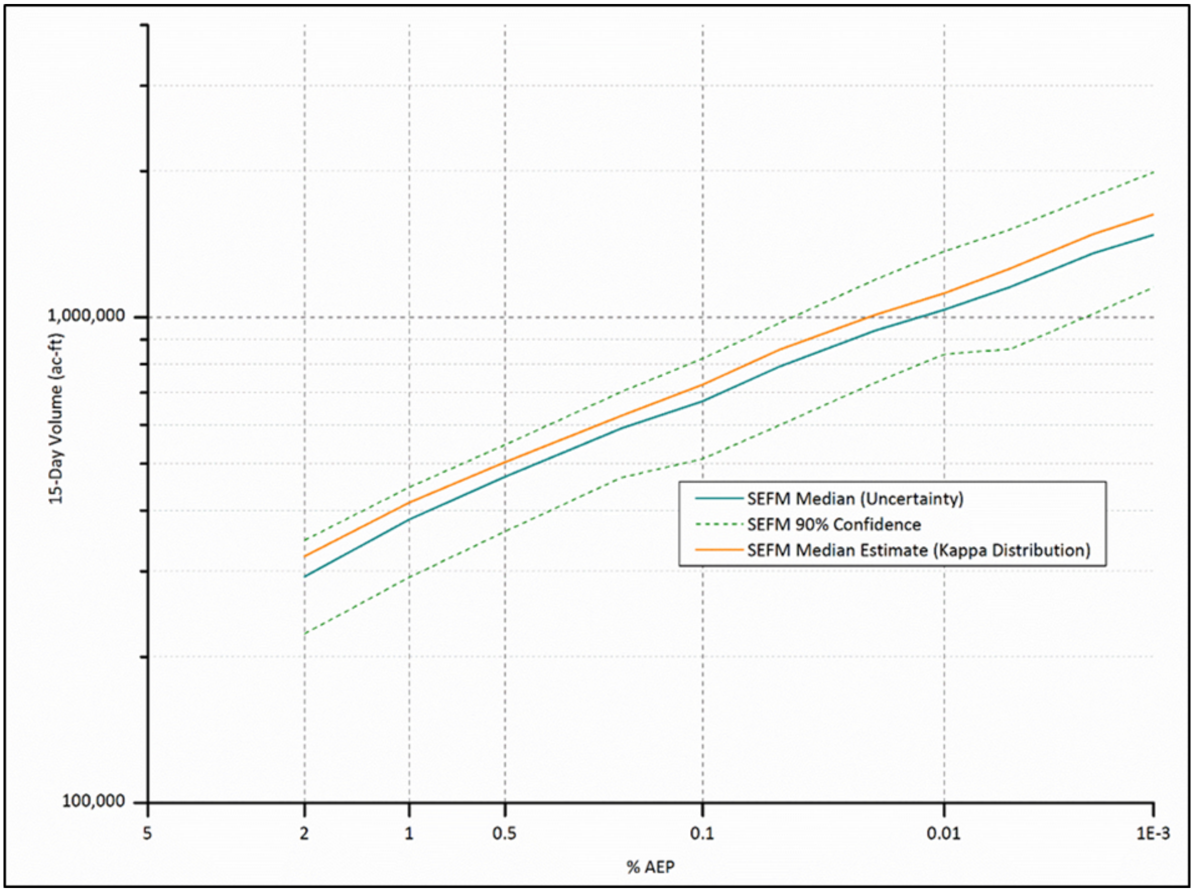


Figure 6-13 SEFM total frequency volume curve with uncertainty for Friant Dam, CA.

Although this project presented frequency relations based on the ranked peak discharge and ranked volume, the hydrologic load used for risk assessment is the reservoir elevation frequency. The maximum reservoir water surface elevation frequency was by routing the SEFM-generated hydrographs.

This study performed reservoir routings based on stochastically generated initial reservoir elevations and operational stage-storage and stage-discharge curves developed during a 1991 PMF routing technical memorandum. Results of the current routing is presented in Figure 6-14. The median maximum reservoir elevation for the 1,000-, 5,000-, and 10,000-year return periods were determined to be 581.1, 587.0, and 588.4 feet respectively.

