Incorporating Regional Rainfall-Frequency into Flood Frequency using RMC-RRFT and RMC-BestFit

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Abstract--Accurate estimates of flood frequency and magnitude are a key component of nationwide flood risk management programs. Quick estimates of at-site flood frequency curves have been historically limited to readily available data, such as historical gauge records, or documented historical floods. Most project sites in the U.S. have limited flood information, with most sites having fewer than 100 years of gauged flow data. Incorporating regional information can be used to effectively substitute space for time, increasing the effective record length and reducing statistical uncertainty in the flood frequency curve. However, incorporating regional information to an at-site flood frequency study has historically been a difficult, laborious, and computationally intensive.

The Risk Management Center (RMC) developed a web-based rainfall-runoff frequency tool (RMC-RRFT) that provides an intuitive step-by-step process for developing flood hazard curves using regional precipitation-frequency information. The RRFT allows engineers, who are not necessarily stochastic modeling experts, to rapidly develop flood hazard curves. After a user uploads a calibrated HEC-HMS hydrologic model of a watershed, the RRFT automates the extraction of NOAA Atlas 14 precipitation-frequency information and performs a stochastic flood event simulation to construct flood frequency curves. The Bayesian estimation and fitting software, RMC-BestFit, provides a framework for merging the RRFT results with at-site flow records, historical and paleoflood data, and regional skew information, resulting in a better understanding of the flood frequency relationship.

This paper will discuss the implementation of RRFT that allows engineers to incorporate regional precipitation-frequency information into at-site flood frequency curves. We will discuss the scalable framework that provides for a wide range of user demands from simple to complex stochastic analysis, and how the results are incorporated into BestFit to produce flood frequency curves. Finally, case studies that apply RRFT and BestFit to develop regionalized at-site flood frequency curves are evaluated.

I. Introduction

A key component for flood risk management programs is the accuracy of flow- and stage-frequency estimates at dams, levees, and river gauge locations. Historically, the ability to quickly estimate at-site flow- or stage-frequency curves have been limited to readily available data. Frequency curves develop through advanced analyses, like stochastic modeling, have required engineers to have expertise in hydrology, meteorology, statistics, stochastic modeling, and maybe even programming knowledge.

With most project sites in the U.S. having less than 100 years of gauged flow data, incorporating regional information can effectively decrease the knowledge uncertainty for at-site frequency curves. Regional skews can easily be added to an at-site flow-frequency curve through several applications, however, often a regional skew study is not available, or it is not applicable to the watershed of interest. Regional rainfall on the other hand is readily available for most of the U.S. through the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (A14) precipitation-frequency data. However, incorporating regional precipitation-frequency data to an at-site flow-frequency study has historically been difficult, laborious, and computationally intensive.

The U.S. Army Corps of Engineers (USACE), Risk Management Center (RMC), has developed a suite of software to facilitate risk analyses within the USACE dam and levee safety programs. A web-based rainfall-runoff frequency tool (RMC-RRFT) provides an intuitive step-by-step process to perform stochastic rainfall-runoff modeling using readily available precipitation-frequency data [1]. RRFT allows engineers, who are not necessarily stochastic modeling experts, to quickly and easily generate rainfall-runoff results that can be incorporated in a flow-or stage-frequency curves. The RMC Bayesian Estimation and Fitting software (RMC-BestFit) provides a framework for merging the RRFT results with at-site flow records, historical and paleoflood data, and regional skew information, resulting in a better understanding of the flood frequency relationship [2], [3].

The focus of this paper will be on two case studies that implement regional precipitation-frequency data using RRFT and BestFit to inform the flow- and stage-frequency curves. The paper will look at a case when no flow or elevation data is available at a dam location, and a case where there is a limited inflow record. The paper will show how these applications can be implemented to provide reasonable flow- and stage-frequency curves and greatly improve our knowledge of the at-site location.

II. RMC-RRFT

In risk assessments of dams and levees, the flood hazard is defined by a frequency curve that describes the relationship between the hydrologic variable (flow, volume, stage, etc.) and its annual exceedance probability [4]. Stochastic rainfall-runoff modeling of flood hazards has historically been a difficult and computationally intensive process that required expertise in hydrology, meteorology, statistics, and sometimes even computer science and computation methods.

To address these challenges, the RMC developed a rainfall-runoff frequency tool, RRFT, which is a web-based stochastic flood modeling application for developing flow- and stage-frequency curves. RRFT provides an intuitive step-by-step process for developing these curves using readily available precipitation-frequency data and hydrologic models, as shown in Figure 1. At the top of the screen, the user is provided with arrowed tabs that walk them through the process.

