Flood Frequency Analysis in a Data Sparse Mixed-Population Watershed

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Abstract

Risk-informed dam safety decision making in regard to flood loads requires understanding of characteristics and magnitudes of very infrequent floods (10,000-years and less frequent). Flood frequency distributions are typically developed using at-site streamflow information from an annual maximum flood series. Other data sources may be leveraged as well to better understand infrequent floods far beyond the period of streamflow record including rainfall-based estimates, historical flood indirect estimates, and paleoflood information. This process can sometimes be straightforward, but limited streamflow data and a mixed flood population (floods caused by different meteorological event types and physical processes) can complicate this process. For this paper, we discuss the methods used to assess flood hazard potential at an earthen embankment dam on the leeward side of the Rocky Mountains in Montana. This region experiences distinct mixed population characteristics, with snowmelt-dominated and rainfall-dominated floods occurring during a similar spring season (April-July). Notably, the June 1964 rain driven event caused widespread flooding in this portion of Montana. Several smaller but similar rain driven events in the month of June have occurred since then in the immediate region. However, only 20 years of annual peak streamflow data were available for the facility of interest, all of which occurred prior to 1925.

In order to estimate the flood hazard as well as develop hydrographs to better understand overtopping erosion potential at this facility, a complex study using multiple independent methods and leveraging nearby data rich sites was completed. Streamflow-based and rainfall-based analyses were developed for the site of interest and a nearby site with a robust streamflow record. The streamflow-based analysis included a detailed paleoflood study with investigations at several sites within the drainage basin of interest and nearby data rich basins to better understand the magnitude of paleofloods and non-exceedance bounds in the area. Further, the streamflow-based analysis featured a unique, hydroclimate-based approach for identifying the mechanisms forcing annual maximum floods in the basin, resulting in both snowmelt-dominated and rainfall-dominated flood frequency estimates. Stochastic rainfall-runoff modeling was completed in both basins using L-moments methods to develop regional precipitation-frequency information to force the model. Results from the nearby basin with ample streamflow data were used to support parameterization and calibration. The results of the rainfall-runoff modeling were combined with the paleoflood and streamflow information as informed priors to develop rain-dominated flood frequency curves, and combined curves with the snowmelt-dominated streamflow-based curve. At all times, data, methods, and insights from the nearby data-rich site were leveraged to improve the analysis at the facility of interest. The curves were developed concurrently to assure results were reasonable for the data poor basin.

The findings helped reduce uncertainty in the flood loadings at the facility and to support a detailed erosion analysis for overtopping.

Introduction

Risk-informed decision making for high hazard facilities requires an understanding of flood characteristics for very infrequent return periods (<10,000-years). There is a high level of uncertainty associated with estimates for these infrequent floods. This can be especially challenging in basins where large floods are caused by multiple mechanisms, a few examples being things like snowmelt, rain on snow, atmospheric rivers, or high intensity convective thunderstorms. Multiple methods can be used to reduce uncertainties associated with these estimates including long reliable streamflow records in combination with historical and paleoflood information as well as rainfall-runoff methods. However, in some cases, streamflow records are limited or non-existent, making flood frequency curve development very difficult and rainfall-runoff model parameterization highly uncertain. In this paper, we will discuss methods used to reduce uncertainties in a data-sparse basin by leveraging information from a nearby data-rich basin.

Study Area

Our study area was located on the leeward side of the Rocky Mountains in Montana. This region generally experiences two distinct flood mechanisms during a similar season: snowmelt runoff and rainfall-dominated floods during the snowmelt runoff period. The flood of record in this region occurred in June of 1964 with rainfall depths as high as 14 inches over 36 hours (Boner & Stermitz, 1967). Other notable rainfall floods of smaller magnitude but larger than the typical annual snowmelt peak occurred in 1916, 1975, and 2018.

The basin of interest for the study was on Willow Creek northwest of Augusta, Montana. One USGS stream gage with an unregulated record existed on Willow Creek upstream of the Willow Creek Dam from 1916 to 1925, yielding 20 annual peak flows. This record length is typically not sufficient for developing a flood frequency curve for return periods needed, <10,000=years, and due to the age of the streamflow, finding adequate meteorological and snowpack information to support calibration and validation of a rainfall-runoff model to reduce uncertainty in the flood frequency curve can be very difficult. However, the nearby basin for Gibson Dam on the Sun River had a very long and current streamflow record. While the Willow Creek basin was further east onto the plains, assessment of meteorologic record for the two sites indicated similar conditions. The location of the two basins is shown in Figure 1. Given the similar meteorologic conditions at the two sites, we developed a full flood frequency analysis including rainfall-runoff modeling for the Gibson Dam basin, and used model parameterization from that study to inform model parameterization for the Willow Creek basin.

