Probabilistic Extreme Flood Hydrographs That Use PaleoFlood Data for Dam Safety Applications

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Introduction

Extreme flood hydrographs are needed to evaluate dam safety issues for situations where the reservoir inflow peak discharge is greater than the maximum spillway capacity, the reservoir has large surcharge storage, and/or the reservoir has dedicated flood control space. Flood runoff hydrographs integrate the drainage basin and channel response to precipitation, given some initial, variable state of moisture throughout the watershed. To conduct risk analyses and dam safety evaluations, probability estimates for extreme floods are required. Probabilistic extreme flood hydrographs are developed to assess the adequacy of the spillway and reservoir flood/surcharge space to temporarily store a portion of the flood volume, and to attenuate or pass the hydrograph peak without overtopping the dam. The hydrographs and probability estimates are used in risk analyses for dam safety. These hydrographs can also be used to establish reservoir operating rules and determine diversions needed for construction.

This report documents statistical and rainfall-runoff techniques used to develop probabilistic extreme flood hydrographs for dam safety risk analyses. A probabilistic extreme flood hydrograph is defined in this report as one that preserves a peak discharge exceedance probability and dependence between volume and peak for a fixed duration. An extreme flood is considered to have an Annual Exceedance Probability (AEP) of 0.005 or less. There are many methods of estimating extreme flood runoff hydrographs, such as unit hydrograph approaches (e.g., Chow et al., 1988), continuous rainfall-runoff modeling (e.g., Bradley and Potter, 1992), and statistical techniques (e.g., USACE, 1975a). These and other extreme rainfall-runoff methods are discussed in-part by NRC (1988), Pilgrim and Cordery (1993), and Nathan and Weinmann (1999). Other than a method presented by Nathan and Weinmann (1999), these references do not describe methods that can be used by practitioners to estimate both extreme floods (peak, volume, duration) and associated probabilities for dam safety. The methods and examples presented in this report are an attempt to bridge part of that gap.

It is well known that extreme flood hydrographs can be described as a multivariate statistical problem with three major factors: peak, volume and duration (e.g., Adamson et al., 1999). The hydrograph shape (arrangement of ordinates in time), is a fourth factor that has seldom received consideration. In most cases, a single factor, usually peak discharge or volume for a given duration, is fixed to simplify the complex, multivariate problem. There has been some recent research in this area using bivariate distributions to jointly model peak and volume (Adamson et al., 1999), and fitting probability distribution functions to describe peak, volume and hydrograph shape (Yue et al., 2002). However, these recent research efforts have neglected three important factors: extrapolating flood frequency distributions; cases where one has paleoflood data; and cases where concurrent peak and volume data are not available.

1.1 Background

Since 1902, Reclamation has continually been involved in developing and applying different flood hydrology methods to estimate extreme floods for spillway design and analysis. These methods have traditionally focused on deterministic and design-centered methods such as using Probable Maximum Precipitation (PMP) to estimate a Probable Maximum Flood (PMF) (e.g., Cudworth, 1989). These methods, developed over the past 50 years, are mature and considered state-of-the-practice.

Reclamation currently uses risk analysis to assess the safety of dams and prioritize expenditures (USBR, 1999b). The ideal flood input required for risk analysis is a frequency distribution of maximum reservoir stages which, for dams with potentially high loss of life, might extend to very low probabilities (USBR, 1999a). Reservoir stages are a complex integration of frequency information on inflow flood peak discharge, runoff volume, hydrograph shape and timing, initial reservoir level, and project operations. An example reservoir elevation frequency curve is shown in Figure 1, and depicts a case where the estimated 1/10,000 Annual Exceedance Probability (AEP) reservoir level exceeds the dam crest. In this idealized case, 95% confidence limits for the reservoir elevation frequency curve are shown as well.

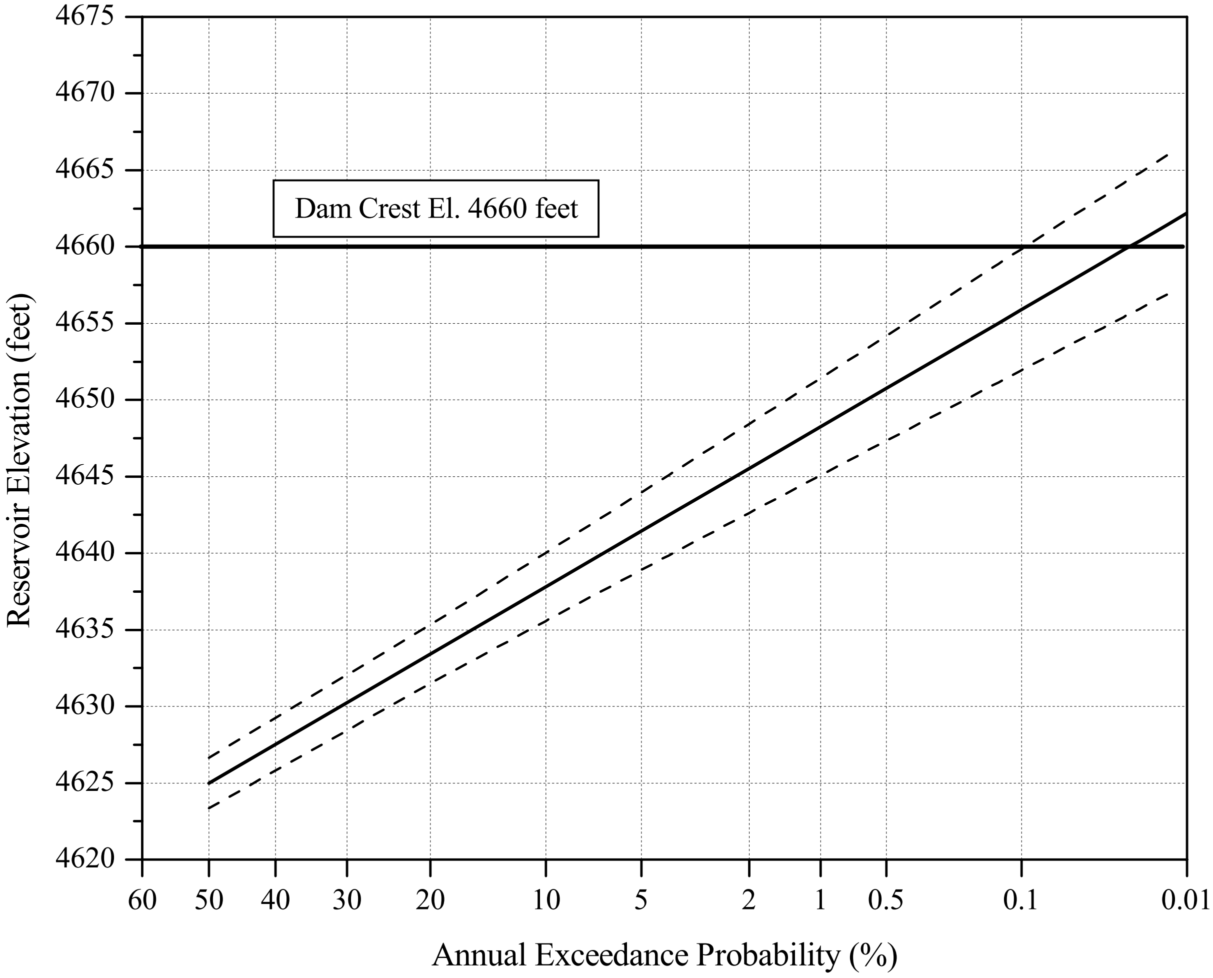

Figure 1.—Example reservoir elevation probability curve for hydrologic risk analysis. The solid line is the median estimate and 95% confidence limits are shown as dashed lines.

Methods to estimate a reservoir elevation frequency curve, including uncertainty, are not well developed. Because it is difficult to directly derive a reservoir elevation frequency curve, the methods presented in this report use intermediate steps so one can approximate the reservoir frequency relationship. Probabilistic hydrographs, developed from scaling streamflow observations, or from rainfall-runoff models, are combined with recommendations for initial reservoir levels for hydrograph routing. One can then determine a maximum reservoir level by routing the given hydrograph and initial reservoir level.

Ideally, an extreme flood hydrograph that was developed for a risk analysis would include a median hydrograph estimate and range of uncertainty (Figure 2). The range of uncertainty could incorporate the variability in peak flow, volume and duration estimates, and attempt to capture the multivariate relationships that are reflected in the hydrograph. Some differences due to basin response could also be included.

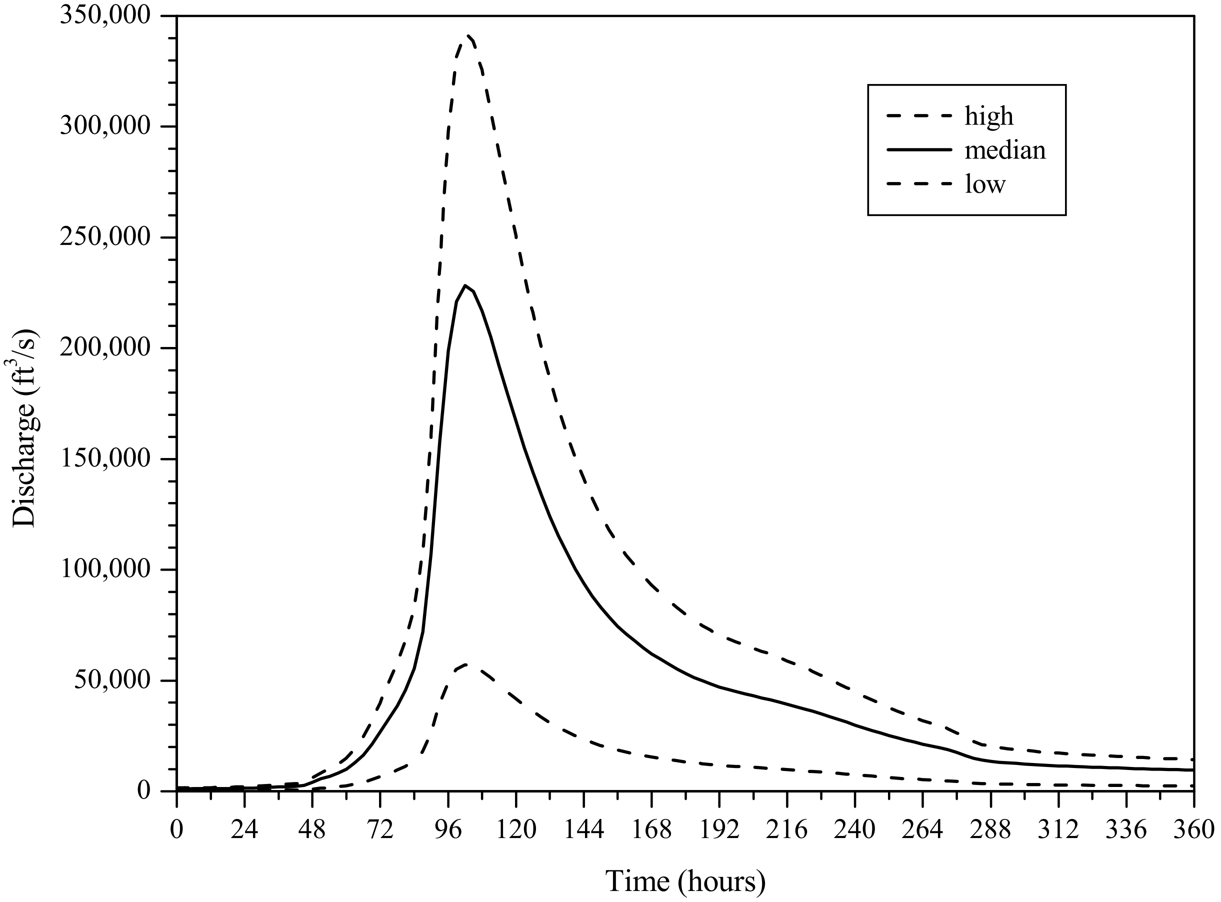

Figure 2.—Example probabilistic extreme flood hydrograph for hydrologic risk analysis. The solid line is the median estimate and the approximate 95% confidence limits are shown as dashed lines.