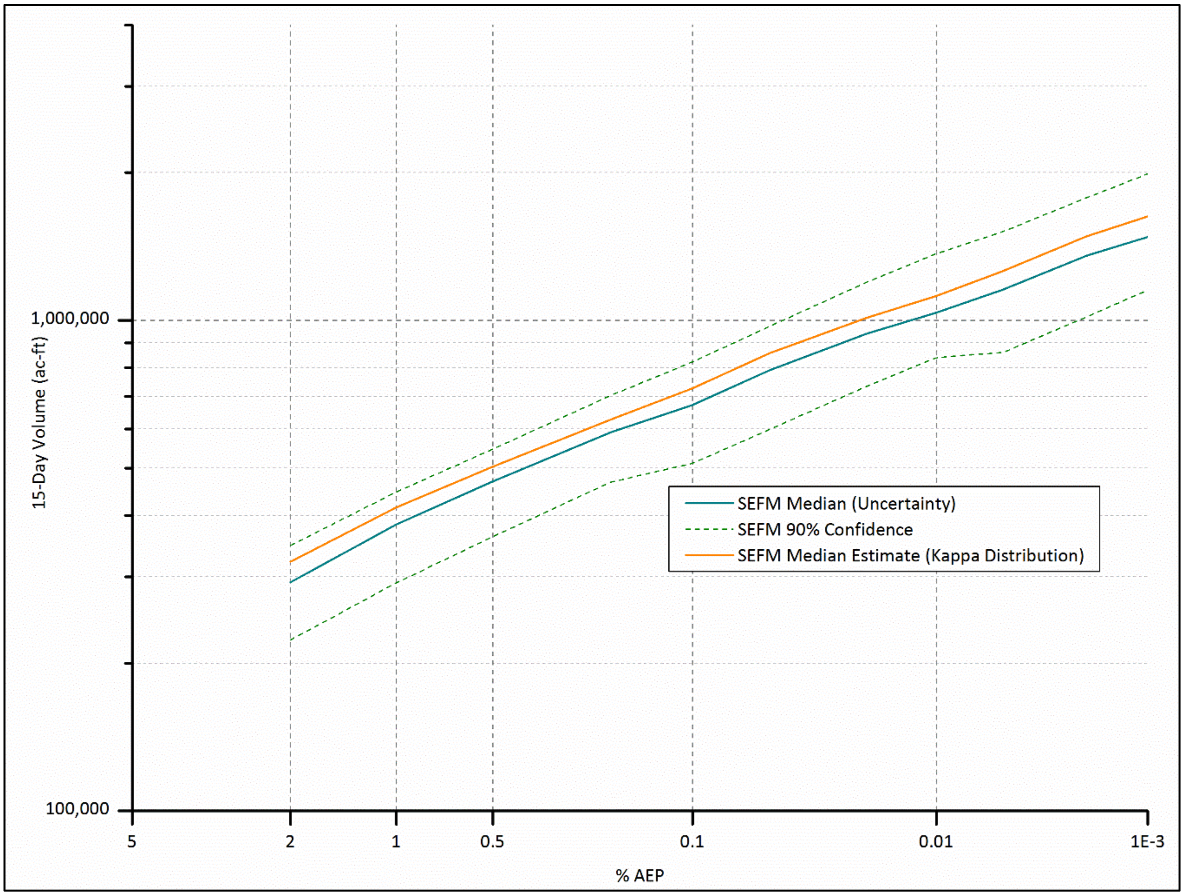


Figure 6-14 SEFM frequency volume curve (median estimate) for Friant Dam, CA.

The flood hazard analysis results presented in this report, including hydrographs, initial reservoir levels, and routed maximum reservoir levels, are appropriate for use in an Issue Evaluation-level baseline risk analysis. A level-pool routing spreadsheet was developed for routing all the hydrographs provided by this study. This spreadsheet provides a static stage-discharge and stage-storage relationship that can be modified for different design alternatives. If any of the alternatives involve changes in operational rules or restrict reservoir elevations, additional stochastic modeling would need to be performed.

6.5 East Park Dam Issue Evaluation – Hydrologic Hazard (2011)

The Hydrologic Hazard for East Park Dam [44] provided a detailed hydrologic hazard analysis as part of an Issue Evaluation Study to address a 1998 Safety of Dams recommendation to quantify flood frequency relationships as part of a greater effort to determine if remedial actions should be taken to accommodate hydrologic events . A summary of the study [44] is documented below.

This study provided flood frequency estimates for East Park Dam, Colusa County, California. The primary objectives of this hydrologic hazard study were to:

1. evaluate multi-day storm sequences with low probability of occurrence and their effects on the hydrologic hazard at East Park Dam.

2. collect site-specific, detailed level paleoflood data with stratigraphy, radiocarbon dating, and hydraulic modeling to supersede the reconnaissance level paleoflood study used for previous hydrologic hazard studies.
3. develop inflow flood hydrographs associated with peak-flow frequency and volume frequency relationships to evaluate the hydrologic risk at East Park Dam.

