The Stochastic Event Flood Model Applied to Minidoka Dam on the Snake River, Idaho

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Abstract

A stochastic event-based, rainfall-runoff model was developed to compute magnitude-frequency estimates for flood peak discharge, runoff-volume and maximum reservoir level at Minidoka Dam. This model was supplemented with probabilistic analysis of historic and potential flood outflows from American Falls Dam. The basic concept of the stochastic model is to employ a deterministic flood computation model and treat the input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the climatic and hydrologic input parameters to vary in accordance with that observed in nature

Flood peaks rather than flood volume were found to be the primary concern because of the limited flood storage in Lake Walcott behind Minidoka Dam. The magnitude frequency curve developed for peak flows revealed that inflow peak flows in excess of 109,000 ft^3/s, the approximate maximum non-overtopping discharge available at Minidoka Dam, would have an annual return period in excess of 10,000-years. The magnitude-frequency curve developed for maximum reservoir elevations confirmed the overtopping probability to be in excess of 1 in 10,000-years.

Introduction:

Minidoka Dam is located on the Snake River below American Falls Dam in southeastern Idaho. Minidoka Dam was constructed between 1904 and 1906. Many structural improvements at the facility and the development of numerous upstream dams on the Snake River and tributaries have created a complex set of circumstances for determining inflow floods at different return periods for Minidoka Dam. To aid in providing the required hydrographs the SEFM (Stochastic Event Flood Model) developed for Reclamation by MGS Engineering Consultants of Olympia, Washington was used. This model, along with past studies of the upstream dams, paleoflood hydrology data, and regional storm and precipitation analysis provides the necessary flood hydrographs for current dam safety studies.

It was not known at the beginning of the study which source of floods, the uncontrolled Raft River and Snake River sub-basins below American Falls Dam, or the controlled flood releases from American Falls Dam, would produce larger floods. There were several studies related to the inflows and outflows from American Falls Dam, but there was no information about the flood potential from the Raft River and other uncontrolled areas below American Falls Dam. The SEFM methodology allowed the uncontrolled areas to be carefully studied and provided the necessary hydrographs for that source of flooding. Previous reports, related to the ability of American Falls Dam to pass very large inflows and other long term stream gage data, were also incorporated to provide the required information for that source of flooding. These two sources of flooding were assumed to be independent. Flood conditions on the Raft River and uncontrolled Snake River sub-basins below American Falls Dam would not necessarily occur at the same time or even in the same year as large floods originating on the Snake River above American Falls Dam. With this assumption, it is possible to combine the flood hydrographs from the two sources into a single inflow hydrograph for Minidoka Dam using the SEFM framework. With this framework, it is also possible to study a variety of storm combinations and different seasonal ground conditions.

Description of Minidoka Watershed:

The Snake River at Minidoka Dam encompasses approximately 15,500 mi^2 of drainage area. The upper reaches of the Snake River are in Yellowstone National Park and flow south through Jackson Lake in Wyoming. Numerous reservoirs have been built in the basin. The largest and most significant manmade reservoirs, and the original construction completion date, include Jackson Lake (1911), Palisades (1957), and American Falls (1927). Many other smaller reservoirs also exist in the basin. American Falls Dam exists approximately 30 river miles upstream from Minidoka Dam and is the nearest upstream dam. American Falls Reservoir is also the largest storage reservoir above Minidoka Dam with approximately 1.7 million acre-feet of storage at the spillway crest, and approximately 3.4 million acre-feet of flood storage at the top of the dam. For Minidoka Dam the combined spillway and outlet works capacity is approximately 109,000 ft^3/s at the dam crest elevation.

North of the Snake River between Minidoka Dam and American Falls Dam is a large area of volcanic deposits. Most of this area does not contribute to any surface flows in the Snake River. The volcanic surface deposits are deep and any rainfall that occurs is quickly passed to the lower depths and into the groundwater aquifer. Only a narrow strip of land north of the Snake River is considered to contribute to surface flows in this reach.