1.2 Objectives

The focus of this research is to develop practical tools for estimating probabilistic hydrographs that can be used in risk analyses for dam safety. The key feature of the research is to utilize peak discharge frequency curves that include paleoflood data as a basis to develop hydrographs. The main objective of the study is to develop feasibility-level probabilistic hydrograph tools that can be used for: flood hydrology studies that supplement the Comprehensive Facility Reviews; for baseline risk analyses; and for detailed risk analyses. The methods are relatively flexible and can be tailored to different investigation levels. The methods need to be adjusted depending on the available data at the site and region of interest. For example, if CFR-level peak discharge frequency curve is available, one could use less detailed methods to develop hydrographs, as 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 that presented elsewhere (e.g., MGS, 2001).

A secondary objective is to develop an initial, simple method to extrapolate peak discharge frequency curves to AEPs less than 1/10,000. A regional index flood method is used as a basis to extrapolate the peak discharge frequency curve when one has paleoflood data.

This report describes the methods and data needed to develop probabilistic extreme flood hydrographs and extrapolate frequency curves. Examples are given that illustrate the application of the methods. The report also contains a brief literature review, and discusses river channel and reservoir routing issues. The limitations of the methods and further research needs are outlined. There are philosophical concepts that helped guide the work presented in this report. The first is that the research capitalized on using existing hydrologic and statistical tools. The overall motivation and approach is to use simple, clear methods that are easily understood. Complexity is added to methods when it is felt that the feature would provide some added benefit. As noted by Klemeš (1997, 1999), this work is more of an engineering "rationale", to provide information for decision-making, rather than scientific research. The research is not intended to directly advance the science of hydrology, rather the purpose is to develop tools that can be implemented fairly quickly and effectively, by moderate extensions to standard methods, and that are used for planning purposes.

1.3 Acknowledgements

This research was made possible through funding by the Dam Safety Research Program in the Reclamation Dam Safety Office, under work order identification PHYPL. Dam Safety Office personnel were supportive of the research ideas. The research was initiated as part of the former Reclamation Flood Cadre work. Several individuals contributed to the research through ideas, reviews, analyses and data. Conversations with Dan Levish, Ralph Klinger and Bob Swain (D-8530) helped clarify concepts and improve use of paleoflood data. Dr. Upmanu Lall (Columbia University), Dr. George Kuczera (University of Newcastle, Australia), and Dan O'Connell (D-8330) provided ideas, inspiration, and suggestions to improve aspects of the methods. Verne Leverson (D-8510) provided precipitation estimates for Rifle Gap Dam. Mr. Louis C. Schreiner, Group Manager, Flood Hydrology Group provided encouragement so that the research and report could be completed.

Probabilistic Extreme Flood Hydrographs from Streamflow Sampling

This section presents statistical procedures to estimate extreme flood hydrographs from streamflow and paleoflood data. Two example applications, for Folsom Dam and Glendo Dam, illustrate the procedures.

General Procedure

Probabilistic hydrographs are constructed based on streamflow estimates from gaging stations, historical data and paleoflood data. Four components are utilized: (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 upon 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.

The assumption about the probability of the hydrograph based on peak discharge is untested. It is widely known that the relationship between peak discharge, runoff volume, and duration is multivariate. However, streamflow data for the largest floods in the western United States indicate that the runoff volumes are linked to peak discharge on an annual basis (USBR, unpublished data). For this paper, the relationships between peak discharge and runoff volumes are estimated via regression. Others (USACE, 1975 a and b; Cudworth, 1989; Beard, 1990; Balocki and Burges, 1994) have utilized the so-called "balanced hydrograph" design flood approach that combines peak discharge and volume probabilities. In the balanced hydrograph method, specific flood volumes (e.g., 1-day, 3-day, 15-day, etc.) for a fixed return period are estimated and assumed to be coincident with a peak discharge that has the same return period. A hydrograph is then constructed for a particular return period and contains the peak discharge and associated runoff volumes nested within it (Cudworth, 1989). Balocki and Burges (1994) showed that the nesting assumption does not hold for several data sets they examined. For many river basins in the western United States, streamflow data indicate that nesting of shorter-duration volumes within longer time periods does not consistently occur (USBR, unpublished data).

The second through fourth assumptions noted above are operational and are not easily tested. Bradley and Potter (1992) conducted frequency analysis on the 3-day maximum mean flow (fixed volume), and related peak discharge to this 3-day flow. Data were generated using continuous simulation. Bradley and Potter's (1992) extreme rainfall-runoff modeling approach is an alternative to extrapolating the maximum mean daily discharge-volume relation. They also note that "assuming a unique relationship between peak discharge and runoff volume can usually be justified when making flood quantile estimates for extreme events because flood-producing conditions of a single season often control the upper tail of flood distributions" (Bradley and Potter, 1992 p. 2381). This statement might suggest that extrapolating the peak discharge-maximum mean discharge relationship is a practical, operational assumption. Other extreme rainfall-runoff methods are discussed by NRC (1988), Pilgrim and Cordery (1993), and Nathan and Weinmann (1999).

Basic streamflow hydrograph methods (e.g., Chow et al., 1988; Bras, 1990) are used to estimate properties for probabilistic hydrographs. These methods include peak and one-day mean discharge identification, and selection of hydrograph shape and duration. Optionally, base flow identification and separation, and direct runoff volume estimation can be done. Peak discharge and mean-daily streamflow records are used because using information from the past is the best source of information on flood magnitudes that are likely to occur in the future (Pilgrim and Cordery, 1993).

Many previous investigators have used unit hydrographs to model the rainfall-runoff process. Unit hydrograph assumptions are listed in Chow et al. (1988), Bras (1990), and many other standard textbooks. One assumption is that the flow ordinates of the hydrograph are proportional to the volume of runoff. Another assumption is that the direct runoff portion of the hydrograph is from rainfall excess; substantial snowmelt runoff is not included (Barnes, 1952; Rogers and Zia, 1982). This assumption is clearly violated in many western United States watersheds, because snowmelt can be a major component of extreme floods. Rogers and Zia (1982) were able to successfully use snowmelt runoff hydrograph data to derive relations between peak discharge and runoff volume. Snowmelt runoff is included in developing scaled hydrographs.

Peak Discharge Probability

The basis for the simplified probabilistic hydrograph procedure is that a peak discharge probability relationship (frequency curve) that includes paleoflood data exists for the site of interest. One can then fit a frequency curve to peak discharge data from gaging stations combined with paleoflood data, and extrapolate the frequency curve to low probabilities (Figure 3). Paleoflood data provides the benefit of documentation on the magnitude and history of low probability floods (Levish, 2002). Recently developed flood frequency programs that use either maximum likelihood (O'Connell, 1999) or moments (England, 1999) can be used to fit probability distributions to peak flow and paleoflood data. Because paleoflood data only provide information on peak flows, it is not currently possible to estimate flow volumes or hydrographs directly from these data. Additional steps and their inherent assumptions are needed to accomplish the linkage between peak and volume.

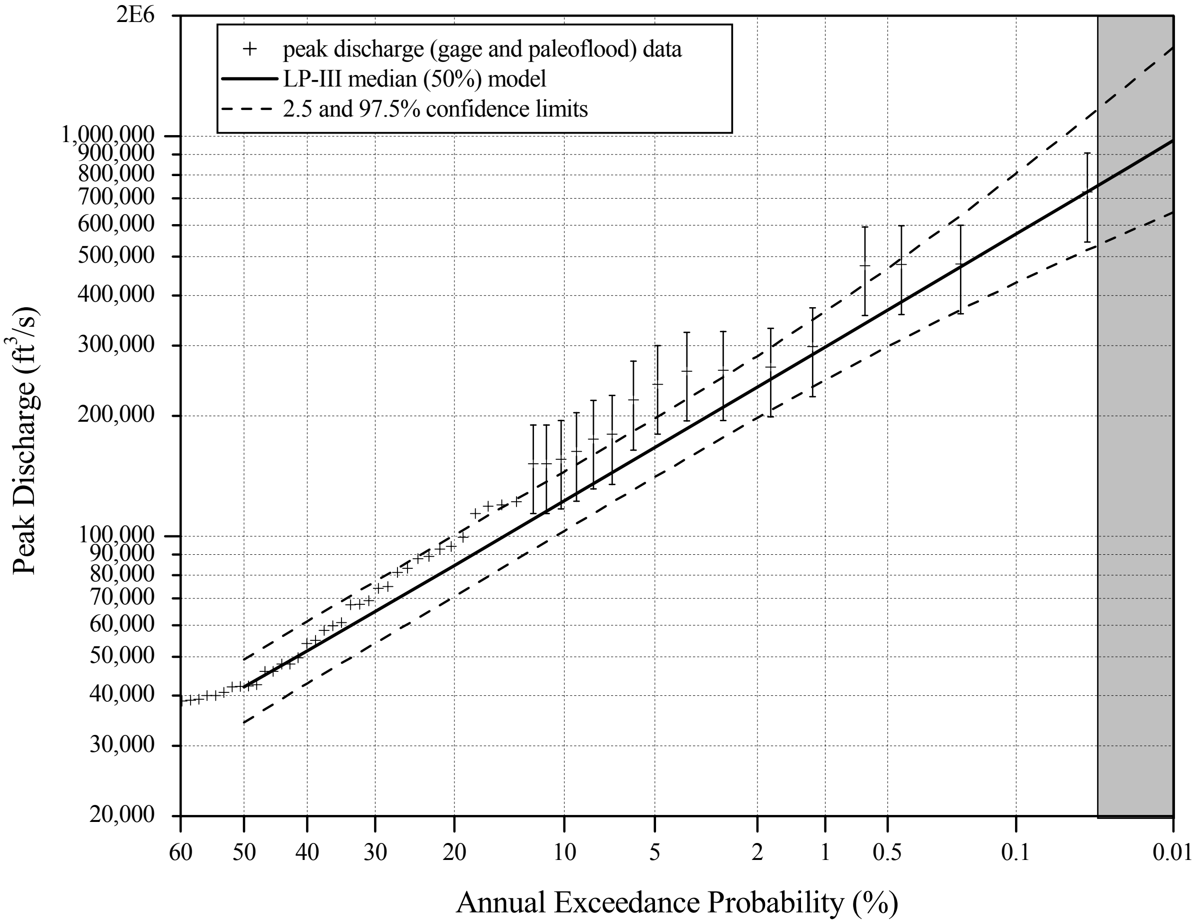

Figure 3.—Example peak discharge frequency curve, including peak discharge (gage) and paleoflood data. The shaded region represents the extrapolation zone of the frequency curve.

Storm Duration Probability

Observed extreme storm durations are used as a basis to select the extreme flood runoff volume duration. A sample of extreme storms that cause large floods is obtained for the area of interest. These data are readily available from the U.S. Army Corps of Engineers storm catalog, Reclamation storm studies, Probable Maximum Precipitation reports (e.g., Corrigan et al., 1999), and state offices (e.g., McKee and Doesken, 1997). Prior to developing peak-volume relationships, extreme storm data are analyzed to determine the variability in extreme storm duration and any relationships between storm month and duration. In addition, one examines the links between extreme storms and flood runoff. A simple, discrete distribution is used to estimate daily storm duration probabilities (Figure 4). The simplification is made because there are usually insufficient storm data to estimate a continuous distribution, and streamflow volume data are readily available only on a daily basis. Levy and McCuen (1999) note the importance of selecting a design storm duration based on rainfall, time to peak, and time of concentration. For this procedure, the storm durations were compared to the hourly hydrograph duration estimates that contained the majority of storm runoff using simple graphical methods. The duration for the majority of runoff for the largest recorded flood hydrographs corresponds closely to the extreme storm duration sample.