The 2011 IE for Friant Dam included a flood frequency analysis utilizing at-site paleoflood data, and two methods to develop flood frequency hydrographs [44]. The two methods included i) the Expected Moments Algorithm [81], and ii) rainfall-runoff modeling method using L-moments precipitation statistics and the Sacramento Soil Moisture Accounting Model (SAC-SMA; [127, 128]). The two methods were based on different base assumptions, different data requirements, and were intended to provide some range of uncertainty associated with the flood frequency estimates. Both methods were used in calculating the ‘best estimate’ hydrologic hazard at East Park Dam.

Paleoflood exceedance and non-exceedance data were collected in a one-mile-long reach located on Little Stony Creek just downstream from East Park Dam. Paleoflood data were derived from field studies, laboratory analyses, and hydraulic modeling at four locations. A chronology for the alluvial stratigraphy that includes sediment deposited by at least three floods and a soil formed on a stable terrace surface representing a non-exceedance bound was established utilizing the extent of soil development, radiocarbon age analysis, and dendrochronology. SRH2D, a two-dimensional depth-averaged hydraulic model [62], was used to estimate peak discharge values associated with the study locations. Paleoflood results indicated an exceedance flood bound with a peak discharge ranging from 8,000 to 10,000 ft^3/s that has been exceeded 3 times in the past 40 to 120 years, and a non-exceedance flood bound with a peak discharge ranging from 42,000 to 48,000 ft^3/s that has not been exceeded in the past 860 to 1,360 years [129].

The recommended hydrologic hazard curve combined results from the two methods. Because the two flood frequency analysis methods were independently developed, were similar in shape, and had a point of intersection, the point of intersection was accepted as the point at which to transition between the two curves. The EMA curve represented the recommended hydrologic hazard curve for AEPs at and greater than 5.0×10^{-5} and the L-moments/SAC-SMA curve was selected to represent the hydrologic hazard curve for AEPs less than 5.0×10^{-5}. (It should be noted that runoff from the East Park Dam basin has a snowmelt component, while the discharge in the lower AEP range is expected to be rainfall dominated.) The 5 and 95 percent confidence limits from the EMA model results were selected to represent the upper and lower confidence limits of the study. The final hydrologic hazard curve for East Park Dam is shown in Figure 6-16 and Summarized in Table 6-7 Summary of final hydrologic hazard results for East Park Dam, CA..