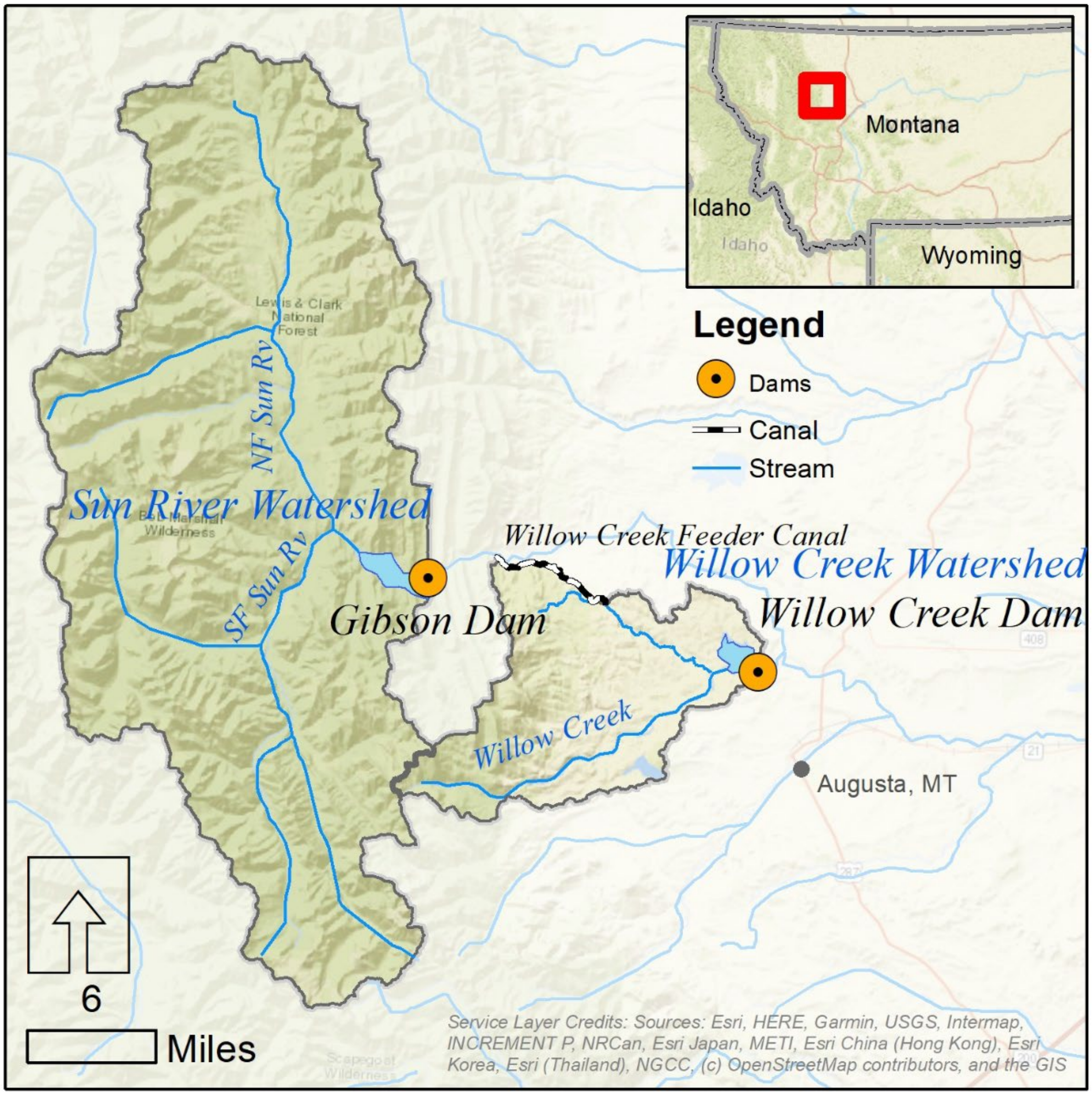

Figure 1. Location map for study basins

Methods

Multiple methods are typically used to develop a flood frequency curve to reduce uncertainty for very infrequent floods required for high-hazard facilities. In this case, we employed observed streamflow records, a detailed paleoflood study, and stochastic rainfall-runoff modeling. For the rainfall-runoff modeling portion of the study, we first parameterized and calibrated the model for Gibson basin given that ample streamflow information for calibration was available. We then used the calibration parameters from the Gibson basin to set initial parameters for the Willow Creek basin. The methods are described in the sections below. The methods used for development of the flood frequency curve are consistent with the methods described in Bulletin 17C (England, et al., 2018).

Streamflow Record Analysis

Streamflow records for both basins were analyzed using the best available USGS and daily reservoir inflow estimates. Due to the nature of the annual floods being driven by both snowmelt and rainfall in this region, annual peaks representing both mechanisms were separated using the streamflow records. This flood mechanism separation process was informed by the best available meteorologic and snow information available for the area for each year. An example illustrating the typical workflow using snow, precipitation, and temperature with daily or sub-daily streamflow is shown in Figure 2 The resultant dataset was an annual peak flow associated with snowmelt and an annual peak flow associated with a rain-driven event for every year of streamflow record.

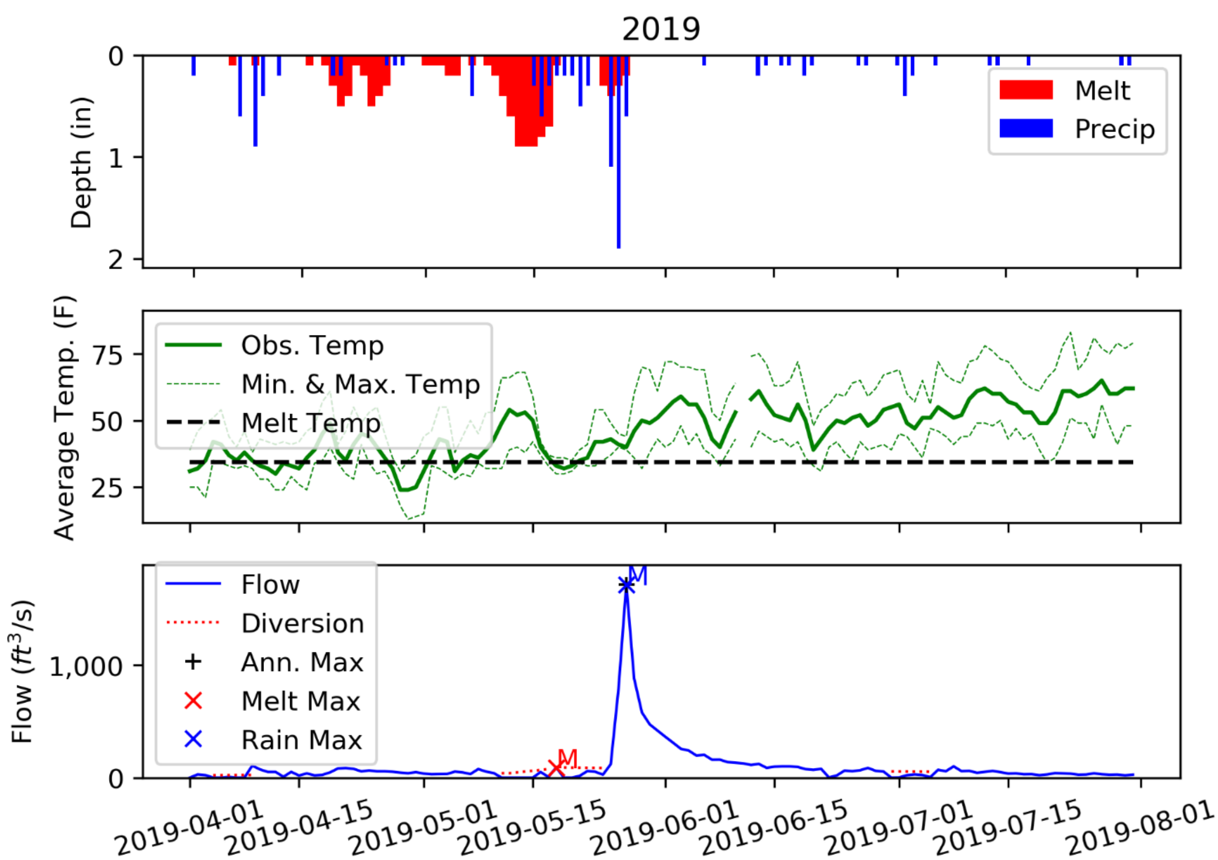

Figure 2. Example workflow for identifying snowmelt and rain driven events by year

Paleoflood

A detailed paleoflood study was completed for the study area in 2018-2020 (Reclamation, 2020a). Six different reaches on different waterways were assessed to identify paleoflood and non-exceedance bounds and age estimates using carbon dating and 2D hydraulic modeling. Several paleofloods with age ranges from approximately 200-700 years were identified. Non-exceedance bounds identified were used to inform perception thresholds in the flood frequency curve development. By assessing multiple streams in the region, the paleoflood team was able to gain a better understanding of stratigraphy and flood history across the study area.