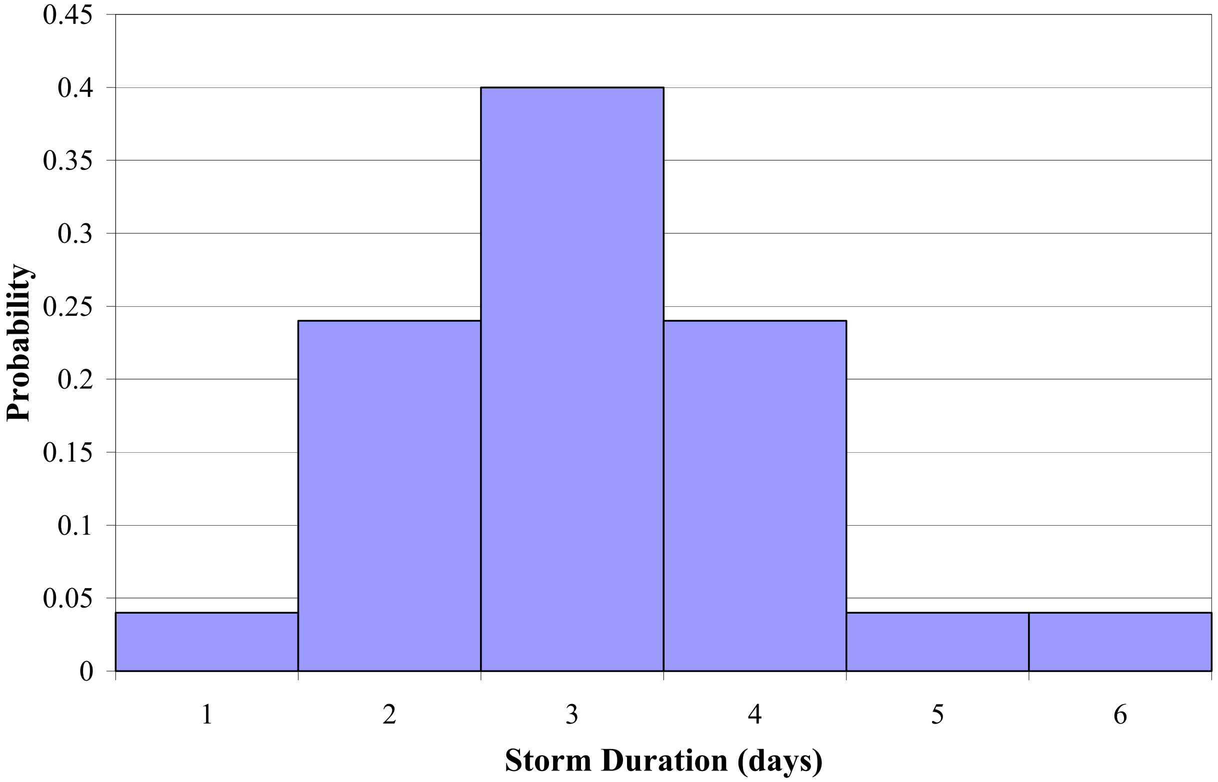

Figure 4.—Example extreme storm duration probability estimates, based on a 25 storm sample from Corrigan et al. (1999).

Peak Discharge-Hydrograph Volume Relationships

Generally following Rogers and Zia (1982), Singh and Aminian (1986), and Molfino and Cruise (1990, and references therein), maximum mean *n*-day flow estimates are related to peak discharge estimates. Extreme flood runoff in many western United States watersheds is from both rainfall-excess and snowmelt runoff. Rogers and Zia (1982) note that runoff hydrographs derived from snowmelt can be used to derive this relation. Maximum mean discharge ($\overline{Q}_d$) for *n*-day periods is related to peak discharge (Q_p), by a power function:

$$\log \overline{Q}_d = a + b \log Q_p \qquad (1)$$

This relationship is shown in Figure 5. The assumed known variable is peak discharge (Qp), with an associated exceedance probability estimate from the frequency curve (Figure 3). The quality of the regression relationship expressed in (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.

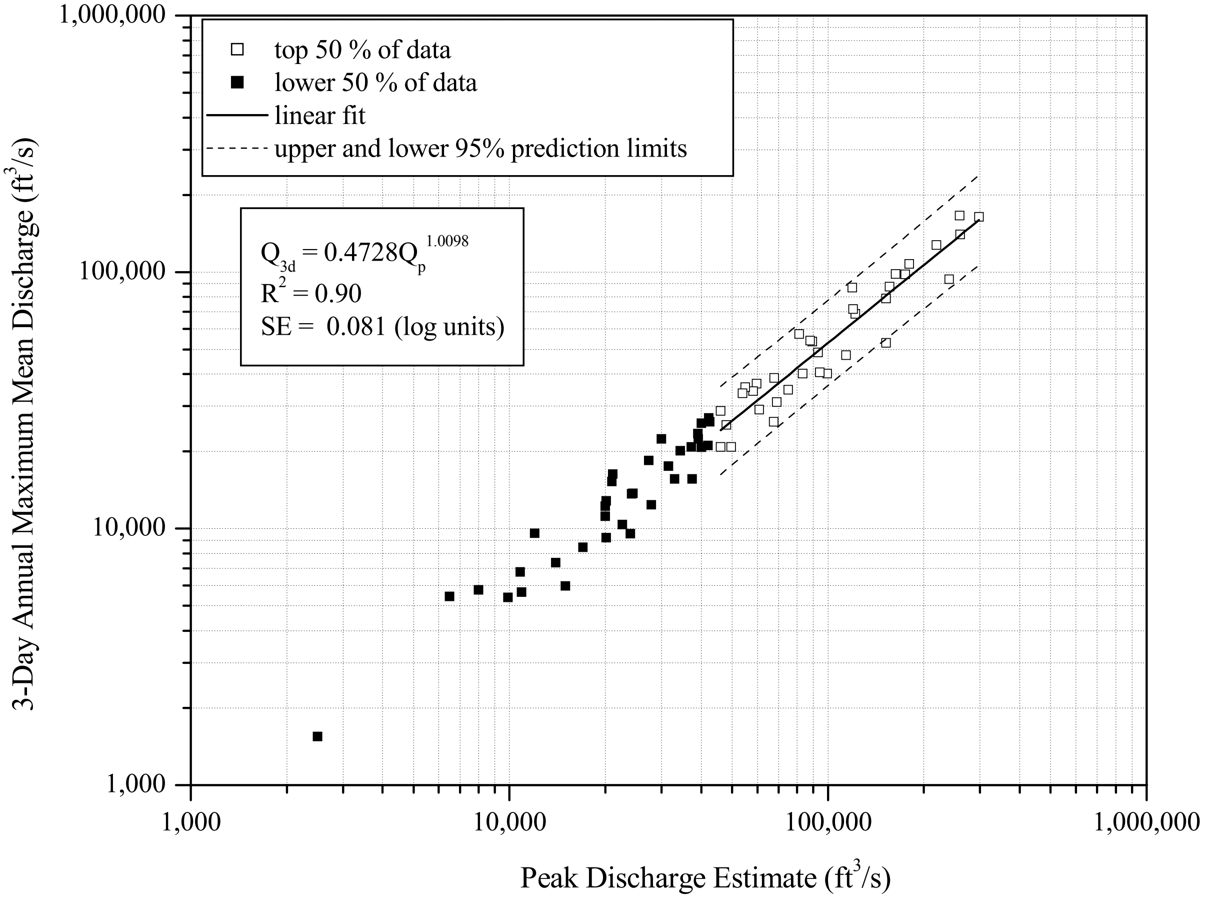

Figure 5.—Example peak discharge-maximum mean daily flow volume relationship for 3-day flow.

Hydrograph Shape and Duration

In areas of the western United States, flood hydrographs can exhibit complex shapes, with multiple peaks (Figure 6). These hydrographs are not typically symmetric or reversible, and it can be difficult to fit simple probability functions (e.g., gamma or beta) to describe their shape. Past applications generally consisted of using a single, averaged unit hydrograph or balanced hydrograph (e.g., Cudworth, 1989) or a mean dimensionless hydrograph (e.g., Craig and Rankl, 1978) to represent the basin response. Instead of relying on a single, average unit hydrograph to characterize the runoff process, multiple observed hydrographs are used to simulate the potential runoff response from extreme floods. Observed flood runoff hydrographs provide the benefit of integrating basin and channel response to actual extreme precipitation in the watershed. One can randomly select a hydrograph from the available sample, compute an extreme flood, and later select a different hydrograph. In this manner, variability is added to the process, and one does not rely on a single response function. One major assumption of this approach is that the observed hydrograph shapes capture the variable characteristics of extreme storms, including rainfall duration, time-intensity pattern, amount, and areal distribution (Linsley et al., 1982), as well as antecedent moisture conditions. A major assumption is that the duration of direct runoff is known. The base time of the direct runoff hydrograph is generally uncertain, and is a function of the base flow separation technique (Chow et al., 1988). The maximum n-day hydrograph ordinates are linearly scaled based on the selected n-day volume.

Antecedent conditions for extreme floods are selected from hydrographs and reservoir elevation data. Hydrograph durations are selected, based on simple graphical techniques, to include the largest runoff volumes and to include antecedent flows. A simple "target" duration can be chosen, for example 15 days (Figure 6), based on design criteria (Cudworth, 1989). Alternately, daily hydrographs can be simulated for the entire flow season.

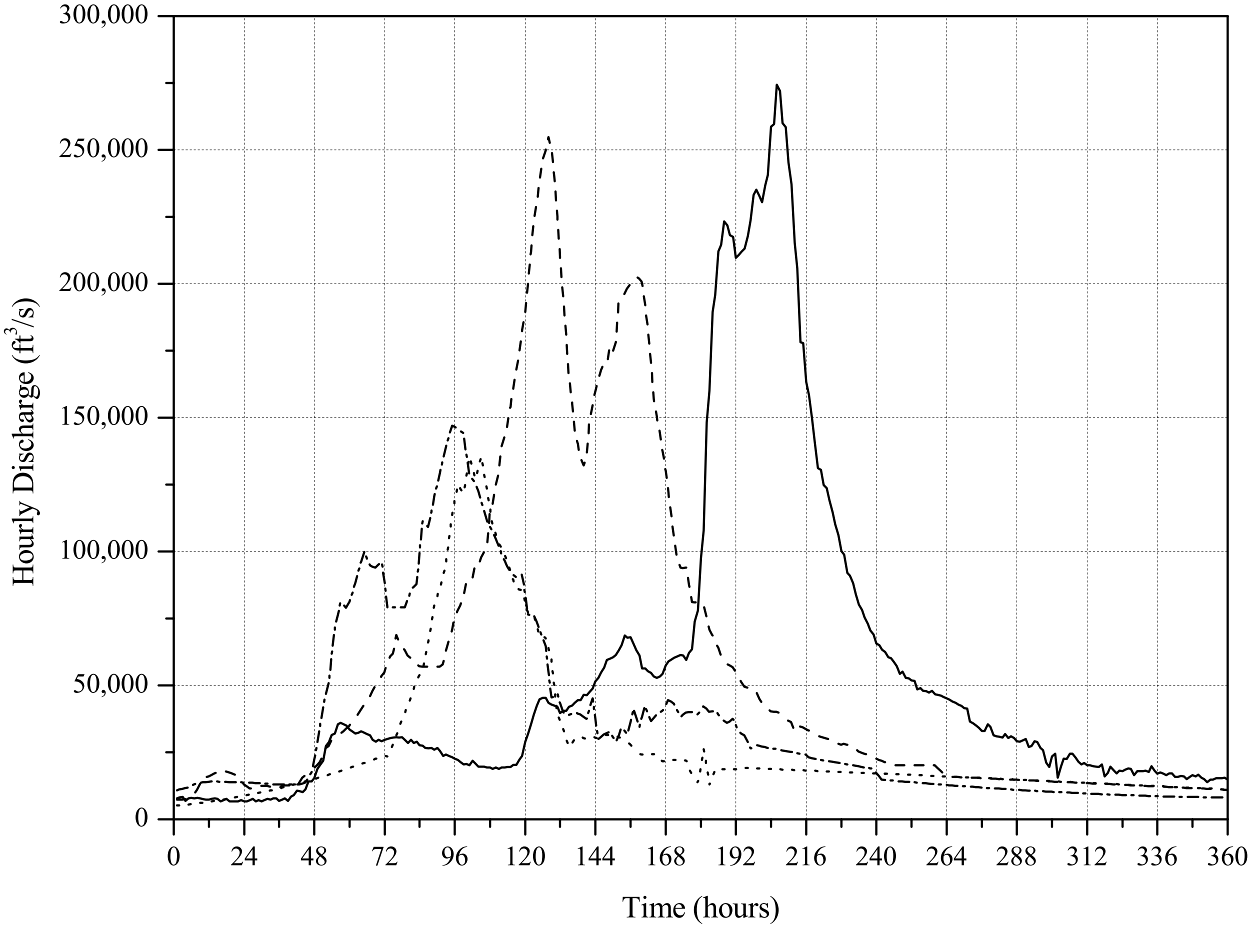

Figure 6.—Example hourly hydrographs for four large floods used for extreme flood scaling.