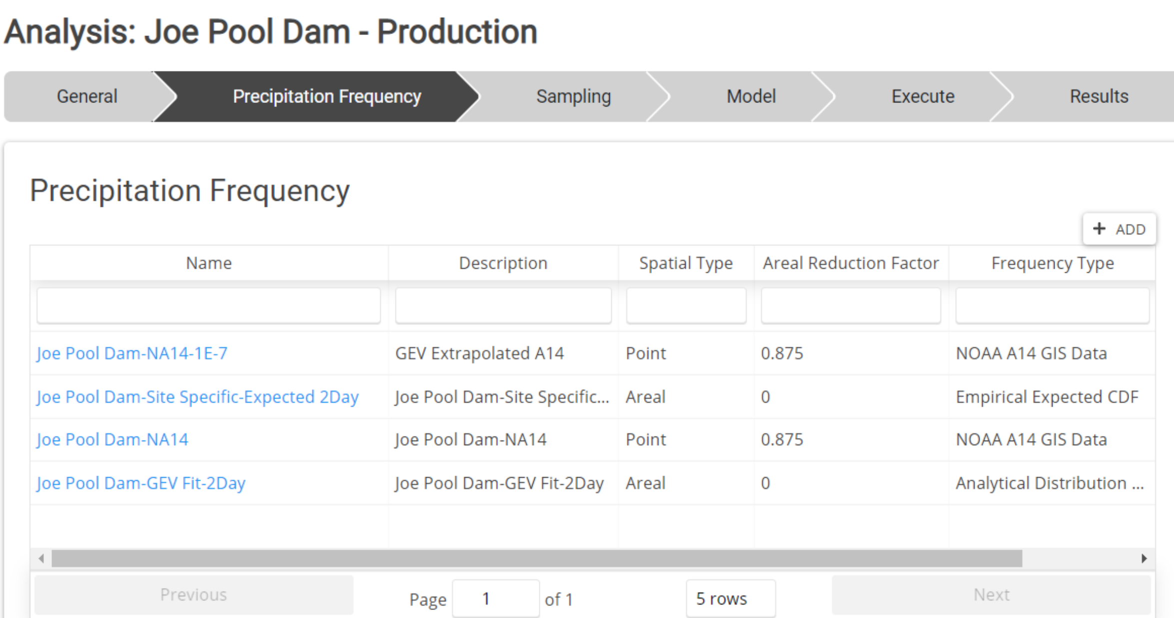


Figure 1. RMC-RRFT Interface Workflow

First, the user needs to define a precipitation-frequency curve. The RRFT can develop a precipitation-frequency distribution for any basin located within one of the 11 NOAA A14 regions[1] and for any of the 19 durations which range from 5 minutes to 60 days. This method requires that the user upload a shapefile of the basin boundary to the RRFT and select a region, duration, and optional areal reduction factor, as shown in Figure 2.

The RRFT will then compute an areal-average precipitation-frequency curve, and output depths for the return periods ranging from a 2-year return period to 1000-year return period. There is no strict limit on the drainage area size; however, it is recommended that basins have a maximum area of 10,000 square miles. RRFT also has the ability to extrapolate the A14 regional precipitation-frequency curves by fitting a generalized extreme value (GEV) distribution to the data, this allows users to generate rainfall depths associated with probable maximum

[1] https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html

precipitation (PMP) events.

Next, the user can select a Monte Carlo sampling plan, upload their calibrated HEC-HMS model, and then execute the stochastic simulation. The Monte Carlo sampling procedure uses an importance and stratified sampling approach to greatly increase the efficiency of the sampling and decrease the computational time. The RRFT can produce reservoir inflow, outflow, and stage-frequency curves for use in flood risk analyses. In addition, the results from RRFT can also be used in combination with BestFit and RMC Reservoir Frequency Analysis (RMC-RFA) [5], [6] to improve the estimated flow- and stage-frequency curves at the dam, as will be discussed in the following sections. For greater details on the RRFT workflow please see [1].

The RRFT represents a considerable advancement in flood hazard analysis technology. Large scale stochastic simulations can now be performed in a cost-effective manner. The tool is geared toward H&H engineers who are not necessarily experts in stochastic modeling. The tool is scalable and provides good results for a screening level assessment up to a more rigorous issue evaluation study or modification study.