The drainage area between American Falls Dam and Minidoka Dam consists of approximately 2,480 mi^2 of uncontrolled drainage mostly from the Raft River basin on the south side of the Snake River. The Raft River basin originates in the higher elevations in the mountains of northern Utah. Much of the Raft River basin valley is nearly flat terrain devoted to range, pasture and some irrigated agriculture. Snow can accumulate in the higher mountain areas, but the lower elevations remain snow free most of the year. Much of the surface water flow comes from interflow and ground water interception. Large rainstorms in the area have not produced large flood events.

Sub-Division of the Watershed for Distributed Rainfall-Runoff Modeling:

Hydrometeorological conditions vary widely across the Minidoka watershed. This required that many of the hydrometeorological inputs be treated in a distributed manner. This was accomplished by subdividing the watershed into zones with common values of mean annual precipitation, elevation, and soil characteristics. This approach allowed for spatial variability in allocating antecedent precipitation and snowpack, setting initial soil moisture conditions, and computing surface and interflow runoff.

The distributed approach was accomplished through the use of Hydrologic Runoff Units (HRUs), wherein the watershed was subdivided into 9 zones of mean annual precipitation, 10 elevation zones, and 9 soil zones. This resulted in 810 HRU combinations that were possible, of which, 393 unique HRU combinations of mean annual precipitation, elevation, and soil zone classification actually occur in the watershed.

The uncontrolled watershed below American Falls Dam was also divided into four subbasins for the final rainfall-runoff modeling and calibration. Subbasins were defined above the one USGS gage on the Raft River and at the main confluence point where the Raft River joins with the Snake River. The HRUs in each of these subbasins are considered individually for rainfall, snowmelt and loss rate calculations. The results for each HRU are then aggregated within each rainfall-runoff subbasin further unit hydrograph processing with the SEFM deterministic rainfall-runoff calculations.

Application of Stochastic Model to Area below American Falls Dam:

The basic concept employed in the stochastic approach is the computer simulation of multi-thousand years of flood annual maxima. This is accomplished by utilizing a deterministic flood computation model, including snowmelt computations, and treating the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the climatic and storm related input parameters to vary in accordance with that observed in nature. Multi-thousand years of extreme storm and flood annual maxima are generated by computer simulation. The simulation for each year contains a set of climatic and storm parameters that were selected through Monte Carlo procedures based on the historical record and collectively preserve dependencies between the hydrometeorological input parameters. Table 1 displays the dependencies between the various model inputs for this portion of the study. An annual maxima series is created for each flood parameter of interest and the values are ranked in descending order of magnitude. Non-parametric plotting position formula and probability-plots are used to describe the magnitude-frequency relationships.

HYDROMETEOROLOGICAL INPUTS FOR STOCHASTIC MODEL			
MODEL INPUT		DEPENDENCIES	COMMENTS
1	Seasonality of Storm Occurrence	Independent	End-of-month storm occurrences
2	Antecedent Precipitation	Independent Varies by month	Precipitation Oct 1st to date of storm occurrence Varies with zones of mean annual precipitation
3	Antecedent Temperature	Independent Varies by month	Varies by elevation zone
4	Antecedent Snowpack	Antecedent Precipitation Varies by month	Varies by zones of mean annual precipitation and elevation
5	September 1st Soil Moisture Deficit	Independent	Set at maximum value, wilting point
6	Initial Streamflow	Independent	Mean monthly flow for Month of storm occurrence
7	Initial Reservoir Level	Independent Varies by month	Resampled from historical record 1980-2005
8	24-Hour Storm Magnitude	Independent	Based on regional analyses
9	Precipitation Temporal Characteristics	Independent	Based on analyses of historical storms
10	Storm Centering	Independent	Four centering patterns, one per sub-basin
11	Precipitation Spatial Characteristics	Independent	Based on storm centering
12	Air Temperatures During Storm	Storm Magnitude Varies by month	Varies by elevation zones Varies with storm temporal pattern
13	Snake River Outflow from American Falls	Independent Varies by month	Resampled from 1929-2005 historical record Scaling used for extreme outflows

Table 1 - Independent and Dependent Hydrometeorological Parameters

Probabilistic Inputs for Initial Watershed Conditions:

Seasonality of extreme storms, antecedent precipitation, September 1st soil moisture deficit, snowpack, antecedent temperature, initial streamflow and reservoir level are all variables. Initial conditions are determined from analysis of historic data records and are included in the model as either random variables with the dependencies noted above or as data sets from which data is resampled during the simulation procedure with knowledge of the starting date for the simulated storm.