Sample Algorithm

The algorithm to develop hydrographs consists of five basic steps that are based on the data and relationships available at a particular location: (1) sample a peak flow for a given probability from the frequency curve; (2) sample a storm duration from the distribution; (3) based on this peak flow and *n*-day duration, estimate an *n*-day maximum mean flow from the peak flow *n*-day regression relationship; (4) randomly choose one hourly flow hydrograph from those available, and compute the ratio of the *n*-day estimated mean volume from the regression relationship to the *n*-day observed mean volume for that hydrograph; and (5) scale the maximum *n*-day ordinates of the selected hourly hydrograph with the ratio from the previous step. It is emphasized that this procedure relies on extrapolation of both the flood frequency curve and the peak flow versus *n*-day regression relationships for most sites.

2.2 Example Applications

Folsom Dam

The procedure was applied to Folsom Dam and Lake near Sacramento, California. Folsom Dam is located on the lower American River, and is a large water supply and flood control reservoir. Some difficulties in implementing the above approach in the American River basin are basin scale (greater than 1,800 mi2), mixed-population rainfall-runoff and snowmelt, significant regulation by reservoirs, and the ability to integrate storm-based precipitation into a model. (Bradley and Potter, 1992, p. 2375) note that the design storm approach is complicated in complex, large, heterogeneous drainage basins. For this initial example, a fixed duration equal to three days was assumed based on the storm duration probability density (Figure 4). It is evident that there are few extreme storms that have been recorded with much longer durations than five days. A Monte Carlo procedure, including sampling from the storm duration histogram, will be part of future research efforts.

Paleoflood data were compiled from several locations upstream and downstream of the Fair Oaks gage on the lower American River. There was evidence in the stratigraphic record of individual paleofloods that were about twice as large as those in the gage record, and one paleoflood that might be about 2.4 times as large as the 1997 peak discharge estimate (USBR, 2002). Data from these sites significantly extend the peak discharge record length. Two discrete paleofloods and an estimate of the 1862 flood were used in the frequency analysis (Figure 3). A log-Pearson Type III distribution was assumed as the frequency function; parameters were estimated using maximum likelihood (O'Connell, 1999).

Peak discharge-n day maximum mean discharge relationships were estimated following the approach listed above; this was also used by NRC (1999). Data from USACE (1987, 1998), peak discharge and paleoflood estimates (USBR, 2002) were used. These flood data include the largest recorded flow estimates on the American River near Folsom and Fair Oaks. As in NRC (1999), regression relationships were developed based on the largest 35 observations of the flood flow data caused by rainfall-runoff. These data included "natural" flows recorded before dam construction (17 observations), and "unregulated" post-dam flow estimates (18 observations).

The relations between 3-day maximum mean runoff volume ($\overline{Q}_{3d}$) and peak discharge (Qp) at Folsom Dam are shown in Figure 5.

Probabilistic inflow hydrographs to Folsom Lake were developed by scaling the eight largest hydrographs; four are shown in Figure 7. These flood hydrographs are predominately rainfall-runoff mixed with snowmelt. A single relationship, based on these mixed-population data, was used to link maximum mean daily flow volume with peak discharge. The 1/10,000 Annual Exceedance Probability (AEP) 50 percentile peak discharge estimate (approximately 977,000 ft3/s, Figure 3) was used to assign the probability and peak to the hydrographs. The 1/5,000 AEP 50 percentile peak discharge estimate (approximately 837,000 ft3/s, Figure 3) was also used. For the use in a risk analysis, sixteen hydrographs were developed for the 1/10,000 and 1/5,000 median AEPs (USBR, 2002). These hourly hydrographs were scaled from the peak discharge-maximum mean flow relationship for the 3-day duration. Estimates for the 1/10,000 median AEP are listed in Table 1.

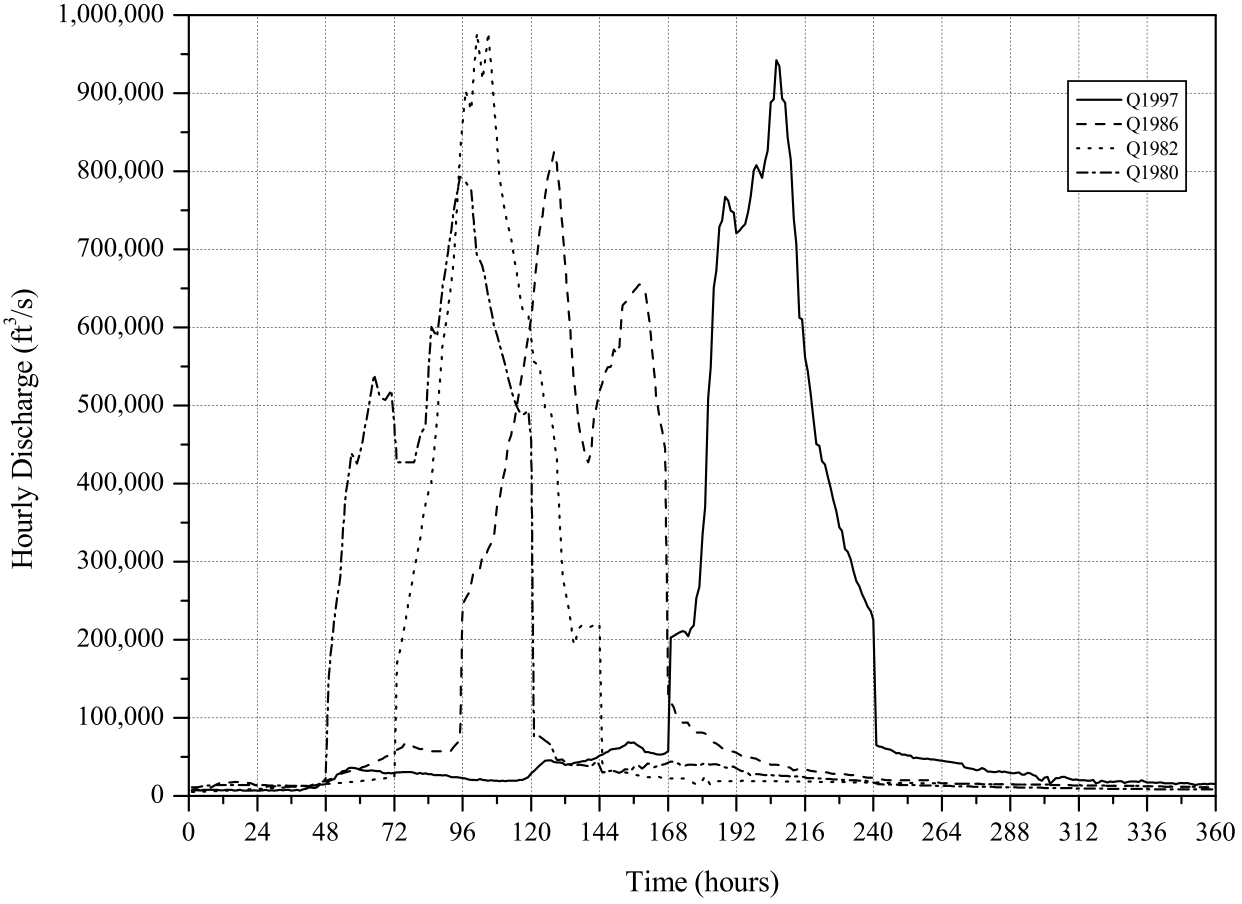

Figure 7.—Example probabilistic hydrographs, Folsom Lake, using 10,000-year median (50%) peak discharge and 3-day volume scaling.

The hydrologic loads for assessing the overtopping risk of Folsom Dam consist of two components: an extreme flood hydrograph, and an initial reservoir elevation. The eight 10,000-year median hydrographs and eight 5,000-year median hydrographs (USBR, 2002) directly provide the first component, and should be considered equally likely representations of the basin extreme flood response. Each of these hydrographs should be routed with varying initial reservoir elevations to assess the overtopping potential of Folsom Dam. Daily reservoir elevations for the period of record at Folsom Dam (1955-2000) indicate that a median reservoir elevation for the November through February period (flood season) is approximately 420 feet, with a quartile range (25 to 75 percentiles) from about 410 to 430 feet (USBR, 2002). This reservoir elevation range should be considered as initial reservoir water surface elevations for routing the hydrographs.

Table 1.—Folsom Lake "representative" inflow hydrograph properties using 10,000-year median (50%) peak discharge equal to 977,000 ft^3/s and 3-day storm duration

Calendar Year Hydrograph Base	Estimated Max Hourly Flow (ft^3/s)	15-day Volume (acre-ft)
November 1950	870,000	3,445,000
December 1955	908,000	3,566,000
January 1963	1,364,000	3,388,000
December 1964	1,011,000	3,788,000
January 1980	794,000	3,651,000
February 1982	978,000	3,527,000
February 1986	824,000	3,841,000
January 1997	942,000	3,828,000

Glendo Dam

The approach outlined above was used to develop probabilistic extreme flood hydrographs at Glendo Dam. Several slight modifications were made to the procedure, based on the available data and runoff mechanisms. There are three difficulties when applying the approach to Glendo Dam: the lack of hourly flow hydrograph data; significant peak flow and streamflow volume regulation from large upstream reservoirs; and mixed-population rainfall and snowmelt runoff with few large floods in the record. The modifications to the procedure include: using daily flow hydrographs, separation of direct runoff volume and modeling base flow, and developing a model between peak flow and direct runoff volume instead of using storm duration.

The modified algorithm, used to develop hydrographs consists of seven basic steps based on the available data for Glendo Reservoir inflows, is: (1) sample a peak flow for a given probability from the frequency curve; (2) based on this peak flow, estimate a one-day maximum mean flow from a derived relation; (3) choose one of 11 unit volume hydrographs and note the base time; (4) choose one of 11 April-August mean daily flow hydrographs, and calculate the maximum mean flow for the base time and use this as the base flow; (5) subtract the base flow from the one-day maximum mean flow, and estimate the direct runoff volume; (6) scale the ordinates of the selected unit volume hydrograph with the direct runoff volume; and (7) add the scaled hydrograph to the base hydrograph from step 4 to complete a composite flood hydrograph.

The data used in the analysis and further details about the method, as applied to Glendo Dam, are presented in Levish et al. (2002). The peak flow frequency curve that was used for the analysis is shown in Figure 8.