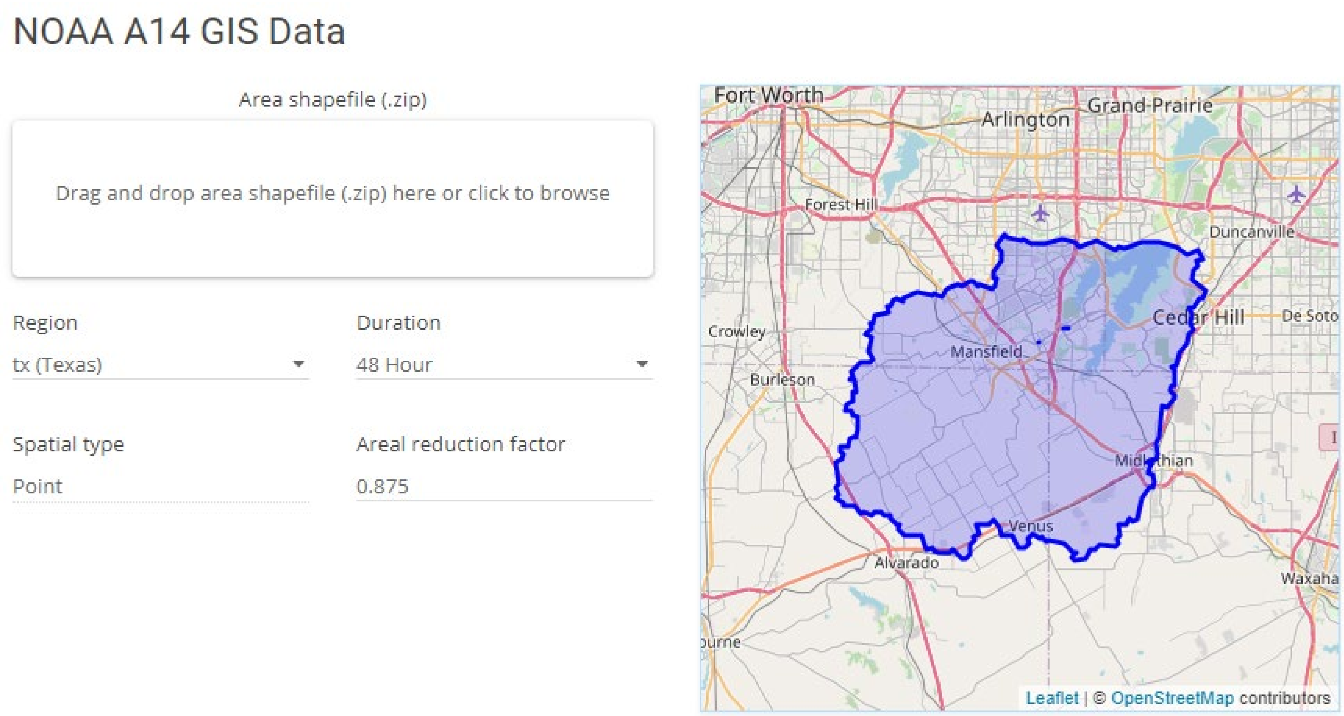


Figure 2: RMC-RRFT Interface for Processing NOAA Atlas 14 Point Precipitation-Frequency Data

III. RMC-BESTFIT

The RMC, in collaboration with the Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory (CHL), developed the Bayesian Estimation and Fitting software (RMC-BestFit) to enhance and expedite flood hazard assessments within the USACE [2]. BestFit is a menu-driven software package, which performs distribution fitting and uncertainty analysis from a choice of thirteen probability distributions [3].

Quantification of uncertainty is particularly important in risk analysis because it allows you to assess the value of reducing the uncertainty through more advanced study. Uncertainty in flood frequency distributions can often be reduced with more and better information through means of additional measurement, data collection and quality control, filling gaps in missing gauge data, and record extension. With BestFit, uncertainty can be reduced by specifying prior knowledge on the parameters through expert elicitation, rainfall-runoff modelling, or regional analysis.

Figure 3 shows an example of a flood frequency analysis that combines at-site data, historical data, regional skew information, and rainfall-runoff results from RRFT. The resulting frequency curve provided high confidence in the estimate of exceedance probabilities for the design flood and the overtopping failure mode at the dam. With the use of BestFit, it was determined the overall risk of failure at the dam was below tolerable risk guidelines. For more detailed discussion on combining data with BestFit, please see [2], [3].

The ability to combine multiple sources of hydrologic information is a major advantage over other traditional frequency analysis methods, such as those that are recommended in Bulletin 17B [7] and Bulletin 17C [8].

USACE is now routinely using BestFit for flood frequency analysis in support of dam and levee safety. The software can also be used for other applications in science and engineering, such as geotechnical and structural reliability analysis.