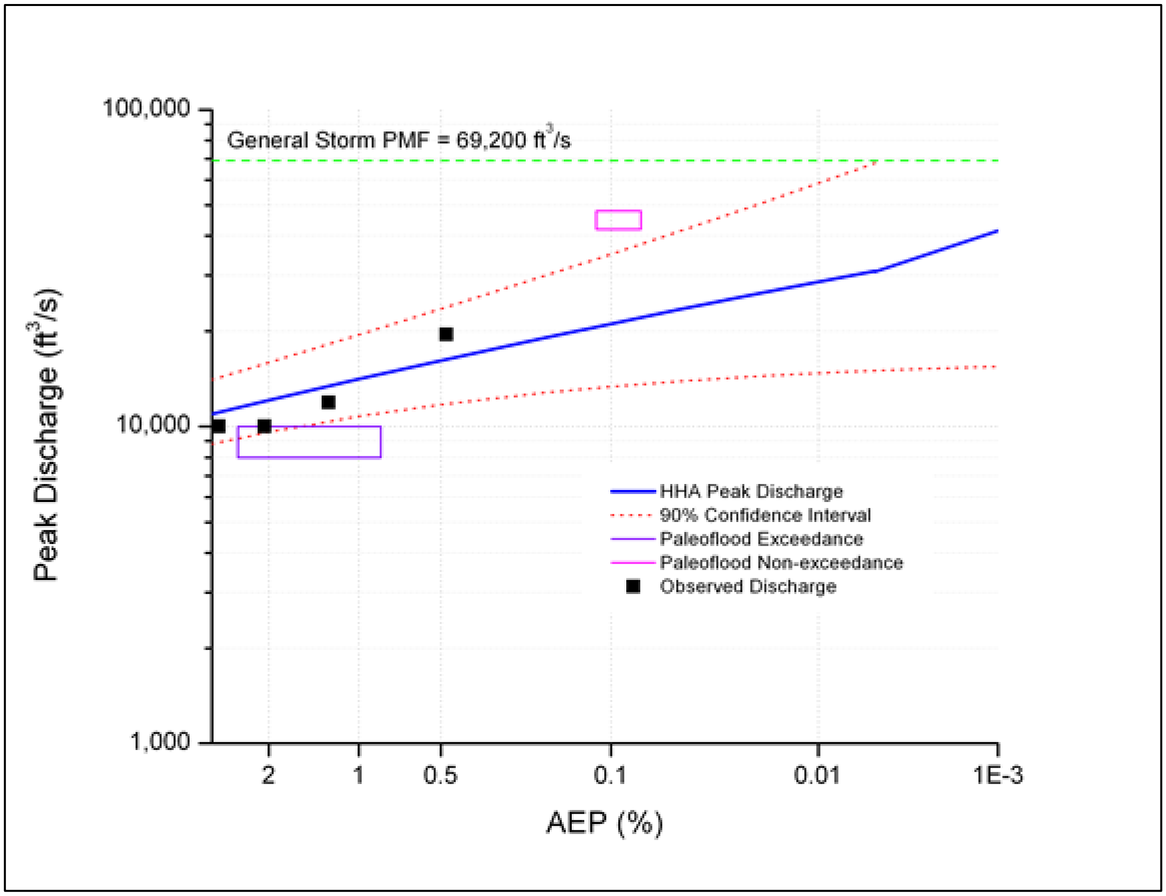


Figure 6-16 Final best estimate hydrologic hazard curves for East Park Dam, CA.

Table 6-7

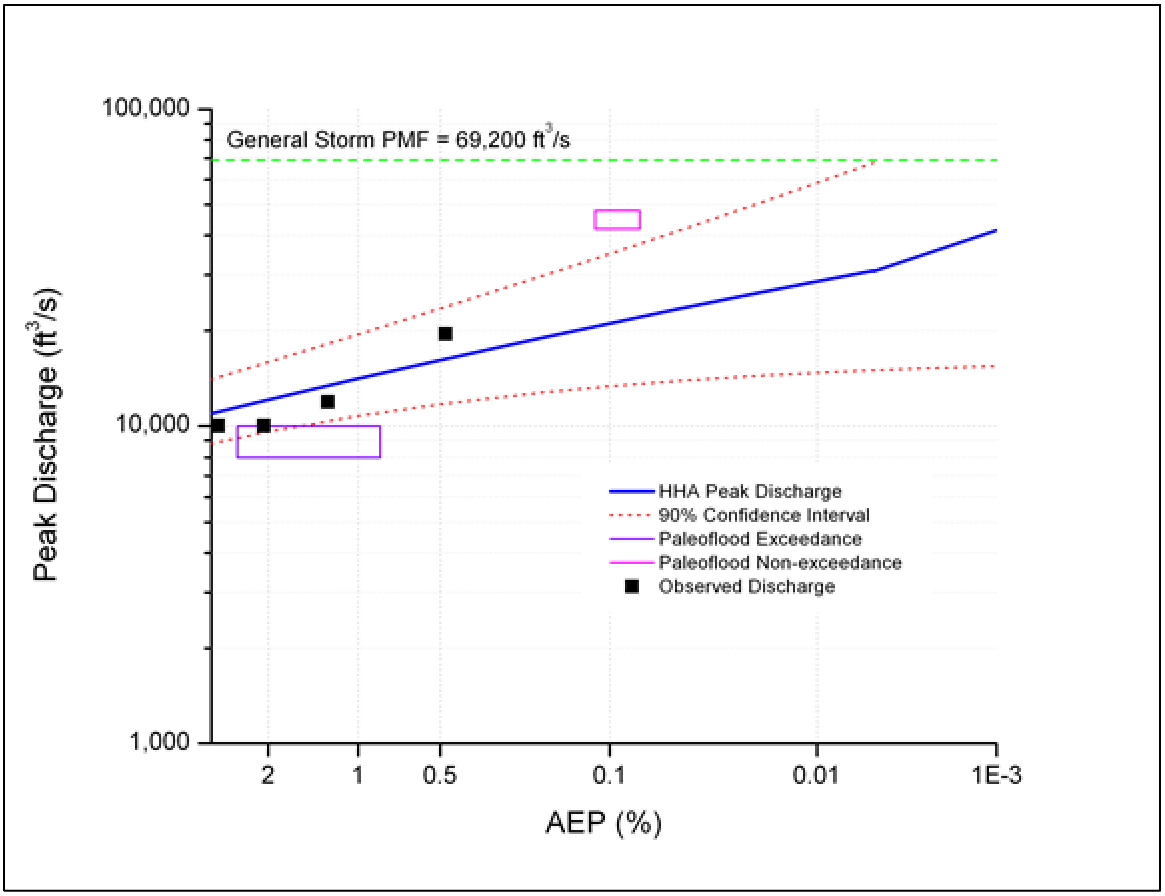


Figure 6-15 Final best estimate hydrologic hazard curves for East Park Dam, CA.