Flood Flow Frequency Analysis

Bulletin 17C (England, et al., 2018) techniques and methods were applied to conduct the flood flow frequency analysis for both Willow Creek and Gibson basins. These methods include the following:

- Mixed population analysis (Reclamation, 1989);
- Systematic records of peak streamflow;
- Site-specific paleoflood data as flows, flow intervals, and perception thresholds; and
- Use of maintenance of variance extension type 1 (MOVE) (Hirsch, 1982 and Vogel and Stedinger, 1985) for converting mean daily flows to peak flows and extending records from nearby sites.

For Gibson Dam, the long period of record for gage records and high-quality calculated inflows aided construction of a systematic inflow timeseries. For Willow Creek, the short period of record for gage records required augmentation—additional systematic records and perception thresholds were estimated using regional flood information, comparison to nearby gages, and deregulation of calculated inflows.

The analysis was performed using the U.S. Army Corps of Engineers (USACE) Risk Management Center's Bayesian Estimation and Fitting software (RMC-BestFit; RMC, 2020). This particular program applies Bayes' Theorem using a Markov Chain Monte Carlo (MCMC) algorithm to estimate distribution parameters.

The flood flow frequency analysis used the datasets described above to develop a snowmelt curve, a rain curve, and a combined curve for each basin. The timeseries used for the analyses are shown for Gibson and Willow Creek basins in Figure 3 and Figure 4, respectively. Comparison of these two figures illustrates the general data scarcity in the Willow Creek basin compared to the Gibson basin. The resultant curves for each basin are shown in Figure 5 and Figure 6.