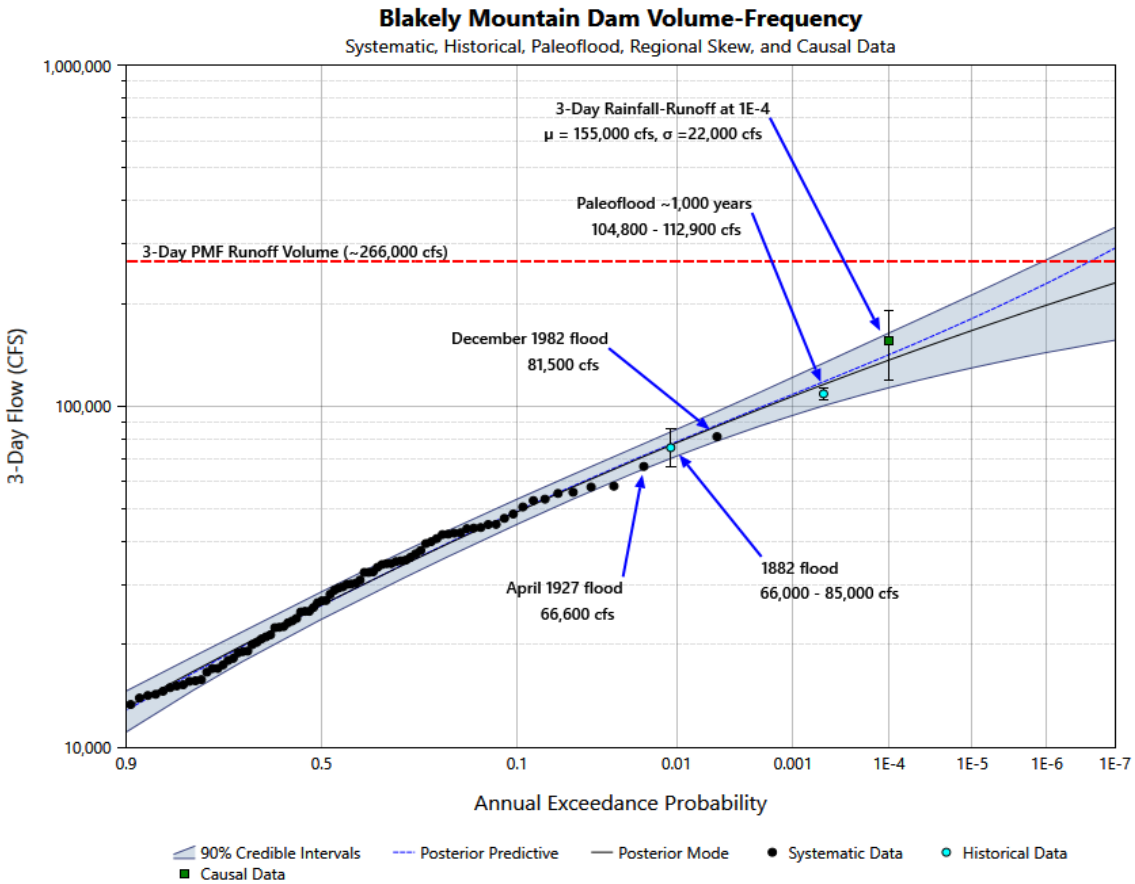


Figure 3: An Example Flood Frequency Curve from RMC-BestFit Application

IV. Case Studies

The following sections describe two case studies that apply regional precipitation-frequency data using RRFT and BestFit to greatly improve our knowledge of flow- and stage-frequency curves of the at-site location. The first case study looks at how to create flood frequency curves when no data is available, and the second case shows an analysis with a limited inflow record.

A. Dam 47

Dam 47 is a National Resource Conservation Service (NRCS) flood control structure located in central Texas. Dam 47 was built in 1968, under the Soil Conservation Service (SCS), as a part of a flood control system to reduce flooding and provide sedimentation and erosion control to benefit agricultural lands downstream. This dam has no inflow or elevation data, which is typical of other NRCS or small dam structures. Without inflow and elevation data it is challenging to develop a traditional at-site flood frequency curves to help make risk informed decisions. However, for this project, RRFT was leveraged to easily develop a stage-frequency curve by incorporating regional precipitation data from A14.

To develop a flow- and stage-frequency curves in RRFT, all that is needed is a shapefile of the basin and a simple HEC-HMS model, which were both readily available. The shapefile is used to develop an areal-average precipitation-frequency curve from A14 point precipitation estimates. Then a Monte Carlo sampling of the precipitation depths was created, which was used to generate the rainfall-runoff response, modeled in HEC-HMS.