Inputs Related to the Occurrence of the Extreme Storm:

72-Hour Extreme Storm – A 72-hour storm that contained an extreme 24-hour precipitation amount was the basis for the rainfall portion of the SEFM input for the sub-basins below American Falls Dam.

Precipitation Magnitude-Frequency Curve for Specified Durations – The 1-day storm was used in the regional precipitation-frequency analysis. The analysis was conducted using annual maxima data for the 24-hour duration from over 150 precipitation gages in southern Idaho, northeastern Nevada, northern Utah, and eastern Oregon. Information from the standard climatological network of rain gage stations was augmented by data from over 40 SNOTEL stations from the same geographic area. The point precipitation rain gage values were taken to be representative of 10-mi^2 precipitation. The basin-average 10-mi^2 precipitation-frequency relationship, figure 1, was developed based on the techniques of Hosking and Wallis [1].

Areal Reduction Factors – The factors used to adjust the 10-mi^2 precipitation values for the Minidoka drainage area were extracted from studies of storm rainfall by Siriwarden and Weinmann in Australia [2].

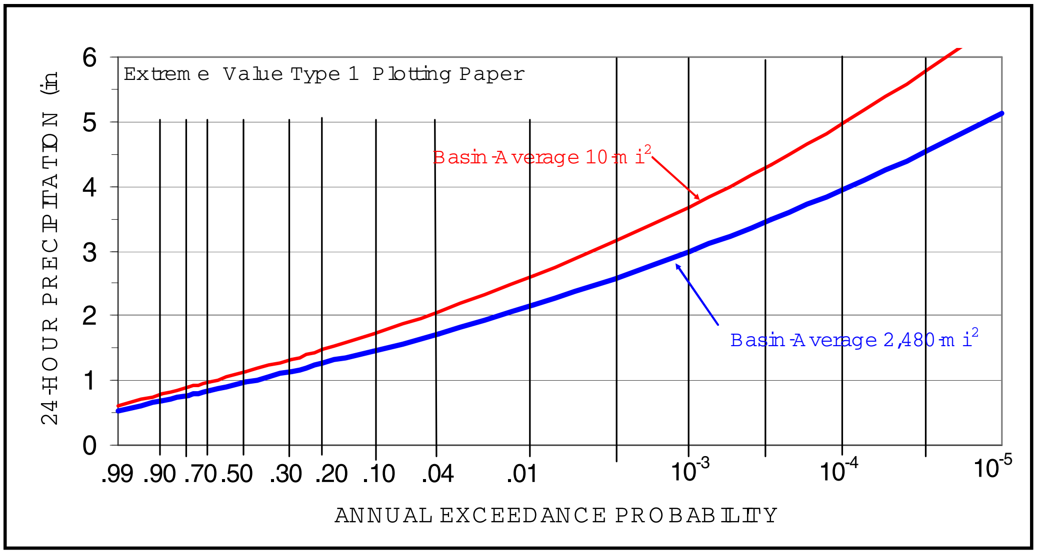

Figure 1 - Basin-average, 24-hour precipitation frequency relationships for the Minidoka basin

Temporal characteristics of 3-day storm events and spatial characteristics of 3-day storm events were also considered based on analysis of historic storm patterns, and random resampling procedures in the SEFM.

Similar procedures were used to define a basin average 24-hour precipitation frequency relationship for the entire contributing drainage area above American Falls Dam, 7,800 mi^2. This relationship is used later to help incorporate the American Falls outflows into the SEFM model for complete inflow hydrographs at Minidoka Dam.