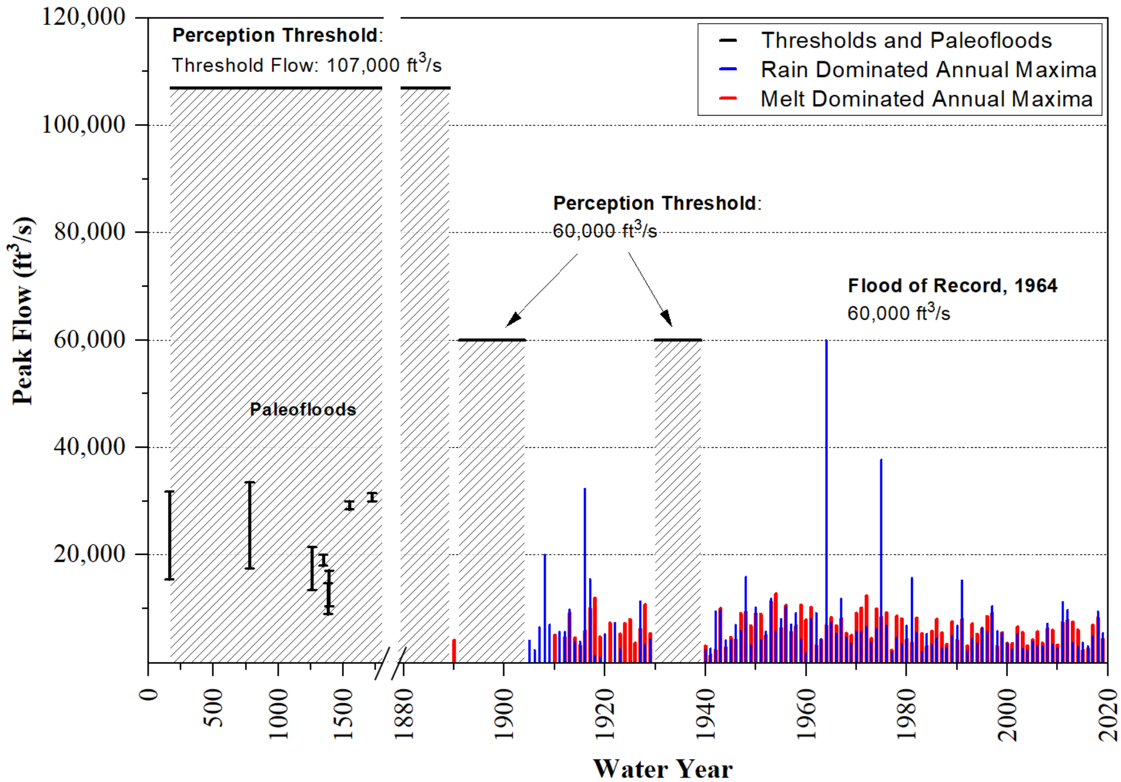

Figure 3. Timeseries for flood flow frequency analysis for Gibson basin

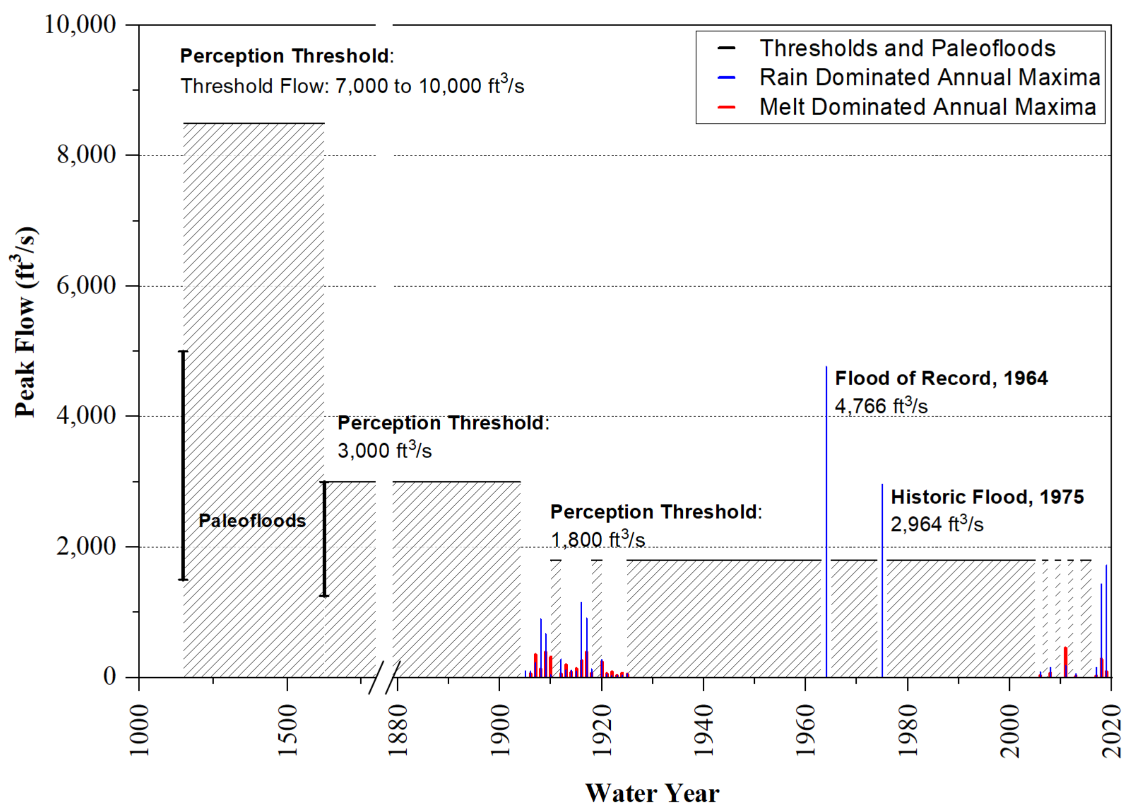

Figure 4. Timeseries for flood flow frequency analysis for Willow Creek basin

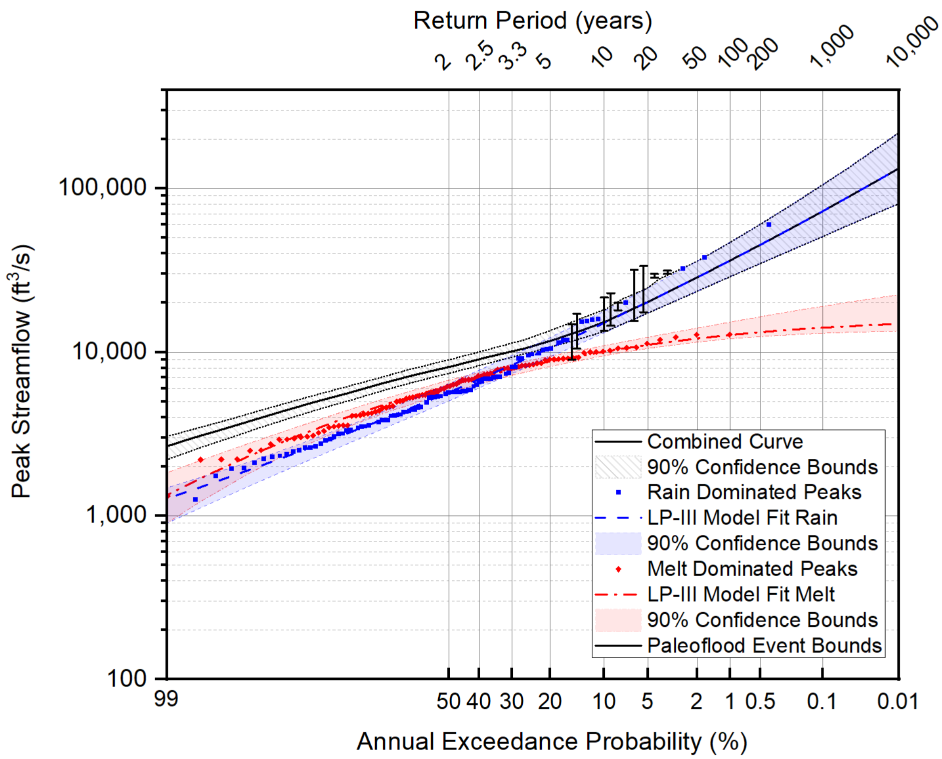

Figure 5. Peak streamflow frequency curve for Gibson basin

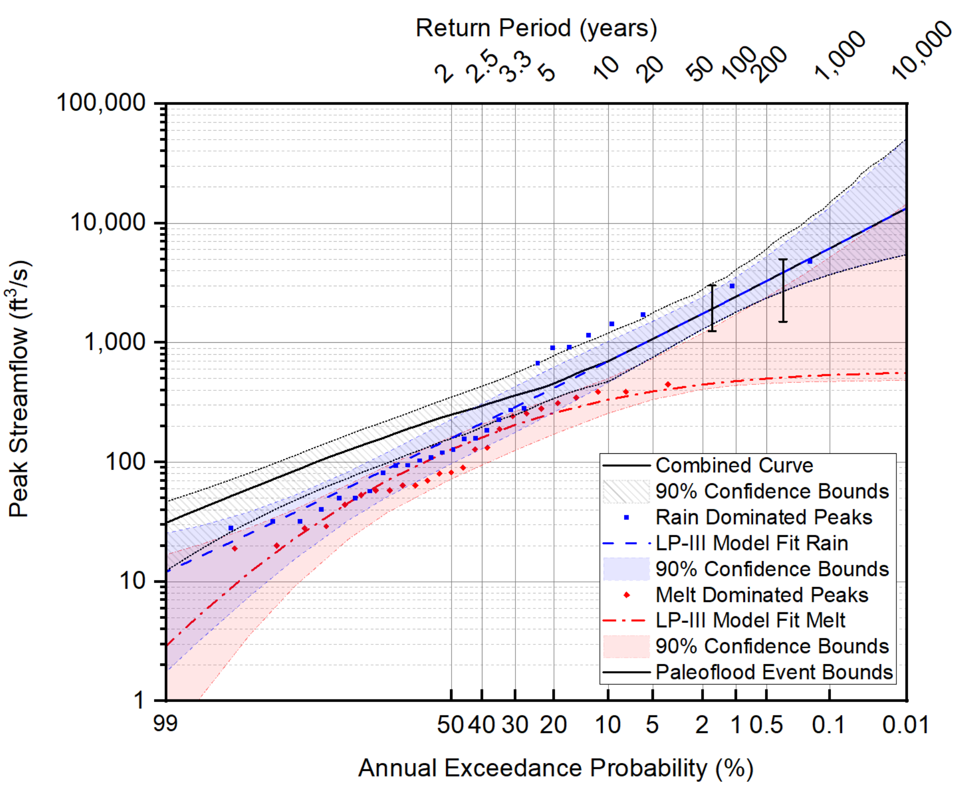

Figure 6. Peak streamflow frequency curve for Willow Creek basin

Rainfall-Runoff Modeling

Stochastic rainfall-runoff modeling was completed to better understand the characteristics very infrequent floods. This study used the Stochastic Event Flood Model (SEFM), which is a quasi-distributed rainfall-runoff model that uses Monte Carlo sampling approach (stochastic) to simulate thousands of years of storm time series and the associated watershed response (MGS Engineering Consultant, 2017). This model uses a modified Holtan approach to developing runoff with subbasins divided into Hydrologic Response Units (HRUs) representing a range of basin and climate characteristics. Snowpack simulation routines within the SEFM model are adopted from the University of British Columbia (UBC) model to simulate snow (UBC Mountain Hydrology Group, 1995).

Meteorological information to force the stochastic simulations includes precipitation-frequency information as well as spatial and temporal characteristics of historical large storms in the region (Reclamation, 2020b). Precipitation-frequency curves were developed for three-day durations using L-Moments methodology for a homogeneous region. The SEFM model samples from this curve during the stochastic simulations to assign a precipitation depth to the storms being simulated. Spatial and temporal characteristics of several historical large storms in the region were used to develop storm templates for the model, which are sampled during the stochastic simulations and scaled to the precipitation-frequency curve being sampled.
The resulting SEFM model uses the total probability theorem to produce a suite of magnitude-frequency curves from many thousands of simulations of storms in the basins. An illustration of this approach is shown in Figure 7. Uncertainty and sensitivity analyses were completed for the basin assuming a range of values for highly uncertain or sensitive model parameters to develop theoretical upper and lower bounds for modeling results. A typical resultant curve from the modeling results is shown in Figure 8.