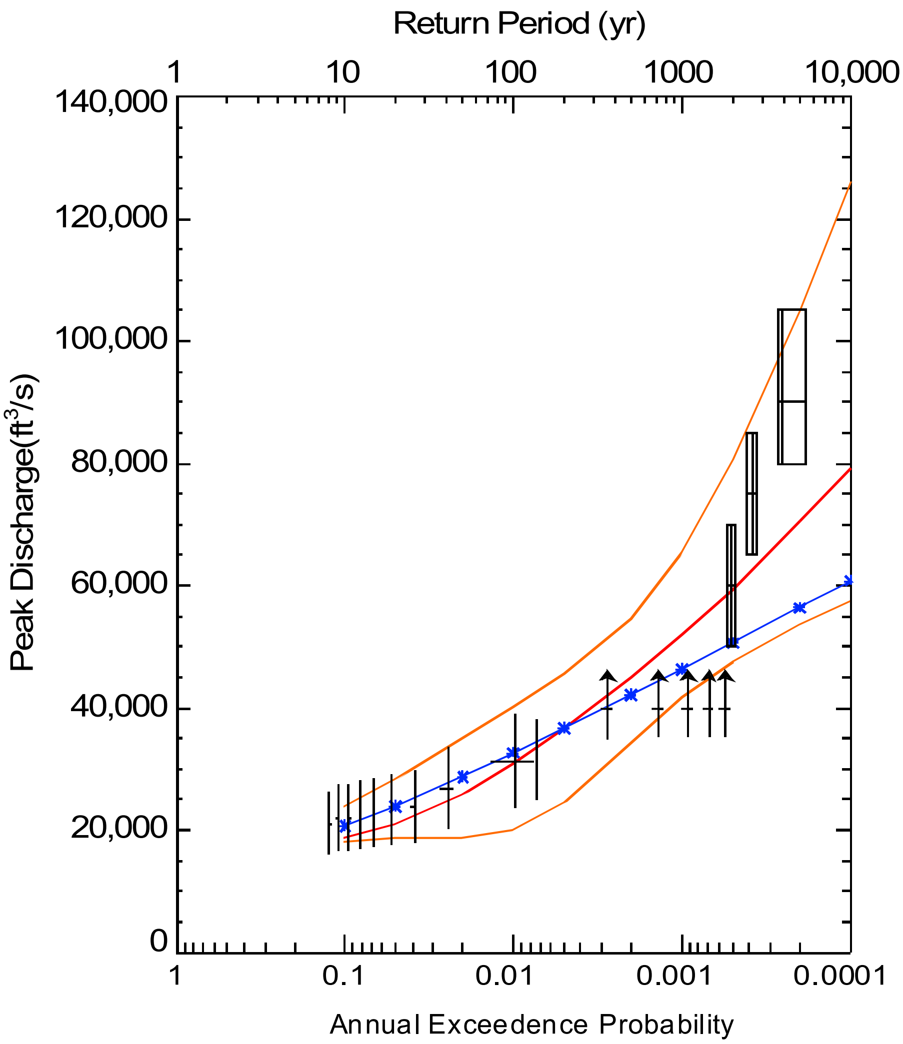

Figure 8.—Peak discharge frequency curve for Glendo Dam.

Maximum mean daily discharge is used as a variable instead of peak discharge; volume is used as the dependent variable rather than maximum mean discharge, and direct runoff is used (e.g., Singh and Aminian, 1986). Direct runoff volume (V_d) is related to maximum mean daily discharge with base flow subtracted (Q_{md}), by a power function (Figure 9):

$$\log V_d = b + m \log Q_{md} \qquad (2)$$

However, the assumed known variable is peak discharge, with an associated exceedance probability estimate; peak discharge estimates are given in Figure 8. A relationship between maximum mean daily discharge (Q_m) and peak discharge (Q_p) is developed to provide a linkage between peak discharge and direct runoff volume, with a power function:

$$\log Q_m = a + b \log Q_p \qquad (3)$$

Base flow separation and hydrograph duration estimates were made from daily flow data using simple graphical methods. A horizontal (linear) relation (Chow et al., 1988) was used as a simple base flow model. Direct runoff volumes were estimated by subtracting base flow. An example of base flow and duration estimation is shown in Figure 9. In this case snowmelt runoff comprises a substantial portion of the direct runoff volume; direct runoff durations were estimated graphically based on general hydrograph shape.

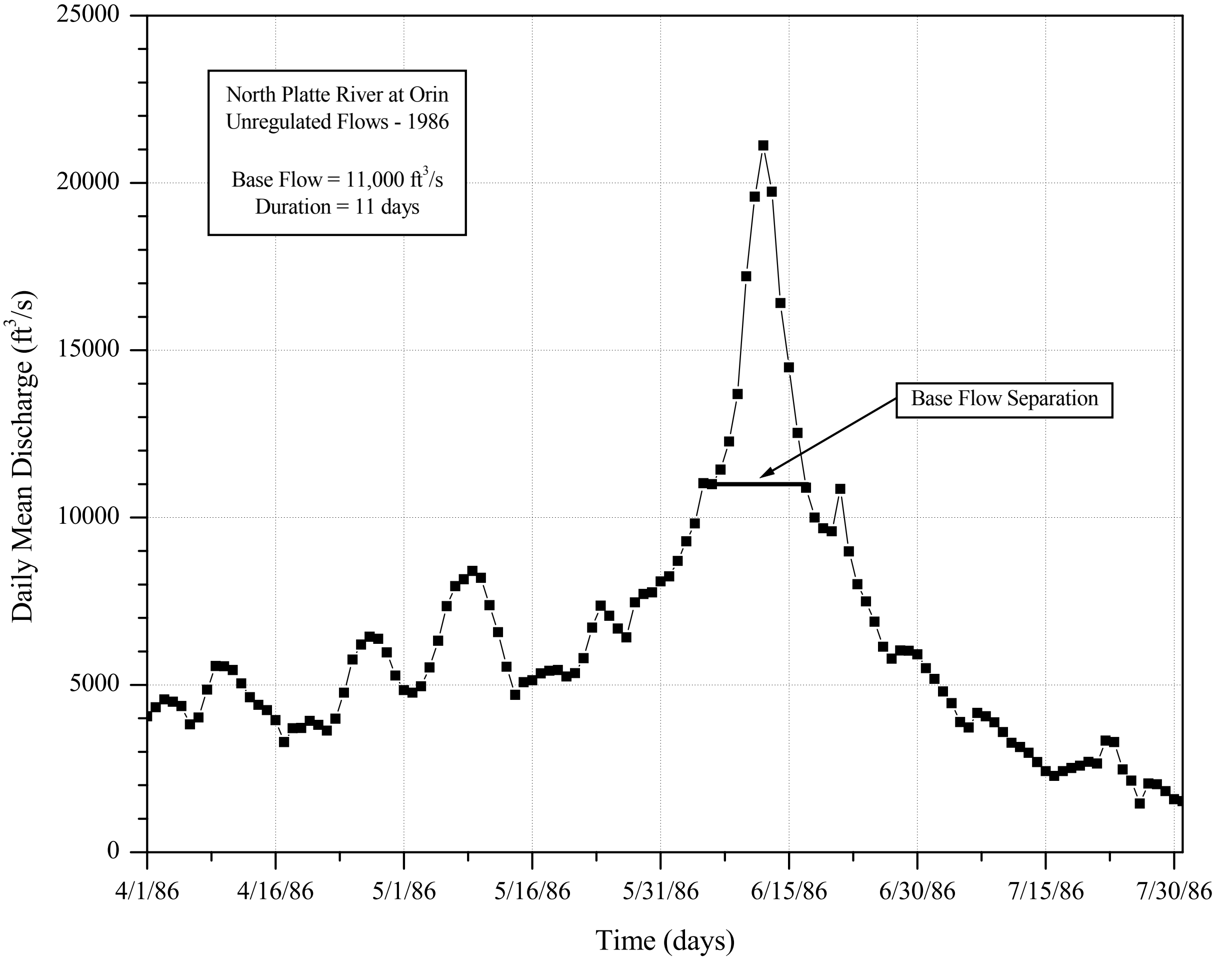

Figure 9: Example base flow and hydrograph duration estimation for inflows to Glendo Reservoir. Water year is 1986.

The relation between direct runoff volume (Vd) and maximum mean discharge (less base flow) (Qmd) at Glendo Dam is developed using the data in Levish et al. (2002). This relation is shown in Figure 10. Dimensionless unit volume hydrographs were developed for each of the 11 direct runoff hydrographs by converting the mean daily flow ordinates to a daily volume and dividing each by the total runoff volume (Figure 11). The snowmelt-dominated flows generally have lower peaks than floods with a large rainfall component. April-August hydrographs also serve as a sample of the antecedent conditions prior to the flood.

Hydrographs consist of five components: peak, volume, duration, shape, and base flow. The first four components are linked by the dimensionless unit volume hydrographs. Probabilities are assigned based on peak flow. Base flow is utilized to incorporate antecedent floods and simulate runoff for the April 1 through July 31 critical flood season (122-day duration). This duration was selected based on peak discharge, streamflow and rainstorm seasonality, and includes the

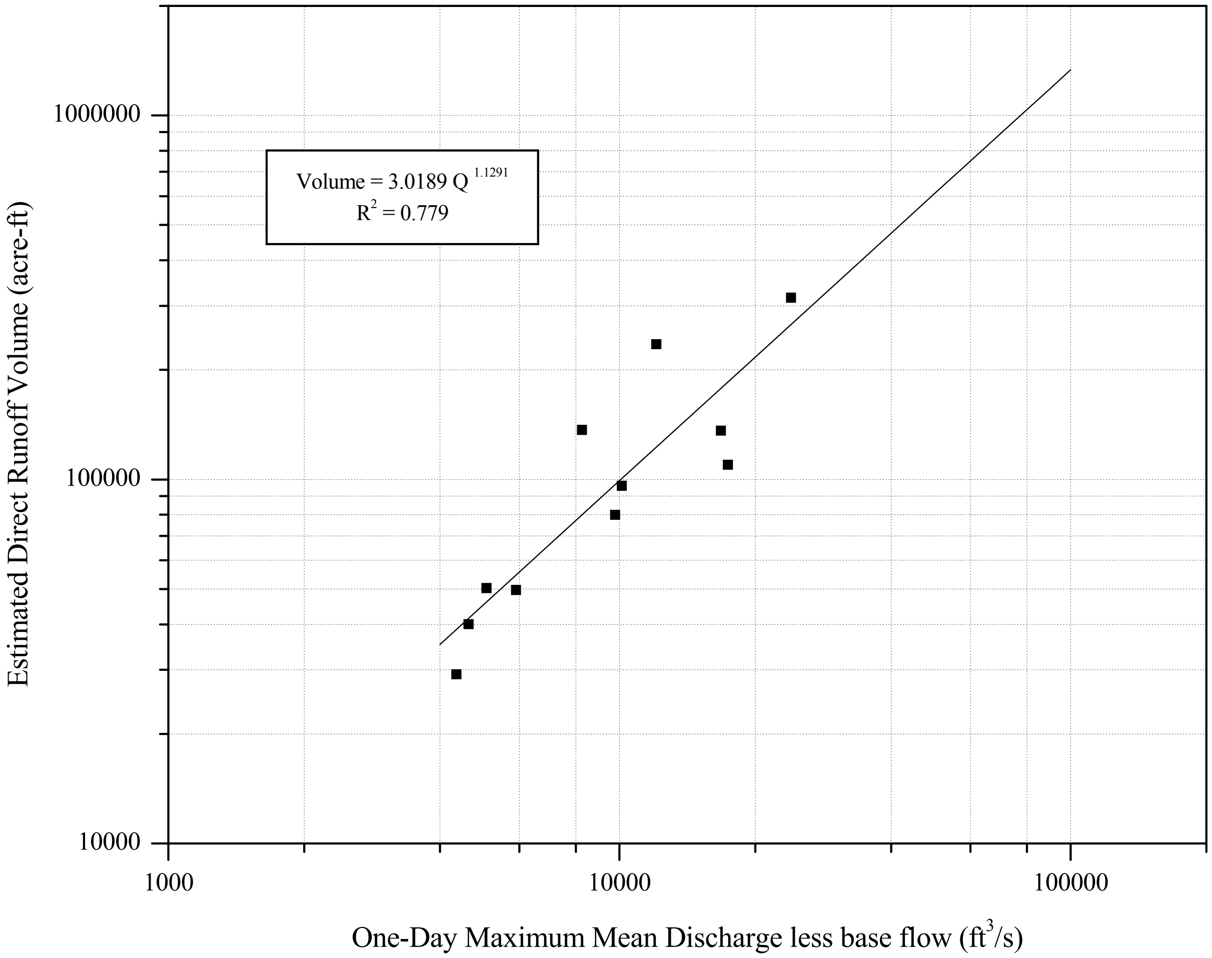

Figure 10: Maximum mean daily flow-direct runoff volume relationship for inflows to Glendo Reservoir.

snowmelt runoff season that typically begins in April or May. In addition, because of the large carry-over storage in Seminoe, Pathfinder, and Glendo Reservoirs, water is transferred from upstream to downstream reservoirs on about April 1 to make room for snowmelt runoff.