Table 6-7 Summary of final hydrologic hazard results for East Park Dam, CA.

Return Period (years)	AEP	Peak Discharge (ft^3/s)			7-Day Volume (acre-feet)		
		Best Estimate	5% Confidence Limit	95% Confidence Limit	Best Estimate	5% Confidence Limit	95% Confidence Limit
100	0.01	14,100	10,750	19,470	40,526	30,898	55,961
200	0.005	16,100	11,710	23,490	46,275	33,657	67,515
500	0.002	18,900	12,740	29,630	54,322	36,617	85,163
1,000	0.001	21,100	13,350	35,010	60,646	38,371	100,626
2,000	0.0005	23,300	13,860	41,100	66,969	39,836	118,130
5,000	0.0002	26,300	14,400	50,440	75,591	41,388	144,975
10,000	0.0001	28,600	14,720	58,620	82,202	42,308	168,486
20,000	0.00005	31,000	14,990	67,910	89,100	43,084	195,187
50,000	0.00002	36,600	15,280	69,200	105,279	43,918	198,895
100,000	0.00001	41,500	15,450	69,200	119,380	44,406	198,895

Frequency hydrographs were developed directly from the SAC-SMA model results. To maintain an increase in volume as return period increased, one hydrograph was selected to represent the overall hydrograph shape. The 2,000-year hydrograph was selected to be the most representative of the basin's runoff response. The final frequency hydrographs were scaled from the 2,000-year frequency hydrograph.

A reservoir routing study was performed in 2012 based on the 2011 IE frequency hydrographs [130]. Four starting reservoir water surface elevations were evaluated: 1185.0, 1197.0, 1202.0 and 1203.5 ft. For each of these starting elevations, the best estimate, and 5% and 95% confidence limit frequency hydrographs were routed.

6.6 Unity Dam Hydrologic Hazard for Issue Evaluation (2017)

The Unity Dam Hydrologic Hazard Study [131] provided probabilistic flood loading estimates as part of an Issue Evaluation to perform a risk analysis to re-examine the probability of failure and annualized loss of life due to hydrologic failure modes [126]. This was accomplished by developing flood frequency hydrographs through stochastic rainfall-runoff modeling using the Stochastic Event Flood Model (SEFM) [20], and updating reservoir routings of new flood frequency hydrographs. A summary of the study [131] is documented below.

This study provided hydrologic hazard estimates for Unity Dam, Oregon and included probabilistic flood loadings and reservoir elevations to be used in a risk assessment to better understand risks from hydrologically induced failure modes. The main objectives of this hydrologic hazard study were to:

1. Calculate peak discharge frequency estimates for events as rare as 1-in-100,000,000 years using multiple data sources and multiple methods. Data sources included systematic records, historical information, paleoflood data, and reconstructed inflow estimates. Methods include EMA and SEFM for hydrologic risk analysis.
2. Identify the duration and seasonality of multi-day extreme storms and use L-moments regional frequency analysis in quantifying hydrologic hazards at Unity Dam.
3. Develop reservoir elevation-exceedance probability relationships, reservoir inflow hydrographs, and inflow volume frequency estimates to assess the overtopping risk at Unity Dam.

A full meteorological study was performed to accurately model the variety of storms that impact the Unity Dam watershed. The season of interest, wherein annual maximum 72-hour precipitation events result in significant streamflow response and, consequently, large inflow volumes to Unity Dam, occur during the spring months between March and May (MAM). Seasonality was determined through historical storms from HMR 57 [132] and from available point observations at local weather station in Tipton, OR. Spatial and temporal patterns of eight historical storms that triggered a streamflow response within the MAM season were identified and used to develop storm templates for use in SEFM. Additional data, including hourly time series of precipitation, freezing level height, and 1000mb temperature were used to develop the storm templates. Continuous daily minimum and maximum temperatures, precipitation, and snow-water-equivalent were used to calibrate SEFM. A regional precipitation-frequency analysis was performed to determine the 72-hour basin-average precipitation-frequency curve for the Unity Dam watershed Figure 6-16. Precipitation depths were randomly sampled from this frequency curve and used as input into SEFM by scaling each of the storm templates.