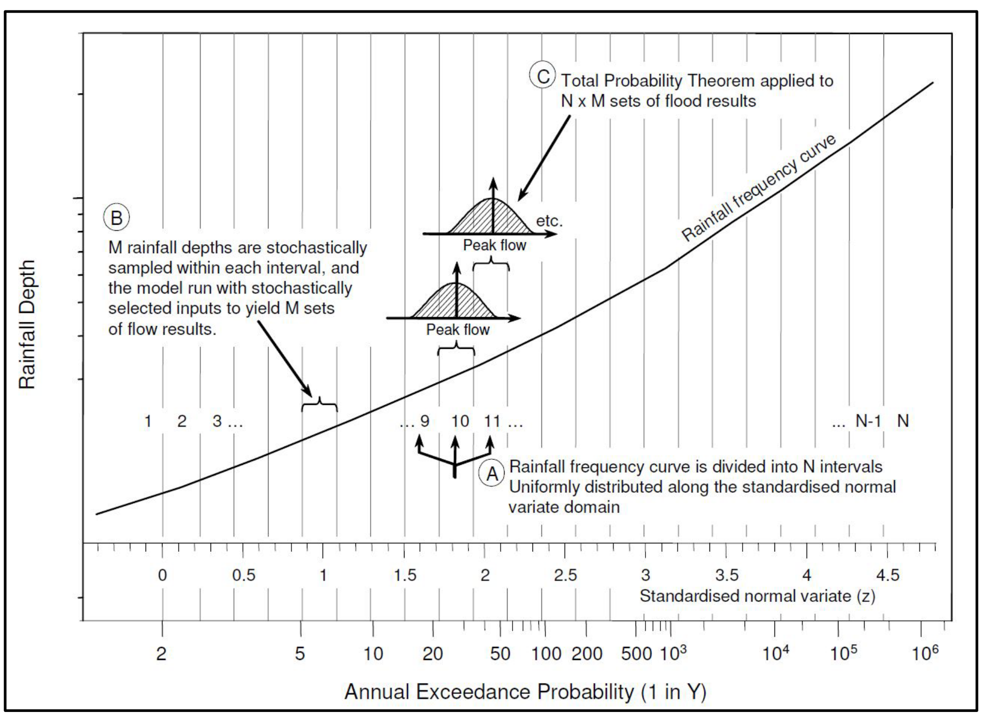

Figure 7. Illustration of manner in which stratified sampling is applied to rainfall frequency curve. Figure taken from Nathan and Weinmann (2013).

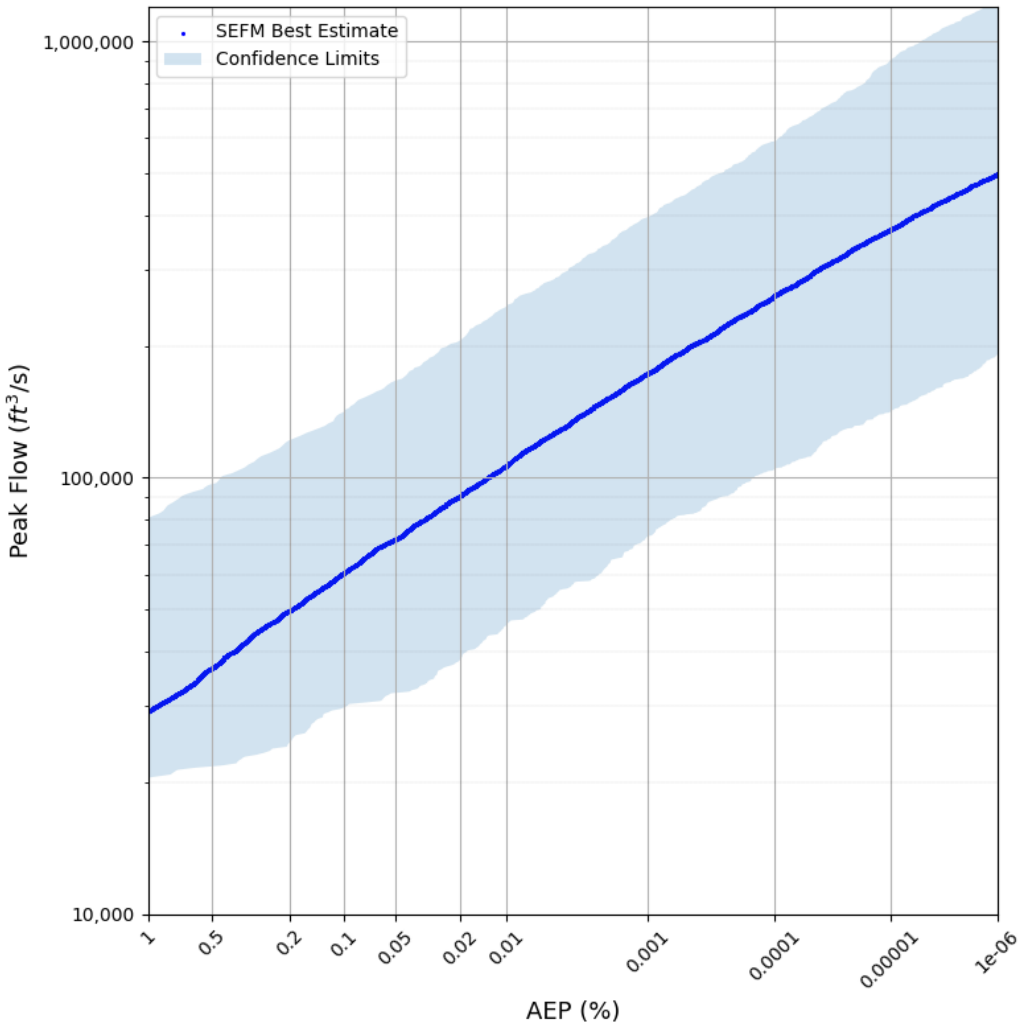

Figure 8. Example of SEFM output for peak flow frequency curve

Model Development and Calibration

The SEFM is run on a daily scale with observed precipitation and snow information in order to calibrate and validate model parameters. For the Gibson basin, there was ample data to support calibration and validation. Model calibration for Gibson performed well (Figure 7). However, for Willow Creek basin, there was very limited data to support high quality calibration effort. For Willow Creek, the final calibration parameters from Gibson basin were applied to an initial parameterization of the Willow Creek SEFM model. Daily flow estimates were generally of low quality for Willow Creek basin, but 2018 flow records had a large rain-driven event in early June that had enough information for at least a high-level validation of the parameterized model suggesting adequate performance for the basin for large events using the Gibson basin parameters (Figure 8).