Inputs Related to Rainfall-Runoff Modeling:

Initial soil moisture deficit for the random month selected for simulation, surface infiltration, deep percolation rate, temperatures during extreme storms used for snowmelt computations, surface runoff unit, interflow runoff hydrographs are among the variables included in the SEFM. Individual simulation input for each of these variables allows for the natural dependencies and probability distributions that can be derived from extensive analysis of available historic data sets.

Simulation Procedure:

One of the key features of the model is the use of stochastic methods for selecting the magnitude and combination of input parameters for computation of floods. A flow chart for the basic simulation procedure for the sub-basins below American Falls Dam is provided in the SEFM Technical Support Manual [3]. Modifications to this procedure were required for this specific study to incorporate flows from the Snake River after having been routed through several upstream reservoirs, including American Falls Dam.

The basic construct for the stochastic simulation can be described as follows. If precipitation data were available for an extremely long period of record (assuming stationary climate), then the storms and all other hydrometeorological parameters associated with those storm events could be used to generate a series of floods. Characteristics of the floods such as peak discharge, runoff volume and maximum reservoir level could then be ranked in order of magnitude and a non-parametric plotting position formula used to describe the magnitude-frequency relationships.

The goal for this simulation was to produce flood frequency estimates out to 10^{-4} AEP. To accomplish this, floods were simulated beyond 10^{-5} AEP to get a representative sample in the region of interest of the frequency curve. For this simulation, we set N in the Gringorten plotting position formula [4] used to compute the storm magnitude to 100,000. With 5,000 simulations, this provided storm magnitudes ranging from 0.05 AEP to 5.6 10^{-6} AEP.

$$P_{ex} = \frac{i - 0.44}{N + 0.12}$$

Where: P_{ex} is the exceedance probability of the 24-hour 10-sq mi precipitation,
i is the simulation number (1 to 5,000 in this case),
N is the total number of years simulated (100,000 in this case).

This approach omits storms smaller than 0.05 AEP (20-year recurrence interval) and greatly increases the computational efficiency. The implicit assumption is that storms smaller than the 20-year cannot produce a 10,000-year flood (a valid assumption). Thus, instead of performing 100,000 simulations to adequately represent the upper end of the frequency curve, a much smaller number (5,000 in this case) can be used to develop the flood-frequency curve in the area of interest.

Calibration of the Stochastic Flood Model:

Calibration of the model to the Raft River sub-basins was limited due to the sparse amount of stream flow data available. One stream gage exists on the Raft River (USGS gage 13078000, Raft River above Onemile Creek near Malta, ID). This gage has peak flow data from 1945 to 2005, with data for the years 1972 through 1984 missing. The stream flow at this gage is reported to be affected to an unknown degree by upstream diversions. The gage has a drainage area of 412 mi^2, and represents only about 1/6 of the total 2,480 mi^2 drainage area between Minidoka Dam and American Falls Dam. The largest flood peak in this record occurred on January 17, 1971, and was only 2,060 ft^3/s. There are no short term precipitation data available for any nearby precipitation gages for that date that would be useful in a calibration effort for this rainfall-runoff model.

The calibration for this SEFM model amounted to adjusting the loss rates and surface unit hydrograph lag time input values until a match to the upper end of the recorded flood-frequency curve was produced at the Raft River gage.

Snake River Floods Originating above American Falls Dam:

The majority of the flows at Minidoka Dam for large summer flood events will originate on the Snake River above American Falls Dam. Several large upstream storage reservoirs complicate the analysis of large floods on the Snake River below American Falls Dam. These dams were not specifically considered in the current study but they were considered in previous flood studies for American Falls Dam.

Outflows from the American Falls project were simulated using a combination of resampling and scaling methods which are described in the following sections.

Resampling of Historical Outflows:

Resampling was utilized for Monte Carlo simulation of outflows from American Falls whenever the variate drawn from the Uniform distribution (U[0,1]) was in the range of 0 to 0.992. Resampling was accomplished by selecting a 20-day time-series of daily flows from the historical record in the period from 1929-2005. The start date of the time-series for a given end-of-month simulation was randomly selected in the time period from the 16^{th} of the chosen month to the 11^{th} of the following month for the selected historical year. This approach is in keeping with the concept of end-of-month simulations, where the chosen end-of-month represents conditions for the two-week period prior and posterior to the chosen end-of-month.