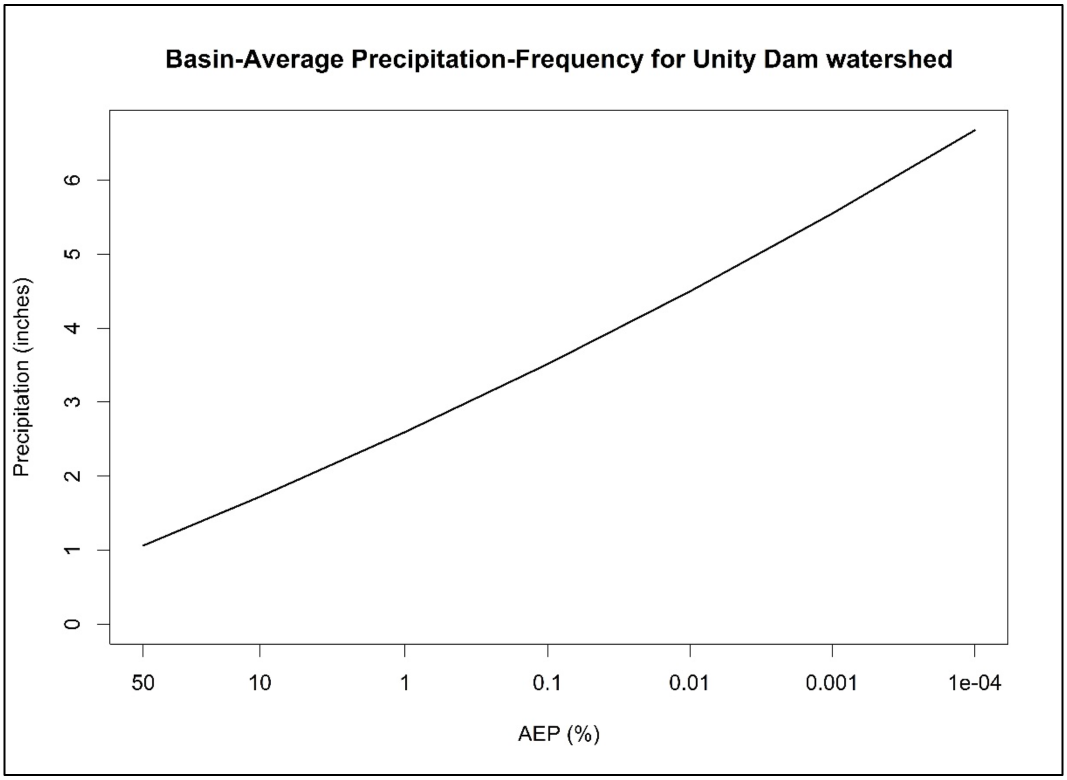


Figure 6-16 Basin-average three-day (72-hour) precipitation-frequency curve, computed by scaling the four-parameter Kappa RGC by the MAM at-site mean for the Tipton station and applying the areal-reduction factor.

Paleoflood data were collected on the Burnt River below Unity Dam to be incorporated in the statistical flood frequency analysis using the Expected Moments Analysis (EMA). Three paleoflood sites provided two non-exceedance bounds. The first indicated that a flood with peak discharge between 5,000 and 15,000 ft^3/s has not been exceeded in the past 370 to 735 years. The second non-exceedance data indicated that a flood with peak discharge between 4,600 and 6,400 ft^3/s has not been exceeded in the past 990 to 1,045 years. The two paleoflood non-exceedance bounds were determined from different paleoflood sites, which means the magnitudes and ages of the non-exceedance bounds may seem contradictory. Still, inclusion of these paleoflood data provides a perspective on the magnitudes of prehistoric floods in the vicinity of Unity Dam, and greater confidence in rarer flood-frequency estimates.

A flood-frequency analysis was performed using the EMA, which digests systematic (recorded), historic (inferred), and paleoflood (reconstructed) peak discharge data to produce a flood-frequency curve with 90% confidence bounds. To extend the period of record used in the EMA analysis, peak discharge data from hydrologically-similar stream gages near the Unity Dam watershed were used. To account for differences in contributing drainage area, the observed peak discharge values were transposed to the drainage area of Unity Dam using the maintenance of variance extension (MOVE) method [53].

Precipitation-frequency estimates, snowpack observations, as well as rainfall storm spatial and temporal patterns were developed as input to the model. Precipitation-frequency depths, spatial and temporal storm patterns, and numerous watershed characteristics were developed and quantified to be used as input to SEFM. A continuous calibration process, over the period 2000-2016, was used to obtain best estimates of SEFM model parameters. Additional calibration was done by comparing SEFM simulated peak discharge and inflow volume frequency curves to those estimated using EMA. Uncertainty for SEFM was estimated using the Latin Hypercube Sampling (LHS) approach. Precipitation-frequency parameters, deep percolation rate, and deep recharge loss were the three sets of parameters that were included in the LHS uncertainty analysis. In all, 11 LHS parameter sets were defined, and the same magnitude-frequency processes were calculated. 90% confidence bounds were defined by computing the 5th and 95th percentiles of the 12 different magnitude-frequency curves (best estimate curve and 11 LHS curves). Twenty-thousand simulations (100 bins with 200 samples per bin) were run for each of the eleven LHS combinations.