The 1-day precipitation-frequency curves (mean, upper confidence interval, and lower confidence interval) for Dam 47, shown in Figure 4, were developed in RRFT. In this case, the upper and lower confidence intervals were used to capture the uncertainty associated with the precipitation-frequency estimates. These curves represent the areal-average precipitation depths for each return period or annual exceedance probability (AEP) based on the size of the watershed. An areal reduction factor (ARF) can be applied to the A14 precipitation depths, however, an ARF was not needed for Dam 47 because the watershed is only 2.2 square miles.

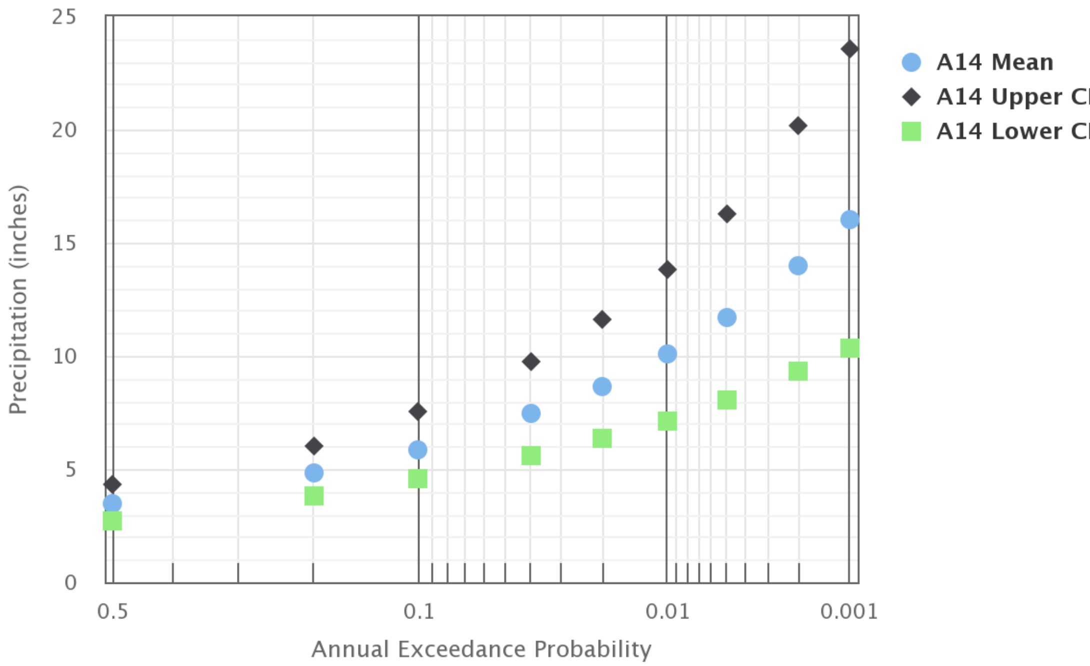


Figure 4: NOAA Atlas 14 Areal-Average Precipitation Frequency Curves for Dam 47

A14 precipitation-frequency estimates extend to an AEP of 1E-03 (1,000-year event), however, this AEP typically is not sufficient for dam safety studies, especially when there is limited or no inflow data, as with Dam 47. Therefore, it was necessary to extrapolate the A14 precipitation-frequency curves to get precipitation depths for the less frequency AEP values that would occur from rare events. RRFT fits a GEV distribution to the A14 curves to extrapolate to less frequent events. For this study, the A14 curves were extrapolated to an AEP of 2E-07 (Figure 5). RRFT also estimates the effective record length (ERL), which is a simple way of measuring how much knowledge the data provides, based on the GEV distribution parameters. The ERL from the A14 precipitation-frequency estimates for Dam 47 was approximately 135 years, which greatly increases our at-site knowledge and can provide a reasonable input to the flow- and stage-frequency curves.