Scaling of Historical Outflows:

Scaling of historical outflow hydrographs was used in the simulations whenever a rare outflow outside the range of the 77-year historical record was drawn by Monte Carlo simulation. This corresponded to drawing a variate from the Uniform distribution (U[0,1]) that exceeded 0.992.

Scaling of historical flows was accomplished in several steps. First, probability-plots were developed for each end-of-month utilizing the 5-day maxima for the period from the 16th of the current month to the 15th of the following month for the historical record from 1929-2005. The 5-day duration was selected because it reasonably matches the time span for the bulk of the runoff hydrograph from the Minidoka watershed. The choice of duration is not overly-critical because the outflow hydrographs from American Falls are very broad and relatively flat.

Next, the probability-plots were extended to an exceedance probability of 10^{-4} by utilizing the findings from the 1974 PMF study for American Falls [5]. Specifically, the 5-day PMF outflow at American Falls for end-of-May (122,300 ft^3/s) was set at an exceedance probability of 10^{-4}. The 5-day "PMF" outflow for other months was estimated based on the end-of-May PMF value and considering the %PMP value from HMR-57 [6], typical snowpacks, and representative antecedent moisture conditions for the various months. The end-of-month "PMF" values were also assigned an exceedance probability of 10^{-4}. A 3rd order polynomial was fit to the probability-plot to allow direct computation of 5-day maxima discharge for any selected exceedance probability.

Lastly, one historical year was selected as a template for scaling outflows for each end-of-month based on the year that contained the largest outflows of the 77-year period for that particular month. A time series of daily outflows was produced by scaling the historical daily outflows from the template by the ratio of the 5-day maximum discharge computed from the 3^{rd} order polynomial for the selected exceedance probability divided by the observed 5-day maximum discharge from the historical year template. For example, for end-of-June, the 20-day daily time-series starts June 21, 1997 with the first 5-days being the period of maximum outflows.

Hydrographs for Minidoka Dam:

In this study 30,000 individual simulations were run. For each simulation the hydrographs for the Raft River from the rainfall-runoff computation were combined with the resampled and scaled Snake River outflow hydrograph form American Falls Dam. Flood routing was done for Minidoka Dam. Inflow peak, volume and maximum reservoir elevation information for the combined hydrograph was then collected. Plotting positions were established for the top 5,000 events for peak, volume and reservoir elevation. Individual computer simulations related to the top events were then used to extract the final hydrographs for the very large return period floods.

After the all-season analyses were completed additional studies were conducted to examine the seasonal behavior of floods. The climatic year was divided into two seasons, summer – April 15 to October 31, and winter – November 1 to April 14.

In this SEFM study hydrographs were prepared that were 384 hours (16 days) long. In the case of the summer hydrographs representing the very large flood releases from American Falls Dam, the 16 days used in this study were patterned after the largest controlled flood event ever recorded on the Snake River below American Falls Dam (in 1997). These 16 days could be considered only a portion of the entire flood hydrograph, with several weeks or months of above normal flows on the Snake River also occurring before and after the peak flows. Starting reservoir elevations for flood routing in the SEFM were selected from the historic data, noting that such long hydrographs have occurred in the past and the reservoir did reach the selected elevation in the month being studied. In all cases the maximum 16 days of flooding occurred in the month of June. Figure 2 displays the resulting all season hydrographs for Minidoka Dam.