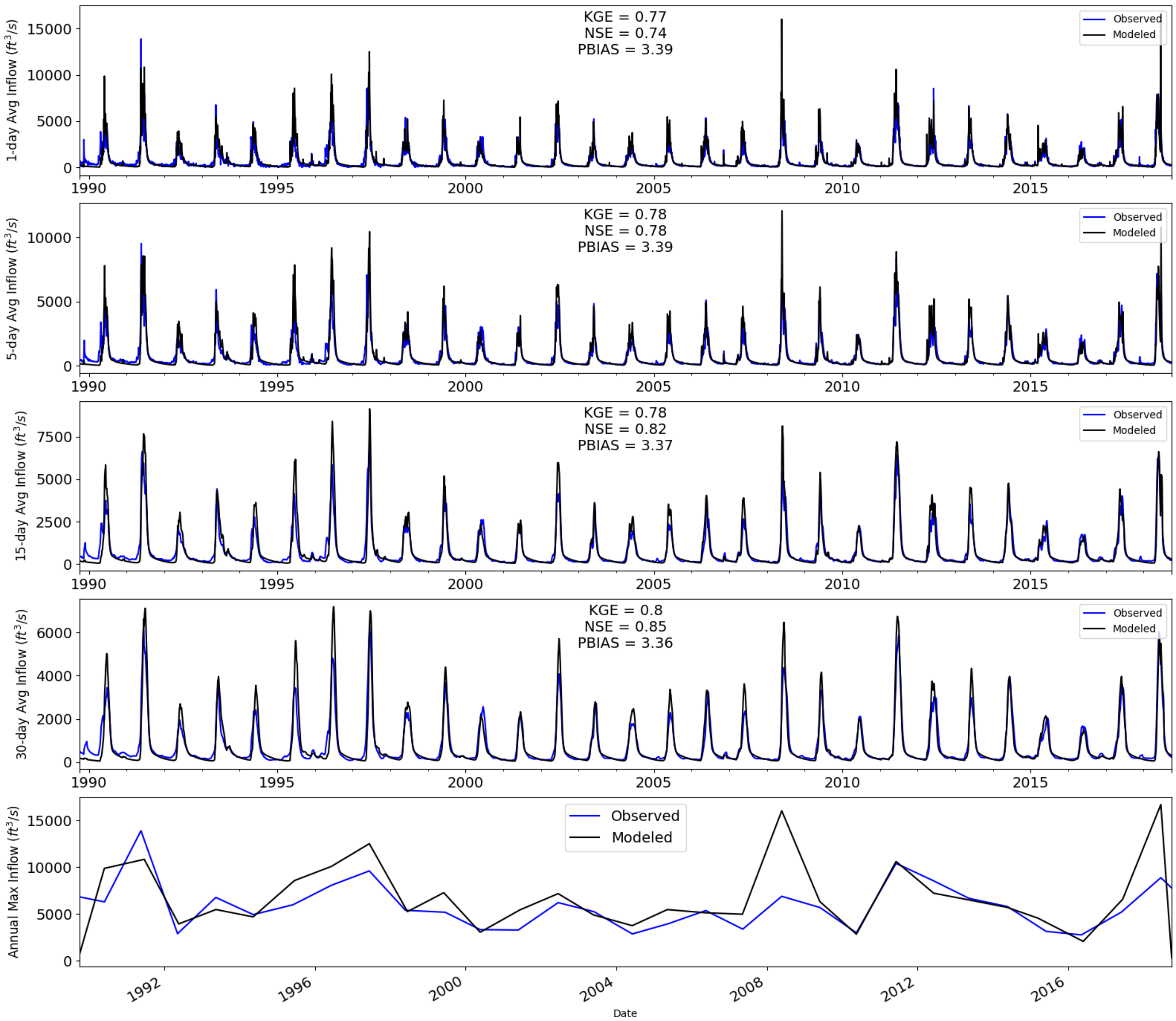

Figure 9. Gibson basin calibration information

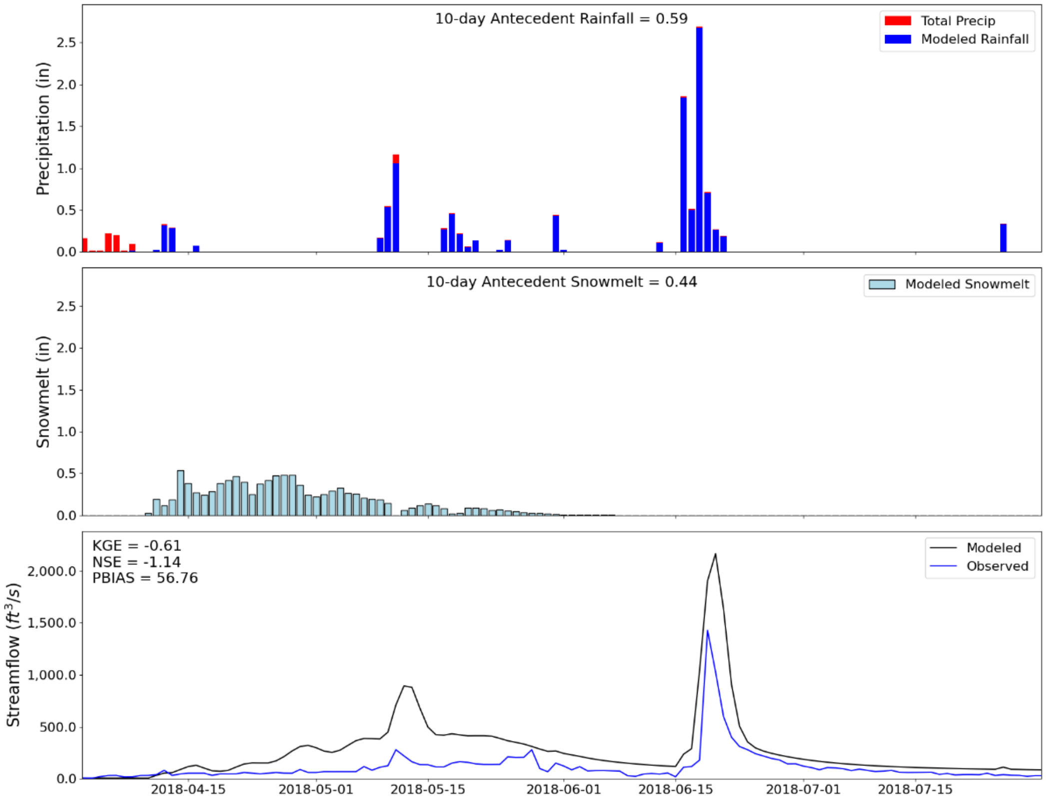

Figure 10. Willow Creek Basin validation

Following calibration and validation, fully stochastic simulations are run to develop flow-frequency curves using the total probability theorem, as described in the previous section. The resulting curves provide magnitude and associated probabilities of simulated floods. These magnitudes were then used in a multi-method approach described in the next section to reduce uncertainty in the final flood hazard curve development.