The calibrated SEFM was run obtain "best estimate" curves of a variety of magnitude-frequency processes, including peak discharge-frequency, inflow volume-frequency, and maximum reservoir elevation-frequency. SEFM estimates were shown to be in agreement with results from both the EMA and the 2009 HHA estimates for the 1-in-100-year peak discharge event. For events rarer than the 1-in-100-year event, SEFM results lie within the EMA 90% confidence bounds, and are significantly less than the 2009 HHA estimates, as the 2009 HHA is anchored by the Probable Maximum Flood value at the 1-in-50,000-year event. Peak discharge frequency results as estimated by SEFM are presented Table 6-8 and Figure 6-17.

Table 6-8 SEFM peak discharge results for Unity Dam.

Return Period (year)	Peak Discharge (ft^3/s)		
	Lower (5th Percentile)	Median (50th Percentile)	Upper (95th Percentile)
100	1,660	2,410	3,490
1,000	3,170	4,460	6,120
10,000	5,140	7,020	8,430
100,000	7,700	10,190	12,020
1,000,000	10,790	13,380	16,300
10,000,000	14,200	17,220	21,600
100,000,000	17,970	21,790	27,460
1,000,000,000	21,860	26,900	34,140

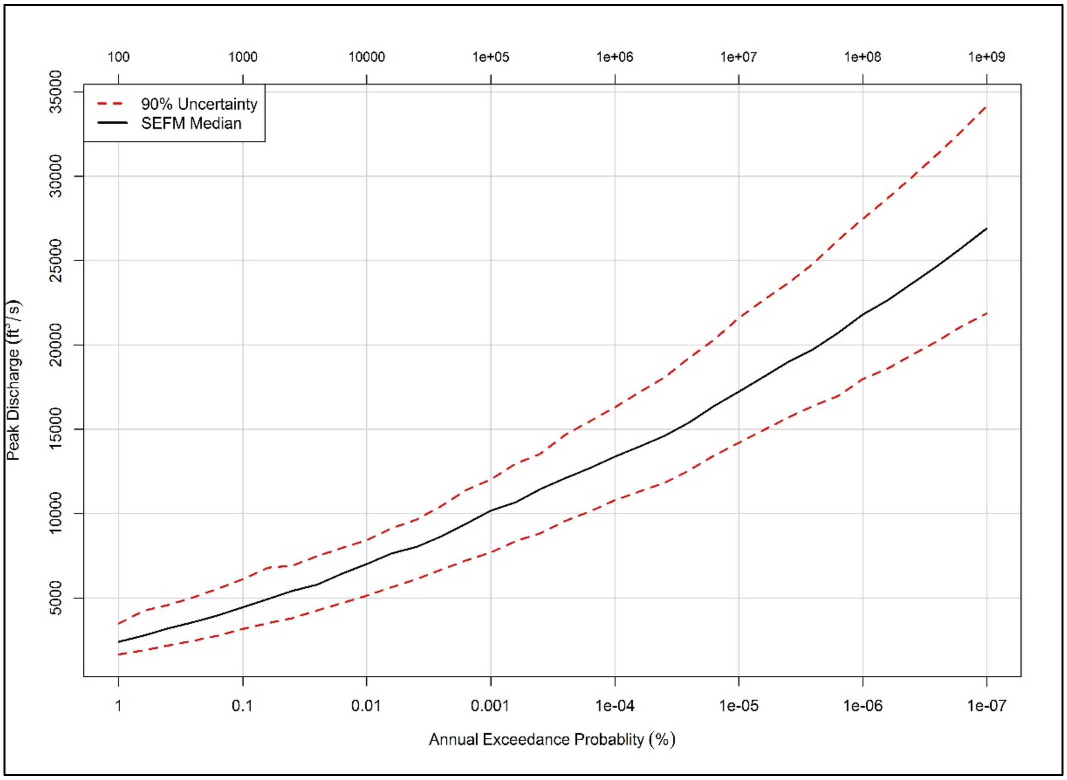


Figure 6-17 SEFM frequency peak discharge for Unity Dam.

One-, 3-, 5-, 7-, and 15-day volume-frequencies with associated 90% confidence intervals were developed from the simulated inflow hydrographs. The 90% confidence interval volumes were developed from the LHS method of uncertainty. Median inflow volumes for all durations are visualized in Figure 6-18.