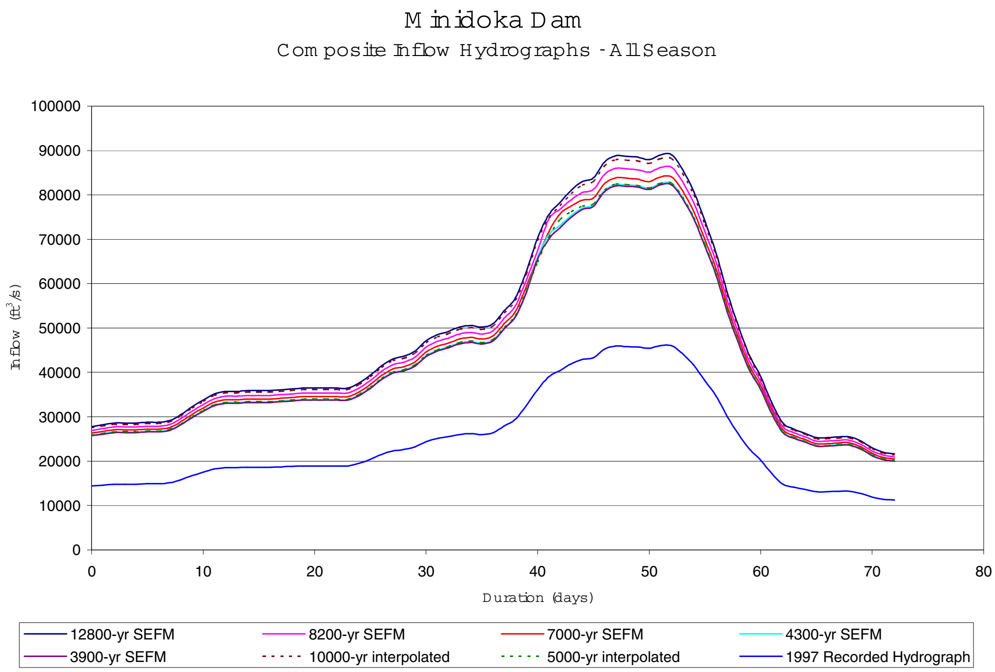

Figure 2 - All Season Hydrographs for Minidoka Dam

Magnitude-Frequency Characteristics of Extreme Floods:

The reservoir inflow magnitude-frequency curve for peak discharges is shown in figure 3. This is the all-season peak flow curve, developed using peaks from all months. The peaks that define the upper portion of this curve come predominately from the summer season releases from American Falls Dam. The curve defined by the data points from the SEFM output represents regulated conditions on the Snake River.