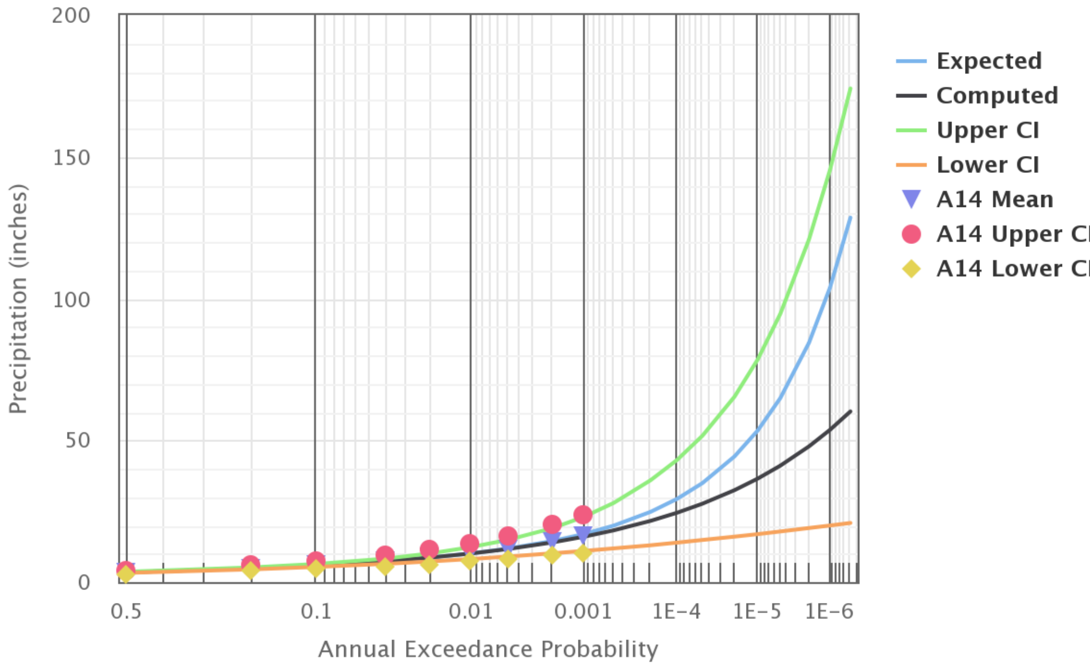


Figure 5: NOAA Atlas 14 Generalized Extreme Value Extrapolated Precipitation-Frequency Curves for Dam 47

A Monte Carlo sampling plan that uses an importance and stratified sampling procedure was used to produce 300 precipitation events based on the GEV extrapolated expected, upper, and lower confidence interval curves. The sampling procedure in RRFT is much more efficient than a typical Monte Carlo simulation and does not require as many samples to produce quality results therefore, needing to sample less events greatly increases the speed of the computations.

The computed curve represents the uncertainty in stage-frequency due to natural variability, the uncertainty bounds (or confidence intervals) represent the uncertainty due to knowledge uncertainty, and. the expected curve represents the combined uncertainty due to both natural variability and knowledge uncertainty [3]. Generally, for risk assessments, the average or expected curve should be used rather than the computed curve to better capture the uncertainty in the estimate. These sampled precipitation depths were used to generate the runoff response of the watershed, simulated in the HEC-HMS model.

The HEC-HMS model consisted of three basin models, which reflect various antecedent conditions, the three observed hyetographs, which reflect typical events, and pertinent data for the reservoir, such as the elevation-storage-discharge relationships. This model was uploaded to RRFT and used to model the runoff response of the watershed. In the stochastic simulation, one of the three observed hyetographs is randomly selected and scaled to the precipitation depth for a given event, based on the sampled precipitation event. For each event, the peak stage was computed in the HEC-HMS model. This process is repeated for each of the three precipitation curves (expected, upper, and lower). Figure 6 shows the peak stage results for all 300 events based on the expected precipitation curve. Again, because RRFT uses a stratified sampling approach, the number of samples and computational time is greatly decreased, as compared to a traditional Monte Carlo analysis. The total probability is calculated for peak stage based on these results and can then be used to make risk informed decisions. Figure 7 shows the final stage-frequency curve for Dam 47 produced in RRFT. In the case of Dam 47, RRFT is the final step to produce a stage-frequency curve for a risk assessment because there is no other information available. In the following case, RRFT will be used to inform the flow-frequency curve to reduce the uncertainty associated with the estimates.