Combination of Multiple Methods

In order to develop final flood frequency curves for both basins, the results of the streamflow flood frequency analysis were combined with the results of the rainfall-runoff modeling using Bayesian methods to improve confidence in the model results. The results from the SEFM rainfall-runoff models were incorporated into the flood frequency analysis by defining prior distributions for the 0.01, 0.001, and 0.0001 annual exceedance probabilities (Coles and Tawn, 1996; Risk Management Center, 2020). The prior distributions represent the distribution of rainfall-runoff results for a given annual exceedance probability (AEP). The priors were incorporated into the frequency curve produced from the rain dominated flood peaks and historical perception thresholds, then the frequency estimates were combined with the melt dominated estimates to produce the final flood frequency curve.

The mean and standard deviation for each of the three prior distributions were determined from the uncertainty and sensitivity analysis from the SEFM model output. A normal distribution was assumed for the priors. The priors for each basin are shown plotted with the flood flow frequency results (discussed in a previous section) in Figure 11 and Figure 12. These plots illustrate that rainfall-runoff modeling results align well with observed streamflow frequency analyses.

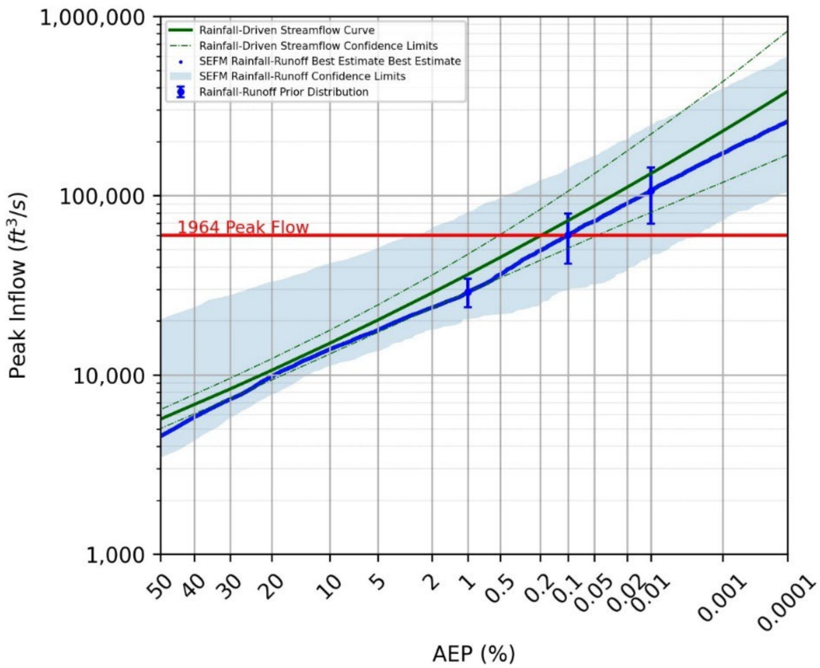

Figure 11. Gibson basin flood frequency curve developed from streamflow, paleoflood, and rainfall-runoff results. Bayesian priors from rainfall-runoff modeling illustrated by three thick blue vertical bars.

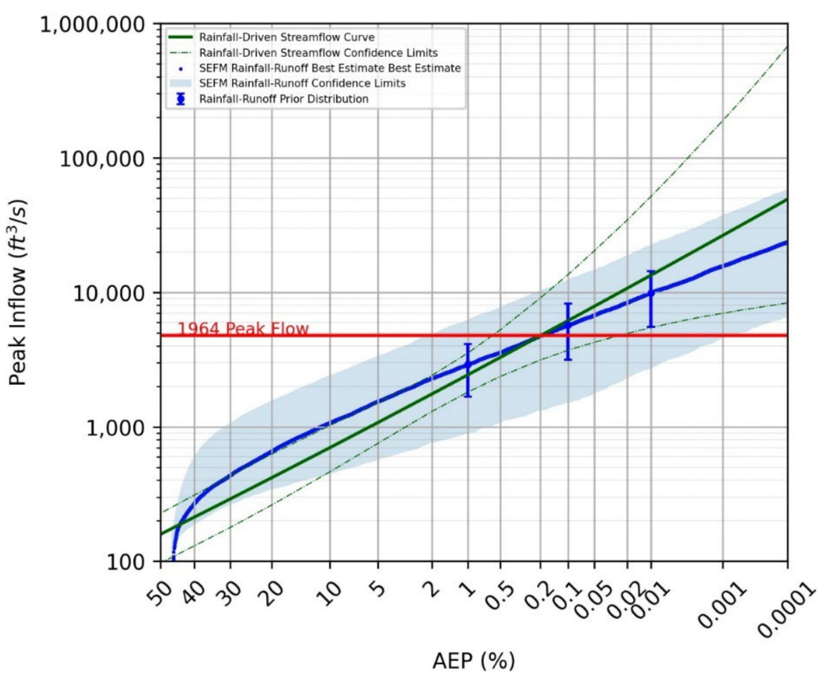

Figure 12. Willow Creek basin flood frequency curve developed from streamflow, paleoflood, and rainfall-runoff results. Bayesian priors from rainfall-runoff modeling illustrated by three thick blue vertical bars.

Results and Conclusions

The results following Bayesian application of the rainfall-runoff modeling to the flood flow frequency curves are illustrated in Figure 13 and Figure 14. Bayesian analysis was completed in RMC-BestFit. The figures illustrate the melt driven flood peaks, the rainfall driven flood peaks, and the priors used from the rainfall-runoff modeling. The final curves are illustrated by the dark blue solid line with the confidence limits of the final analysis shown through the dark blue shading. Notable flood magnitudes including the 1964 flood of record and the rain-on-snow probable maximum floods (PMFs) are also shown in red. These final results illustrate the combination of the use of streamflow records, detailed paleoflood information, and rainfall-runoff modeling.