Probabilistic inflow hydrographs to Glendo Dam were developed from the four largest-volume hydrographs. A single relationship, based on these mixed-population data, was used to link direct runoff volume with maximum mean daily flow. The 1/10,000 AEP, 97.5 percentile peak discharge (approximately 126,000 ft^3/s) was used to assign the probability and peak to the each of the four hydrographs. Each dimensionless volume hydrograph was scaled from the maximum mean flow-runoff volume relationship, and combined with the base flow for the same year. The hydrographs are shown in Figure 12; properties are listed in Table 2. In addition to the hydrographs developed using the 1/10,000 AEP, 97.5 percentile peak discharge, four hydrographs were also developed using the median (50th percentile) peak discharge for a 1/10,000 AEP, equal to 79,200 ft^3/s (Figure 8).

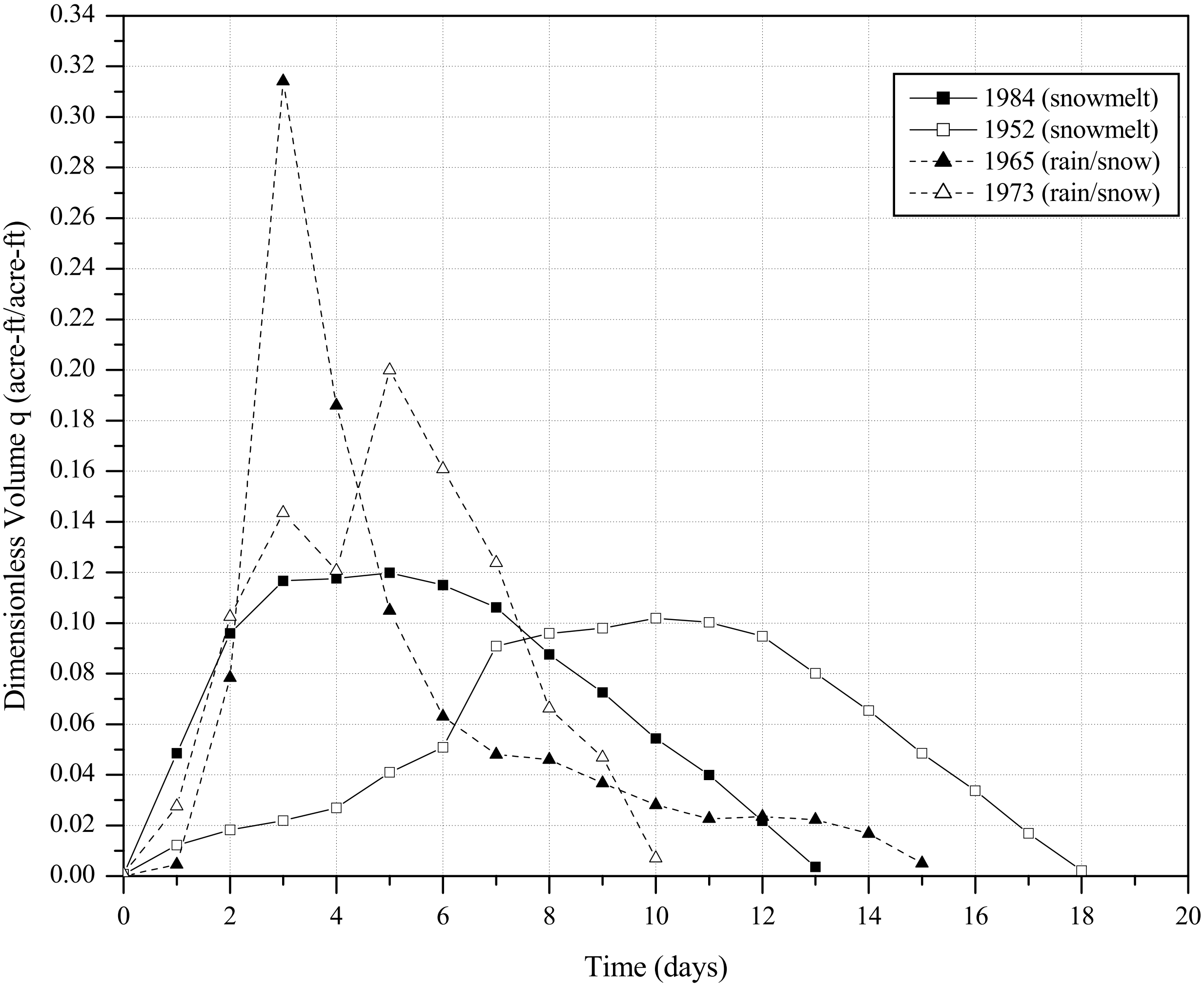

Figure 11.—Example dimensionless unit volume hydrographs used to construct inflow flood hydrographs to Glendo Reservoir.

Table 2.—Glendo Reservoir representative inflow hydrograph properties using 10,000-year upper 97.5% confidence limit (126,000 ft^3/s)

Water Year Unit Hydrograph Base	10,000-Yr 97.5% Max 1-Day (ft^3/s)	Estimated Max 1-day (ft^3/s)	Total Volume (acre-ft)	Duration Estimate (days)
1908	121,600	125,600	1,739,000	14
1984	121,600	101,500	1,841,000	13
1973	121,600	159,000	1,738,000	10
1952	121,600	87,400	1,857,000	18

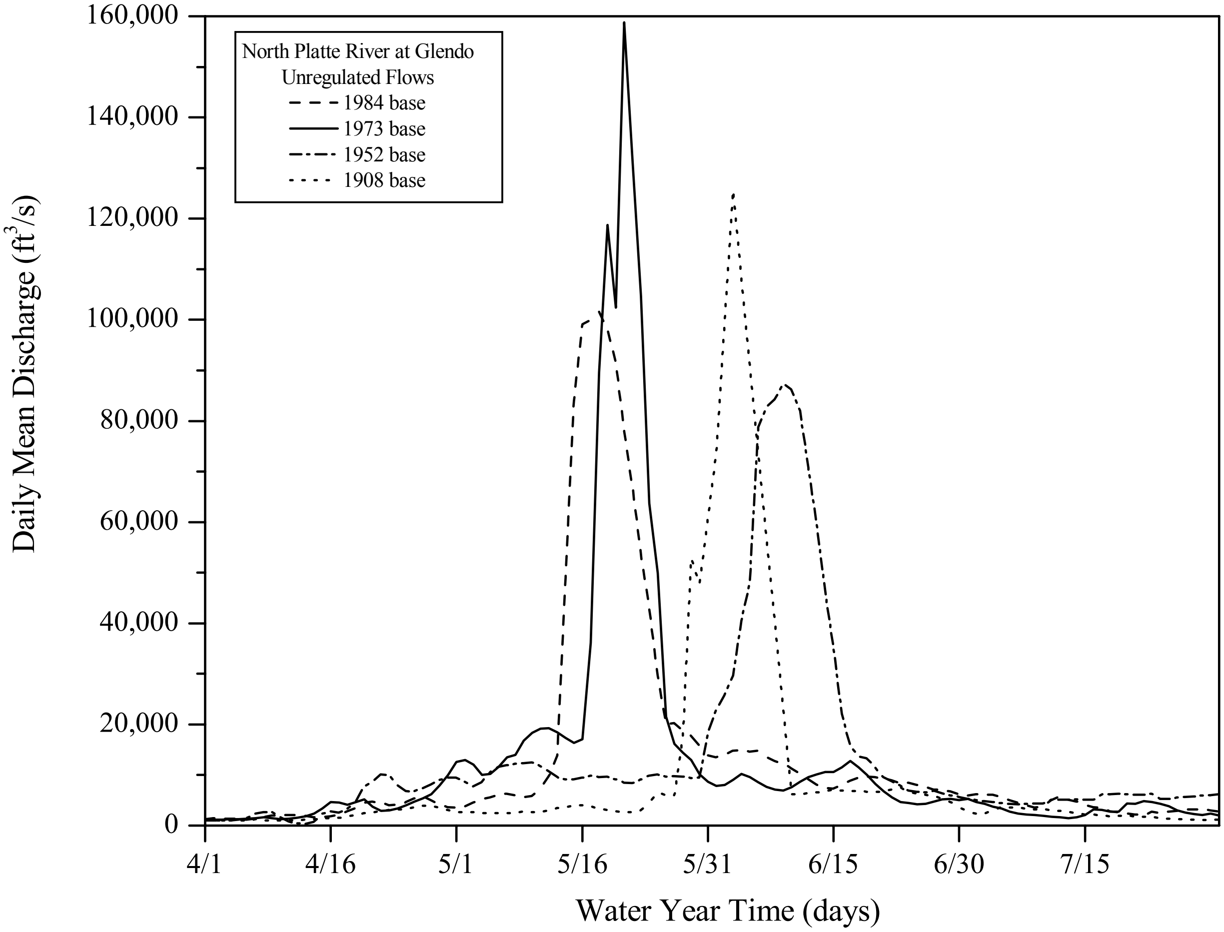

Figure 12.—Estimated 10,000-year inflow hydrographs to Glendo Reservoir, using 10,000-year upper 97.5% confidence limit (126,000 ft^3/s).

Probabilistic Extreme Flood Hydrographs Using Rainfall-Runoff Models

This section presents two methods to develop hydrographs based on rainfall-runoff models. The general procedures are outlined. An example that illustrates each method is given.

3.1 General Procedures

There are two general procedures used in this report to develop probabilistic extreme flood hydrographs from rainfall-runoff models. The first method is to use a rainfall-runoff model with an estimate of extreme precipitation and calibrate the model to a peak discharge frequency curve with paleoflood data. The second method uses rainfall-runoff output hydrographs as a basis to scale to match peak discharge estimates at specified probabilities. Both methods assume that one has a peak discharge frequency curve that encompasses the probabilities of interest.

The rainfall-runoff modeling procedure used here is similar to that traditionally used in design flood estimation (Pilgrim and Cordery, 1993). A deterministic, design event-based unit hydrograph rainfall-runoff model is used. The major components to the procedure are selecting a unit hydrograph, estimating loss rates, estimating precipitation (magnitude, storm duration, spatial and temporal distributions), and calibrating to a peak discharge frequency curve. In this approach, the modeling components are selected so that one approximates an "AEP neutral" approach. An AEP-neutral approach involves selecting model inputs and parameter values such that the 1 in Y AEP design rainfalls are converted to the corresponding 1 in Y AEP floods (Nathan and Weinmann, 1999 p. 5).

The rainfall-runoff method can be simple or complex, depending on the use of the extreme flood information. The procedure outlined here is fairly simple. A deterministic approach is used in that all input values are fixed. The modeling procedures can follow those traditionally used for PMP/PMF studies (Cudworth, 1989). The rainfall-runoff model selected is HEC-1 (HEC, 1990) or FHAR (USBR, 1995). For simplicity, the SCS dimensionless unit hydrograph or Reclamation dimensionless unit hydrographs can be used. For small basins, one can choose a single unit hydrograph for the basin. One can use a constant loss rate (e.g., 0.15 inches/hour), or use average infiltration rates derived from county soils maps. The SCS runoff curve number or Holtan infiltration models (Rawls et al., 1993) are simple alternatives to using a constant loss rate. For detailed studies, the Stochastic Event Flood Model (e.g., Schaefer and Barker, 1997) can be used with rainfall derived from regional precipitation frequency analysis using l-moments (Hosking and Wallis, 1997).

The precipitation estimation can be the most time-consuming part of the procedure, depending on the available information. The most important task is to develop point or basin-average extreme precipitation probability estimates. Regional precipitation frequency analysis using l-moments (Hosking and Wallis, 1997) is one way to determine storm probabilities. One may be able to obtain precipitation probability distributions for the region of interest from the National Weather Service (e.g., NWS, 2001). In lieu of a detailed regional precipitation frequency study, one can extrapolate existing relationships from NOAA Atlas II (e.g., Miller et al., 1973), by assuming a logNormal distribution (e.g., Lane, 1997). The storm duration is another critical feature that needs to be estimated. A storm duration can be selected based on the basin lag time or a regional extreme storm catalog (e.g., McKee and Doesken, 1997). Precipitation spatial and temporal distributions can be estimated based on published hydrometeorological reports or from other published reports, such as Frederick et al. (1981) and Zehr and Meyers (1984) for the southwest.