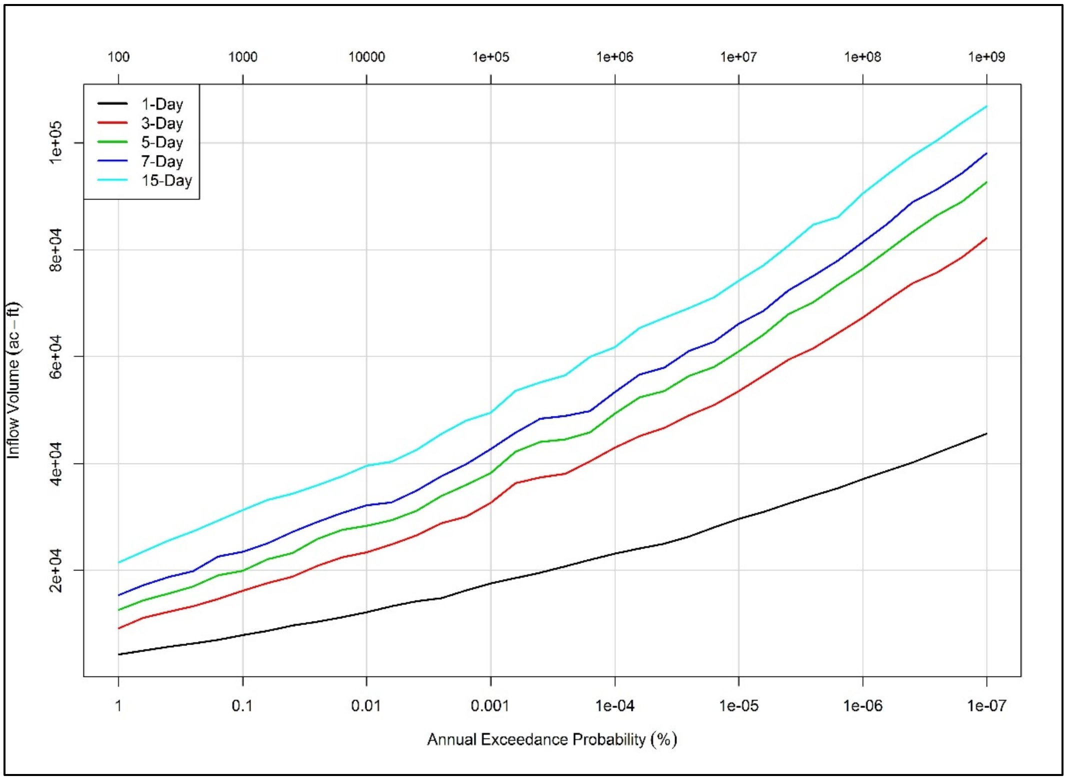


Figure 6-18 SEFM median inflow volume frequency curves for all relevant durations. Return periods are indicated on the top axis.

7 SUMMARY AND CONCLUSIONS

This report summarizes methods applied by Reclamation for developing hydrologic hazard curves for use in evaluating dam safety issues. Such methods rely on extracting information from existing studies to the fullest extent possible. The procedures and analysis techniques defined in this report allow for the possibility, and even plausibility, that peak discharge and volume estimates may exceed the PMF. This is a function of the uncertainty and inconsistency among and between analysis techniques. Therefore, in these cases, Reclamation considers the PMF to represent the upper limit to hydrologic risk.

The procedure for developing hydrologic hazard curves 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. The potential dam failure mode and dam characteristics impact the type of hydrologic information needed to assess the problem. The specific elements selected to be incorporated in an analysis of hydrologic hazards should consider the tolerable level of uncertainty. 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 effort and the sophistication of analysis techniques increases the reliability and level of confidence associated with the results.

Although Reclamation has used a variety of methods for assessing hydrologic risk, the methods described in these guidelines are not all inclusive. New techniques for developing hydrologic hazard information can be added to these guidelines as they are developed by the extreme flood hydrology community.

The amount of effort expended on analyzing a hydrologic hazard depends on the nature of the problem and the potential cost of the solution. A staged approach toward evaluating a hydrologic safety issue is recommended. Initially, very little effort is expended to determine the magnitude of the hydrologic hazard. Reclamation attempts to make use of all available studies for the site of interest. Often, the PMF and initial flood frequency studies are the only hydrologic studies available before the start of a probabilistic investigation. When other hydrologic studies have been performed, available data will be used to decrease uncertainty in results as well as to provide an overall assessment of hydrologic risk.

When multiple methods are used, alternative hazard curves are developed by weighting results from the individual analyses. A team of hydrologists evaluates the alternatives and selects a weighting scheme that is most representative of the site for use in the risk assessment. Selection of the final hydrologic hazard curve depends on the experience of the hydrologists and the assumptions that went into each analysis.

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