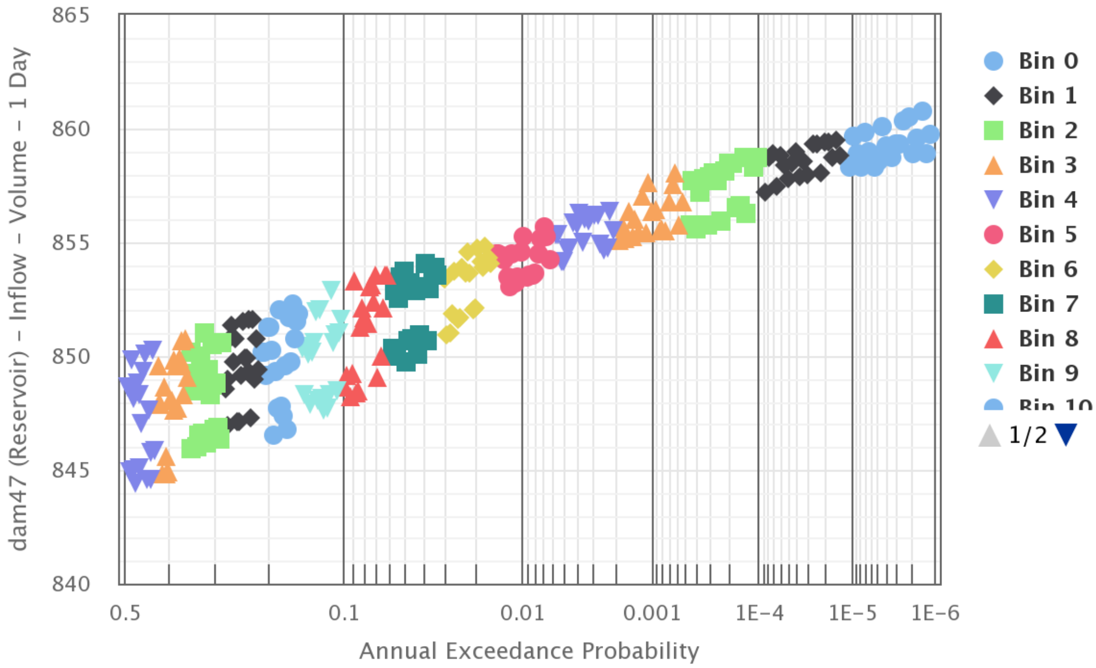


Figure 6: Peak Stage RRFT Results for Dam 47

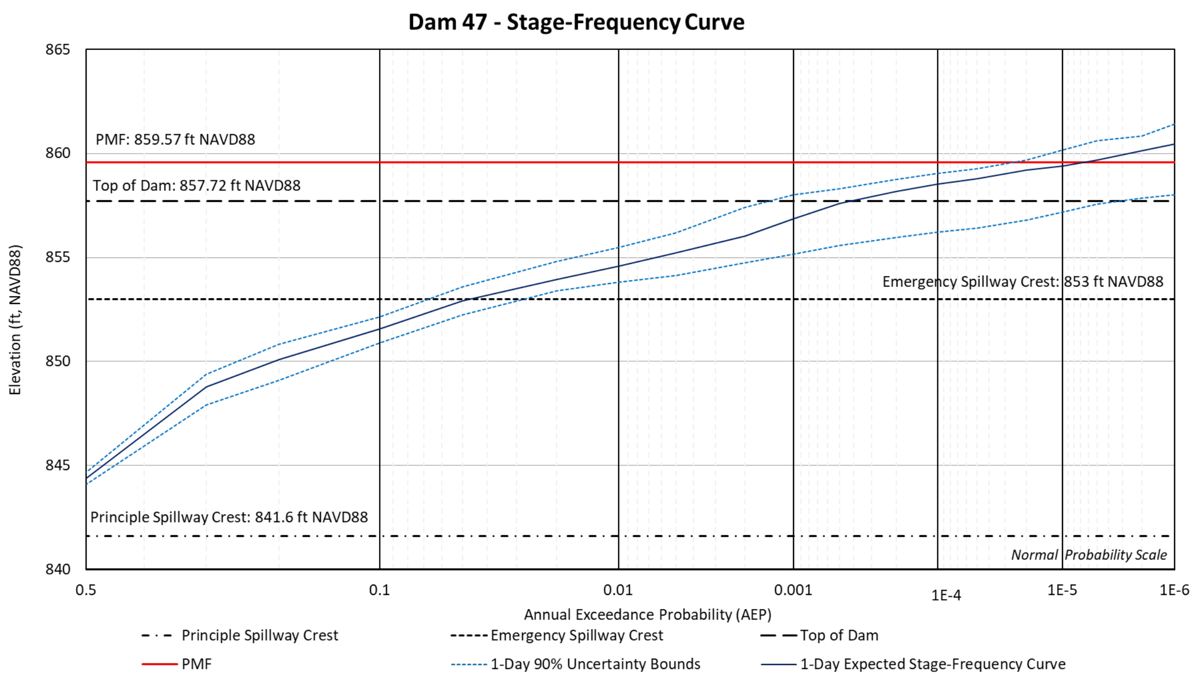


Figure 7: Final Stage-Frequency Curve for Dam 47

For small dams or dams that do not have any inflow or stage data, or very limited data, it can be challenging to develop traditional at-site flood frequency curves. However, incorporating regional precipitation-frequency data by leveraging the capabilities of RRFT, resulted in the development of flow- and stage-frequency curves, as well as the uncertainty associated with the results, which can be used to make risk informed decisions relating to dam safety.