The rainfall-runoff model is run for fixed point rainfall probabilities (e.g., 1/1,000 and 1/10,000 AEP), after selecting unit hydrograph, loss rates, and developing precipitation input. The model-generated peak flows are then compared to the peak discharge frequency curve. The model components can subsequently be adjusted (calibrated) to match the peak discharge frequency curve. Lag time and infiltration are two components that can be adjusted. The process is then repeated for the peak discharge frequency confidence limits. In this way, one has a hydrograph and volume estimate for the lower, median and upper confidence limits for a given probability.

In contrast to developing inputs to and applying a rainfall-runoff model to a watershed, an alternate procedure is to use observed hydrographs and model output hydrographs as a basis to scale. This method can be used when there are very few recorded hydrographs at the site of interest. This simple procedure involves selecting hydrographs and scaling the hydrograph ordinates by the peak flow from the flood frequency curve. There are three steps to this method: (1) selecting hydrographs and types to use as a basis to scale; (2) defining antecedent flood and base flow; and (3) adjusting the ordinates of the hydrograph to match peak discharges with specified annual exceedance probabilities. The general idea is that by selecting different observed and model hydrographs one can capture some variability in volume, duration, runoff response and subsequent maximum reservoir levels for extreme floods. At least three hydrographs should be used: the hydrograph used for the original design of the structure (if available), the largest recorded flood in the basin at or near the location of interest, and one or more PMF hydrographs, such as the general storm PMF and/or thunderstorm PMF. Typically the original design and PMF hydrographs are based on different assumptions and the durations and/or unit hydrographs are not the same. If the durations and unit hydrographs for the PMF and design floods are the same, then other hydrographs need to be selected. Depending on the region and available storm data, the largest-volume hydrographs (typically spring, fall or winter seasons) are usually selected for analysis. The thunderstorm hydrograph is not analyzed. For simplicity, a single antecedent flood is selected, and is chosen based on the PMF study and season for analysis. In most cases, the antecedent flood is usually a 100-year, 15-day snowmelt hydrograph or a 100-year rainfall-runoff hydrograph. After selecting the hydrographs, the ordinates of each is scaled to match peak flow estimates for selected annual exceedance probabilities. The antecedent flood (no scaling) is then added to the scaled hydrograph.

3.2 Example Applications

Two example applications are presented. The analysis for Rifle Gap Dam illustrates the use of a rainfall-runoff model and AEP-neutral approach. The example for Red Willow Dam involved scaling of observed and rainfall-runoff model output hydrographs.

Rifle Gap Dam

Extreme flood hydrographs were developed at Rifle Gap Dam for a Risk Analysis (England, 2000a). The HEC-1 model was used to estimate the hydrographs. The basin subdivision and lag times were estimated from the PMF study. Flood inflow hydrographs to Rifle Gap Reservoir were constructed for the 1,000-year and 10,000-year return periods by utilizing the HEC-1 rainfall-runoff model (HEC, 1990). Three hydrographs were estimated for each frequency based on the median peak discharge-frequency curve and upper and lower confidence limits.
A 72-hour duration rainfall design storm was used. A constant infiltration rate (0.15 inches per hour) was assumed for the basin. A Soil Conservation Service (SCS) dimensionless unit

hydrograph was used to transform excess precipitation into runoff. Watershed lag times were adjusted in order that model-generated peak discharges match flood frequency curve estimates.

Existing point rainfall frequency relationships (Miller et al., 1973) were extrapolated from the published 100- and 500-year estimates, assuming a lognormal distribution, to obtain 1,000- and 10,000-year frequency estimates for the 30 minute, 1, 2, 3, 6, 12, 24, 48, and 72-hour durations. The unit hydrograph lag time for Rifle Creek basin (Cudworth, 1989) was used to select the critical rainfall duration. The 3-hour duration was selected to represent the 1,000- and 10,000-year point values; values for the other durations (one through 24 hours) were adjusted based on the 3-hour value. Inter-storm duration probabilities were estimated based on relations in Frederick et al. (1981). Basin-average rainfall (spatial distribution) was computed by reducing point values to the drainage basin area using a relationship for the southwest (Zehr and Meyers, 1984). A front-end loaded rainfall temporal distribution was selected based on an existing storm catalog and Frederick et al. (1981).

Flood inflow hydrographs to Rifle Gap Reservoir were developed based on peak discharges from the frequency curve for the 1,000- and 10,000-year floods. Simple comparisons of hydrograph peaks with the spillway capacity indicated the dam would not be overtopped by the lower and middle flood hydrographs. However, the peak (16,400 ft3/s) and volume (13,500 acre-feet) of the 10,000 year return period hydrograph (upper confidence limit) are about 1.5 to 1.75 times greater than the original inflow design flood. The Waterways and Concrete Dams Group routed the hydrographs with three different assumptions for initial reservoir water surface elevations (normal, top of conservation storage, maximum observed) to determine maximum reservoir levels. Example hydrographs for Rifle Gap Dam are shown in Figure 13.

Red Willow Dam

Extreme flood hydrographs were developed at Red Willow Dam for a Risk Analysis (Camrud and Klinger, 2000). Three hydrographs were used as a basis to scale: the June 21-22, 1947 flood in the Red Willow basin, the 1955 Inflow Design Flood (IDF), and the 1984 Probable Maximum Flood (PMF). The largest recorded flood hydrograph available in the basin was for the June 1947 flood. It appears that the May 1935 flood peak on Red Willow Creek is larger than the June 1947 flood based on indirect measurements; however, only peak estimates for that flood event are available (Camrud and Klinger, 2000). The Inflow Design Flood (IDF) study was completed in 1955 by the Regional office. This hydrograph has a 157,000 ft^3/s peak and a 2-day volume of 114,000 acre-feet. The PMF hydrograph was developed in 1984 by the Lower Missouri Regional office. The 1984 PMF hydrograph (without the antecedent flood) has a peak of 277,500 ft^3/s and a 3-day volume of 224,800 acre-feet. A 100-year rainstorm was used as the antecedent flood.

Nine probabilistic hydrographs were developed to estimate a range of inflows to Red Willow Dam (Camrud and Klinger, 2000). To associate probabilities to each of the hydrographs, the 10,000-year peak discharge at the 50th percentile, 5 and 95% confidence limits (86,900 ft^3/s, 168,000 ft^3/s and 337,000 ft^3/s, respectively) from the flood frequency analysis were applied to each of the hydrographs. Each of the routed hydrographs included the unscaled 100-year antecedent flood as defined in the 1984 PMF study. Example scaled hydrographs based on the 10,000-year peak flow are shown in Figure 14.

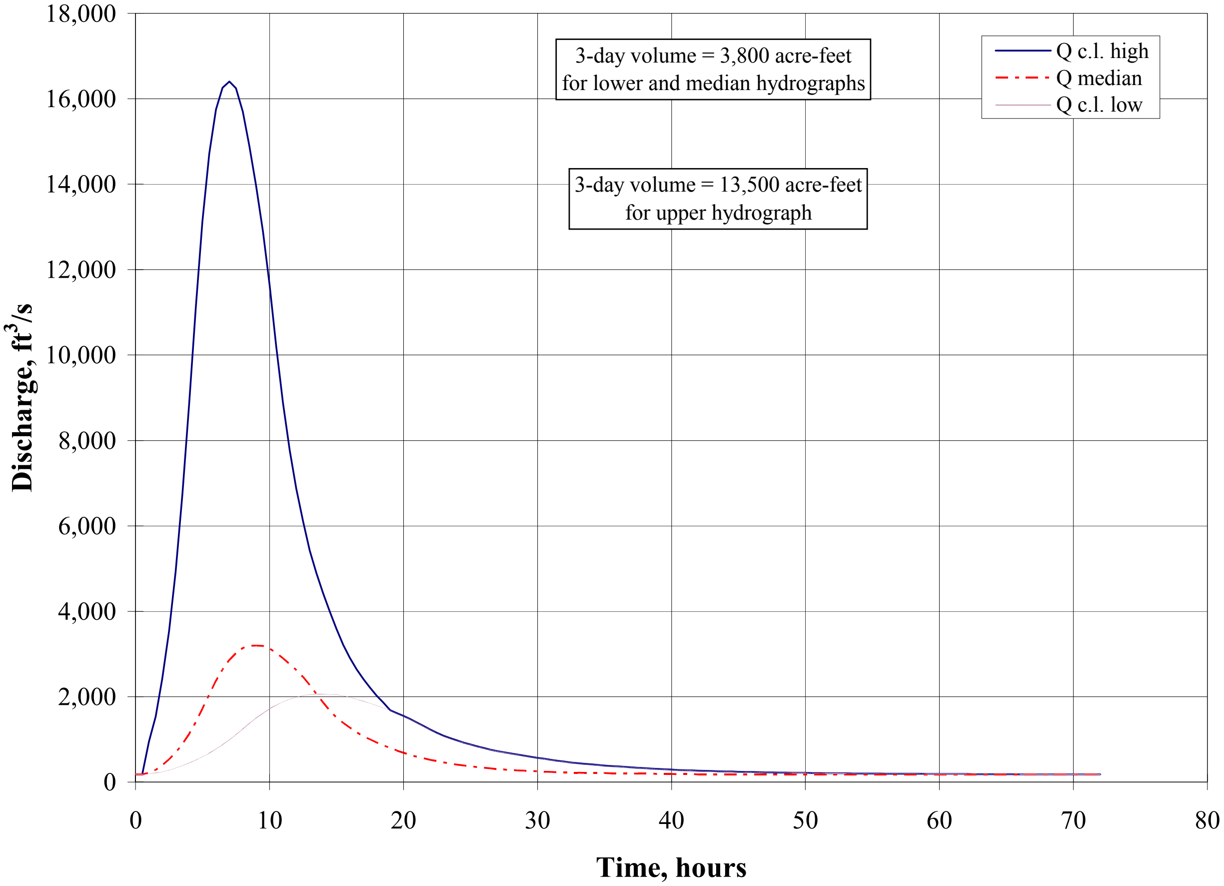

Figure 13.— Example inflow hydrographs to Rifle Gap reservoir, 1/10,000 AEP based on peak flow frequency curve and rainfall-runoff model.

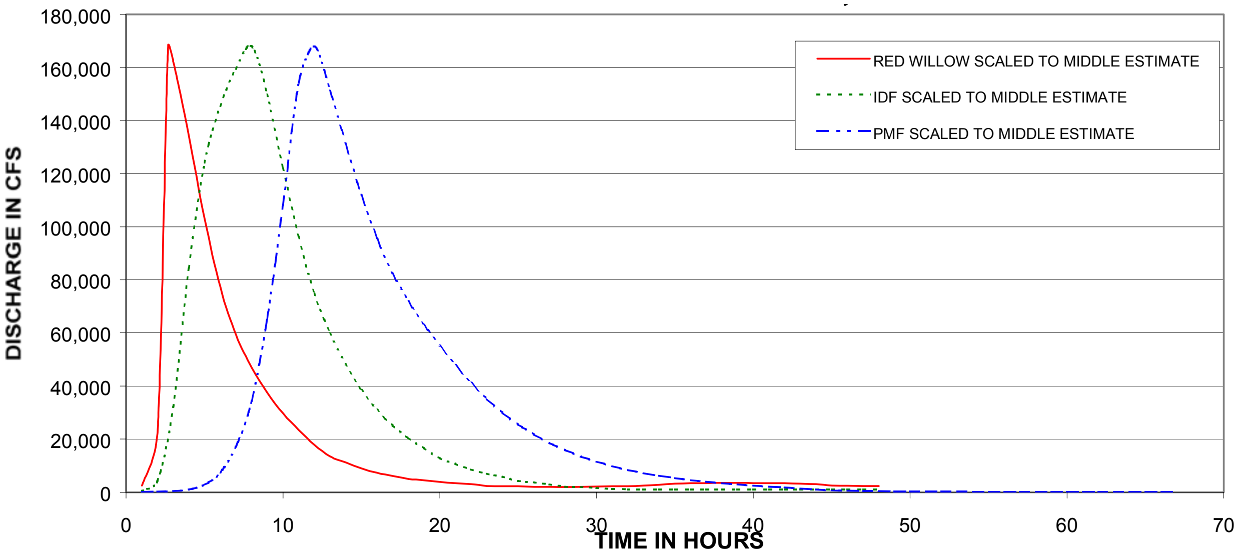

Figure 14.— Example hydrographs for 1/10,000 AEP median (50%) peak discharge (168,000 ft^3/s), Red Willow Dam.