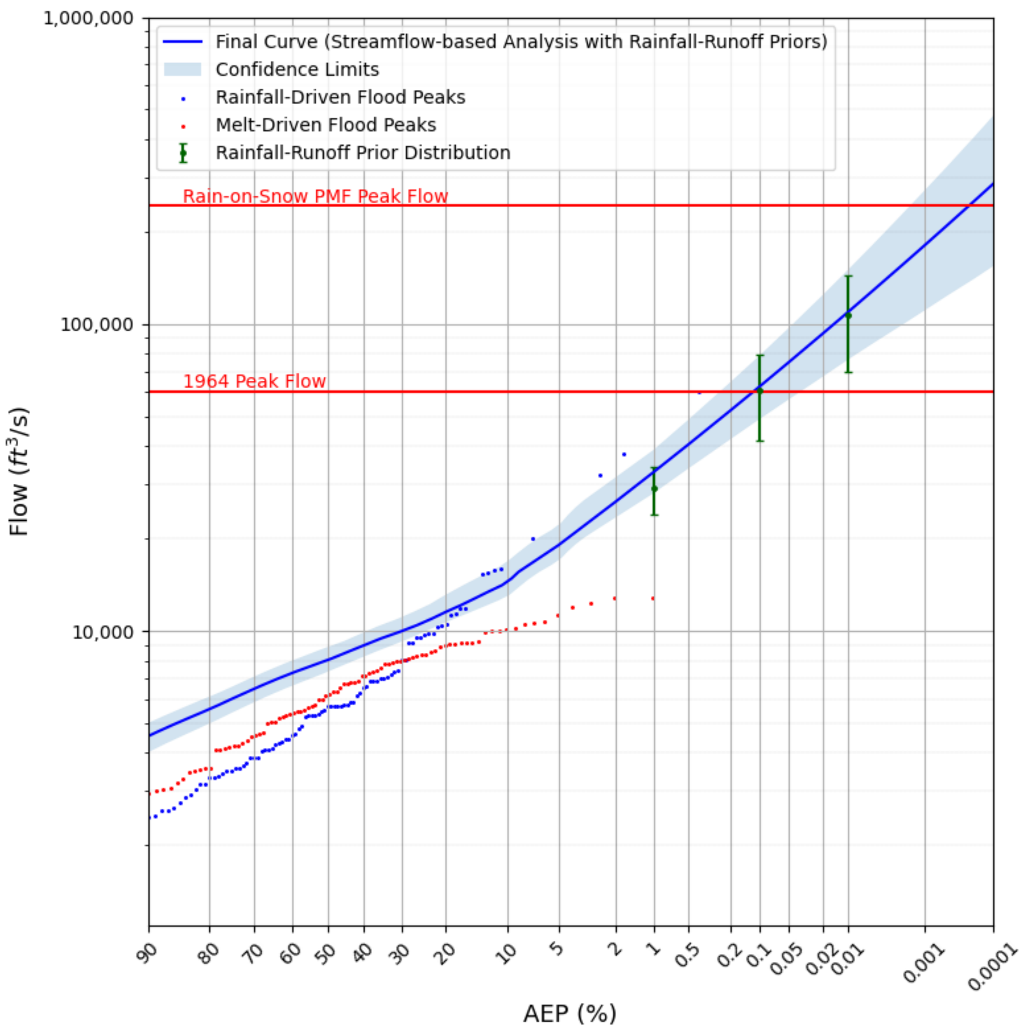

Figure 13. Resultant curve following Bayesian incorporation of rainfall-runoff results for Gibson basin

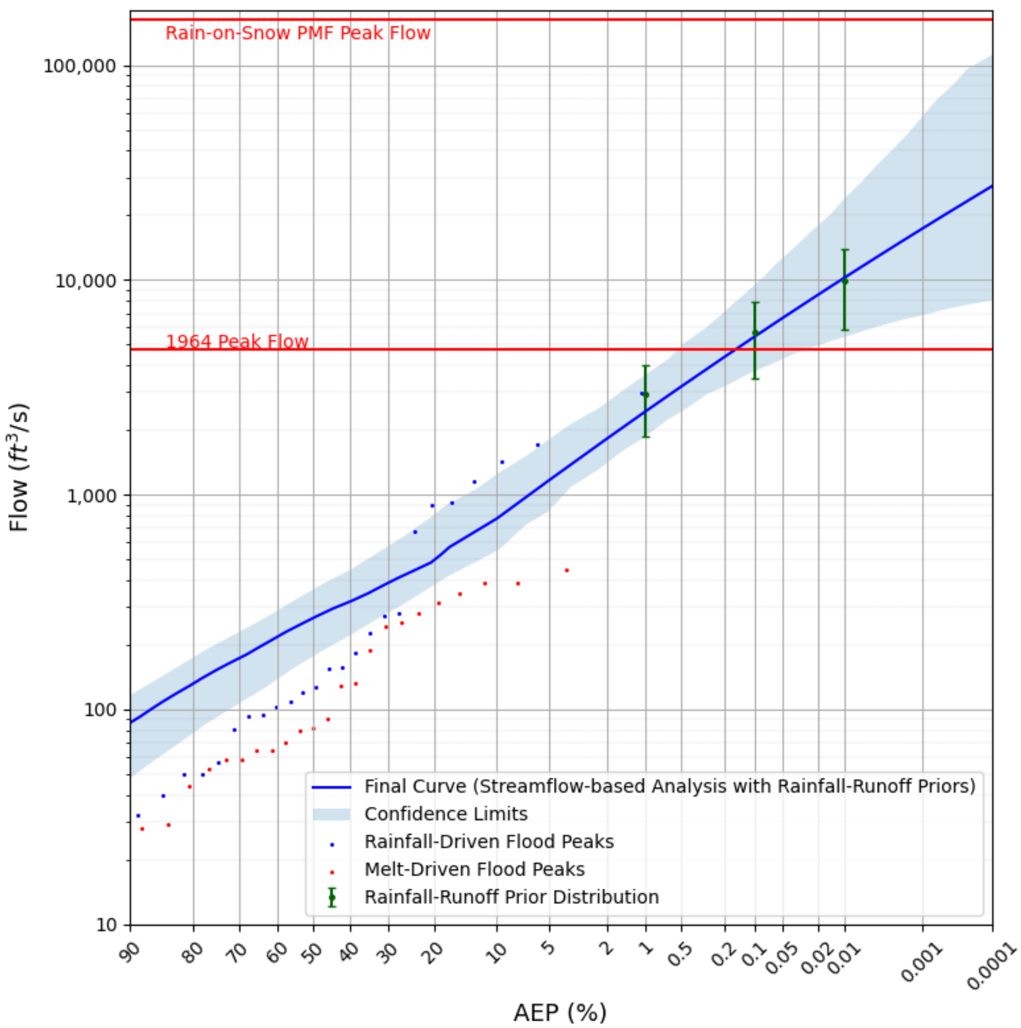

Figure 14. Resultant curve following Bayesian incorporation of rainfall-runoff results for Willow Creek basin

The methods and results shown here illustrate the advantages of using multiple methods and datasets in a mixed-population watershed with limited data to reduce uncertainty in flood estimates for very infrequent floods. In this case, our basin of interest, Willow Creek, had very limited data from primarily only the early 1900s to support curve development very infrequent floods. Here, we were able to leverage a nearby data-rich site at Gibson basin in order to support development of the Willow Creek curve. The methods used included streamflow analysis, detailed paleoflood study on multiple reaches, and rainfall-runoff modeling. The rainfall-runoff modeling portion of the study leaned heavily on high quality, long record, and modern data availability of the Gibson basin to help parameterize and validate the model for the Willow Creek basin with satisfactory results. The resultant flood flow magnitudes from the rainfall-runoff modeling were used in a Bayesian analysis to help improve estimates of the flood frequency curve for very infrequent floods. Prior to this analysis, the only flood assessment for the Willow Creek Basin was a Log Pearson Type III distribution fit to 20 years of annual peak flow data that ceased data collection in 1925. By using the multiple methods, we were able to drastically improve confidence in estimates for this site.

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