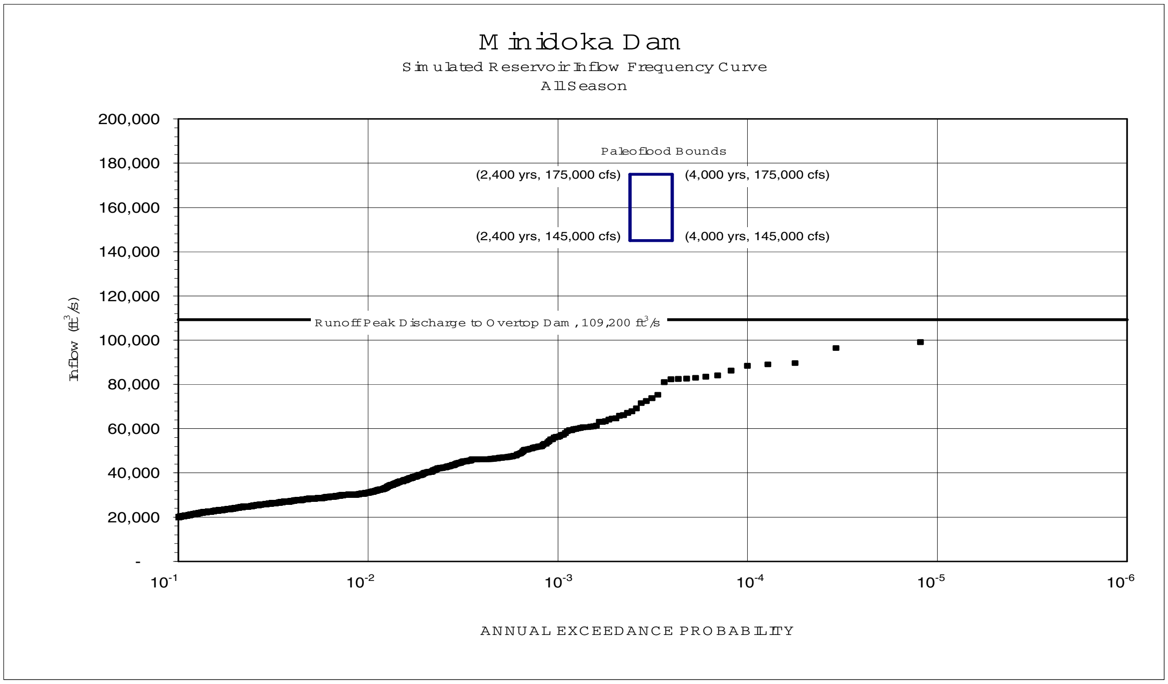

Figure 3 - Minidoka Dam All Season Peak Inflow Frequency Curve

Non-exceedance bounds from the paleohydrology study [7] are also included on this plot.

The maximum non-overtopping discharge possible at Minidoka Dam (109,200 ft^3/s) is also indicated by a straight line on this plot. It can be seen that at an annual exceedance probability of 10^{-4} (return period of 10,000-years) the calculated inflow peak, for all season flood events, is less than the maximum non-overtopping discharge possible at Minidoka Dam.

Finding and Conclusions:

Return Period (yrs)	Mindidoka Dam Inflow (ft^3/s)	Minidoka Dam Reservoir Elevation (ft)	Mindoka Dam Inflow Volume (ac-ft)
100	31035	4245.6	796252
500	46817	4245.6	1245180
1000	56226	4245.8	1351197
5000	82606	4247.7	2225561
10000	88341	4248.2	2468206

Top of dam elevation equal to 4249.85
Maximum total discharge prior to overtopping is approximately 109,000 ft^3/s
Volume is for 16-days (384 hours)

Table 2 Summary of Peak Inflow, Runoff Volume and Reservoir Elevation

The results of this study provided information for Bureau of Reclamation dam safety risk analysis and related studies for Minidoka Dam on the Snake River (table 2). The data provided included complete peak flow, volume, and reservoir elevation frequency curves out to annual exceedance probabilities of 10^{-4} as well as complete accompanying hydrographs. Minidoka Dam was shown to have the enough designed spillway capacity to safely pass a 10,000-year flood event. Complete hydrographs, for two different seasons, were provided for potential future spillway modifications that might be considered for other than flood hydrology safety issues.

The frequency curves derived in this study included the impacts of

1. A large and highly regulated river system combined with a large unregulated river system
2. A mixed population of flood sources for peaks and volumes
3. Two distinct seasons for current operations and spillway rating curves and for future designs related to possible spillway improvements

References:

1. Hosking JRM, and Wallis JR, Regional Frequency Analysis - An Approach Based on L-Moments, Cambridge Press, 1997.
2. Siriwardena L and Weinmann PE, Derivation of Areal Reduction Factors for Design Rainfalls in Victoria for Rainfall Durations 18-120 Hours, Cooperative Research Centre for Catchment Hydrology, Department of Civil Engineering Monash University, Victoria Australia, Report 96/4, October 1996.
3. Schaefer, M. G., General Storm Stochastic Event Flood Model (SEFM) Technical Support Manual, prepared for U. S Bureau of Reclamation, by MGS Engineering Consultants, Inc., Olympia, WA, October 1998, revised January 2006.
4. Gringorten II, A plotting Rule for Extreme Probability Paper, Journal of Geophysical Research, vol. 68, pp. 813-814, 1963.
5. US Bureau of Reclamation, "Flood Routing Study for American Falls Dam Comprehensive Facility Review – Technical Memorandum No. AMF-8130-CFR-2005-1," July 2005.
6. National Weather Service, Probable Maximum Precipitation for the Pacific Northwest States – Columbia, Snake River and Pacific Coastal Drainages, Hydrometeorological Report No. 57, US Department of Commerce, NOAA, Silver Spring, MD, October 1994.
7. U. S. Bureau of Reclamation, "Paleoflood Study on the Snake River near Minidoka Dam, Idaho," November, 2006.

The complete study includes many additional references