Reservoir Routing Issues

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 (Nathan and Weinmann, 1999 p. 57). 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 flood control pool. This assumption has been criticized as being unduly conservative (Newton, 1983 p. 914), who notes that 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.

There are several difficulties in estimating annual probabilities for reservoir levels. The most common approach is to compute the percentage of time the reservoir water surface exceeds a certain level. This computation is a duration curve. Mosley and McKerchar (1993, p. 8.27) provide a definition for flow duration: “A flow-duration curve (FDC) plots cumulative frequency of discharge, that is, discharge as a function of the percentage of time that the discharge is exceeded. It is not a probability curve, because discharge is correlated between successive time intervals, and discharge characteristics are dependent on the season of the year.” This also applies to daily, monthly and annual maximum reservoir levels. In many cases, maximum reservoir levels are serially correlated at sites with large carry-over storage. The probability estimates are percentages of time, and not annual exceedance probabilities. A simple serial correlation test (Salas, 1993) can be used to distinguish if daily, monthly or annual reservoir levels are correlated. The correlated data can be used to estimate maxima, minima and percentiles of reservoir levels (e.g., Figure 15) as long as annual probabilities are not assigned to the data. The most important point is to estimate and recommend a range of reservoir levels for a risk analysis.

For example, daily reservoir elevations for the period of record at Folsom Dam (1955-2000) indicate that a median reservoir elevation for the November through February period is approximately 420 feet, with a quartile range (25 to 75 percentiles) from about 405 to 430 feet (Figure 15). This reservoir elevation range should be considered as initial reservoir water surface elevations for routing the hydrographs.

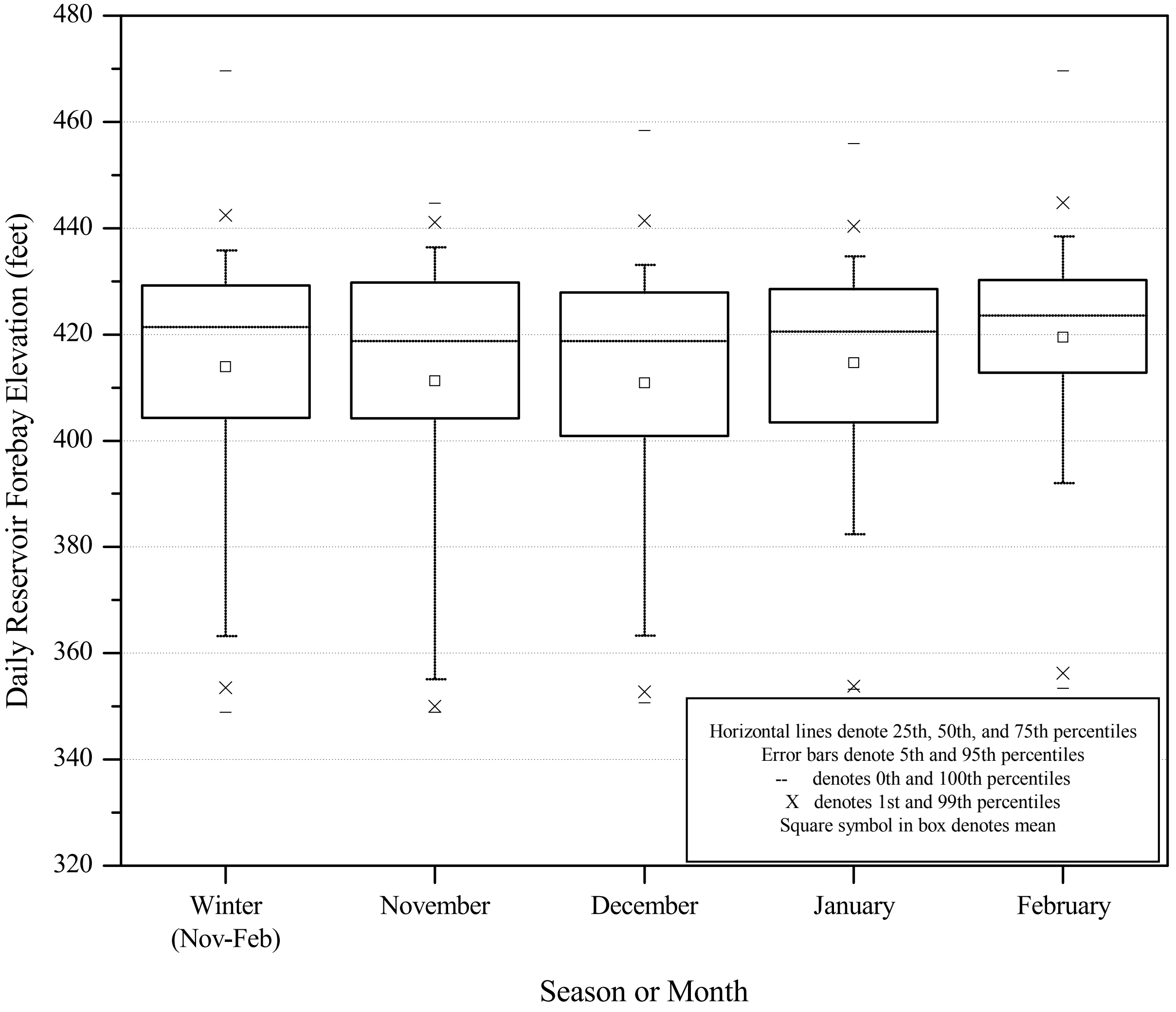

Figure 15.—Daily reservoir elevation percentiles for the period of record at Folsom Lake shown as box plots for the extreme flood season.

Discussion, Limitations and Further Research Needs

This report presented statistical and rainfall-runoff based techniques to develop probabilistic extreme flood hydrographs for dam safety. A method to extrapolate peak discharge frequency curves was also presented. A peak discharge frequency curve with paleoflood data was the basis for the methods in this report. Reservoir routing and channel storage issues were briefly discussed. There are several assumptions and limitations to the methods outlined in this report that are discussed in this section. This work is more of an engineering “rationale”, to provide information for decision-making, rather than scientific research. The research is not intended to directly advance the science of hydrology; rather the purpose is to develop tools that can be implemented fairly quickly and effectively, by moderate extensions to standard methods.

5.1 Streamflow Sampling

This report demonstrated the use of a statistical technique to develop probabilistic extreme flood hydrographs. Four components were used to develop the hydrographs (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 major factor in the methods was a peak discharge frequency curve, based on paleoflood data, and extrapolated to 1/10,000 AEP. The assumption was that the paleoflood data could be used as the basis to extrapolate the frequency curve to the AEP of interest.

This procedure can be considered as an improvement to prior statistical procedures, because it eliminates several arbitrary assumptions: (1) the use of a single duration for runoff volume; (2) the use of “nested” flood probabilities for a fixed duration; (3) the use of a single hydrograph (basin response function); and (4) the use of a single initial reservoir level. The major advantages to the present procedure are: (1) it is conceptually simple to understand; (2) it is based on available data; and (3) it capitalizes on existing statistical techniques. However, the procedure has not been fully tested to date. Further work needs to be done to test and improve the procedure. Routines need to be written to automate the sampling of distributions in a Monte Carlo framework. The uncertainty in peak discharge frequency curves, peak-volume regression relationships and uncertainty in initial reservoir levels need to be included, at a minimum. A reservoir routing routine needs to be added, so one can automatically determine a maximum reservoir elevation for the proposed many combinations (thousands) of selected hydrographs and initial reservoir levels. The variability of each component, and how each piece affects the computed maximum reservoir elevation, needs to be investigated. Results from this method should also be compared with results from traditional, deterministic flood hydrology procedures.

There are some major limitations to this method. As it is based purely on statistical procedures, there is no current way to verify that the extrapolated flood frequency distribution and extrapolated peak-volume relationship are physically meaningful. The method is appropriate for appraisal or feasibility –level studies. The procedure does not separate snowmelt runoff from rainfall-runoff processes. It also does not include effects of upstream reservoirs. Alternative, stochastic-deterministic rainfall-runoff based procedures, calibrated to the flood frequency curve, may supersede this procedure when more detailed analyses are needed. Reclamation is currently investigating the performance of a physically-based, two-dimensional distributed rainfall-runoff model for predicting large floods and extrapolating flood frequency curves. Research on defining upper limits to frequency curves are needed as well. The current approach does not include an upper limit on the distributions.

The Corps of Engineers is also developing probabilistic flood hydrographs using the HEC-1 rainfall-runoff model with stochastic meteorological and hydrologic inputs. The Corps study includes the effects of upstream reservoirs; correlates initial reservoir levels to antecedent flood conditions; and ties rainfall magnitude, duration, and distribution directly to the production of flood hydrographs. While these studies introduce additional uncertainty into the analysis by the selection of model parameters, Reclamation can use these results to evaluate the appropriateness of the assumptions used in the scaling approach to developing flood hydrographs.

5.2 Rainfall-Runoff Modeling

The rainfall-runoff based procedures presented in this report are simple and based on existing deterministic rainfall-runoff modeling procedures. There are many strengths and weaknesses to the procedures. The strengths are that the approaches are simple and use existing methods. However, there are many limitations, both in applying rainfall-runoff models and in scaling model hydrographs.

The approach that uses a rainfall-runoff model to estimate hydrographs depends on three major factors: model selection, precipitation input and the use of fixed input values. The unit hydrograph procedure, as noted above, is a linear method. This assumption can affect the shape of the peak discharge frequency curve, and have a significant impact on extrapolated results (Pilgrim and Cordery, 1993). The AEP-neutral assumption, where the 1 in Y rainfall causes the 1 in Y peak discharge, is overly simplistic. In most cases, the probability of the estimated runoff is much lower than that of the rainfall (Linsley, 1986). A continuous rainfall runoff model can be used to alleviate this issue, but the input data requirements can be substantial. The most difficult input to derive is the extreme storm rainfall. There are few locations in the western United States where extreme rainfall probability estimates are available and storm models have been constructed. Except possibly in some special cases, there is no typical storm pattern: storm rainfall occurs in an infinite variety of time sequences and areal patterns (Linsley, 1986). Further work is needed to develop extreme precipitation probabilities and storm estimates in the western United States. The use of fixed input values is also simplistic. Following Schaefer and Barker (1997), one can estimate distributions for the major input variables. One major limitation is that the rainfall runoff modeling procedure, as currently specified, is not calibrated to the basin of interest except for adjusting model parameters to match the peak discharge frequency curve. Additional model calibration steps are needed to ensure that the hydrographs match the shape and timing of the largest recorded extreme floods in the basin.

The procedure that uses output hydrographs from rainfall-runoff models needs testing at many more sites to examine the viability of the approach. This procedure completely depends on the hydrographs that are selected for scaling, and the properties of those hydrographs. Other procedures as outlined in the report are preferred to using this simple scaling method. The procedure can possibly be improved by developing additional relations between peak and volume.

Conclusions And Recommendations

Based on the research conducted for probabilistic extreme flood hydrographs and presented in this report, four conclusions are made.

1. Probabilistic extreme flood hydrographs can be developed based on a peak discharge frequency curve and paleoflood data. These hydrographs can subsequently be used in a risk analysis.
2. Two general methods can be used to develop extreme flood hydrographs: statistical procedures and rainfall-runoff methods. Both approaches are relatively straightforward to implement and are developed by coupling existing tools. Overall, the methods perform fairly well. However, limited testing of scaling rainfall-runoff model hydrographs has been done.
3. A simple flood frequency extrapolation method was developed using a log-Normal distribution and rainfall frequency curve for sites where one has detailed paleoflood data.
4. Initial reservoir levels for extreme flood hydrograph routing are a critical factor and should be varied by selecting different levels based on past reservoir performance instead of using fixed, initial levels.

From the methods and case studies shown in this report, two recommendations are made for implementing the procedures and continuing flood studies for dam safety.

1. Continued extreme flood investigations are needed for predicting large flood hydrographs and extrapolating flood frequency curves.
2. The procedures outlined in this report should be subject to further testing and application at other site where risk analyses are needed. Results from the different methods should be compared.

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Mission Statement

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.