B. Joe Pool Dam

Joe Pool Dam, a USACE project authorized for flood management, is located in the Dallas-Fort Worth metropolitan area. Joe Pool Dam was built to capture rainfall-runoff for flood management downstream through downtown Dallas. Built in the mid-1980s, the period of record inflow is limited to 1986 to present, providing 35 years of systematic data to inform the flood hazard for a dam safety risk assessment. Often, dam safety risk assessments are focused on extremely rare events on the order of 10,000 to 1,000,000 years. Therefore, the flow- and stage-frequency curves must be extrapolated out to these extreme events based on the starting information of 35 years of systematic record. In a highly urbanized area, it is important to have as much knowledge as possible to reduce uncertainty in the extremely rare events and make the best possible risk inform decisions.

For this case study of Joe Pool Dam, the first step was to add knowledge to the inflow record by incorporating any known historical events and a threshold flows based on the largest known events in recent history, like the April 1922 event that led the largest recorded monthly rainfall and flood rated death toll in Dallas-Fort Worth history. Other information to extend the period of record, such as a paleoflood study, was not viable because this area is almost completely urbanized. There was a regional skew analysis developed by the USGS in 1996 [9] available for this geographical region, however, it also could not be used to inform the inflow record with a regional skew as the study was for natural basins with less than 10% imperviousness; the Joe Pool watershed has approximately 20% impervious area. Therefore, the only regional information available to further inform the inflow record was A14 precipitiation-frequency data.

Figure 8 shows all the information available from USGS or USACE records, including 2 historical events and threshold flows that were added to BestFit as input data. This information equates to a 50 year ERL.

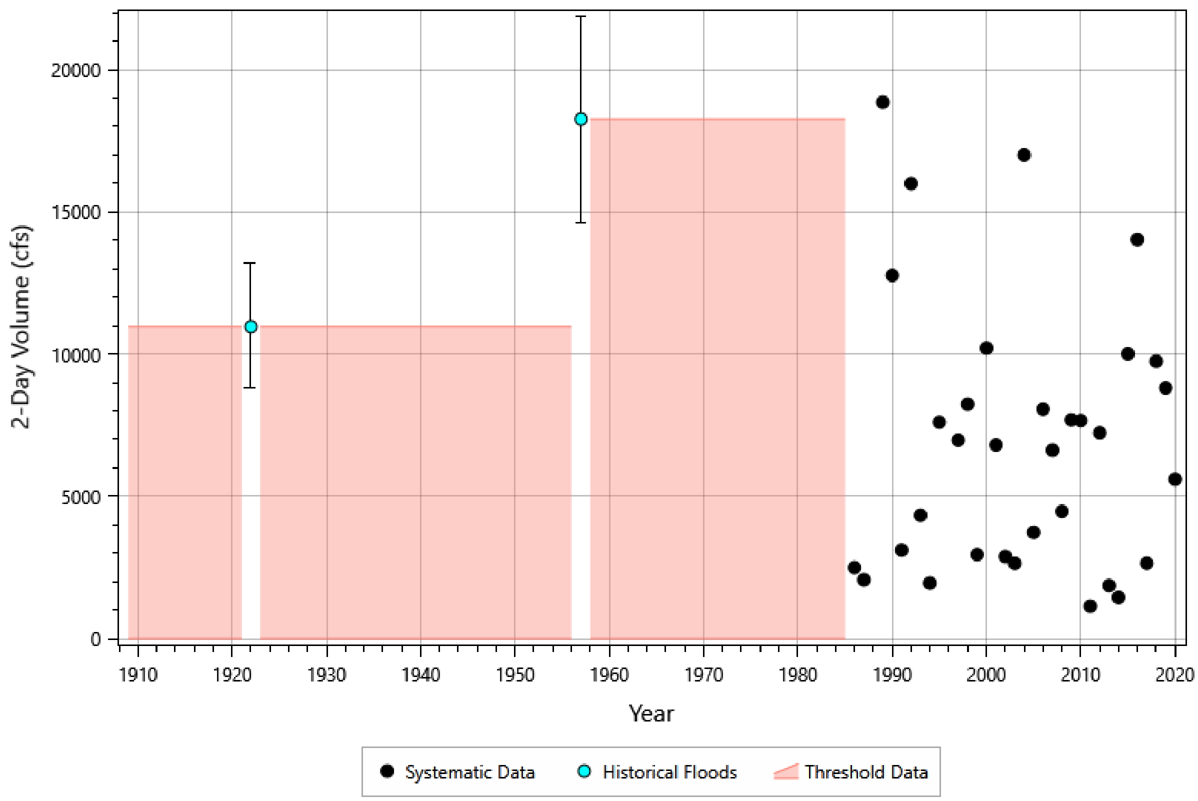


Figure 8: Joe Pool Dam Inflow Input Data for BestFit

A14 Volume 11 was recently completed for Texas in 2018, which incorporated recent extreme rainfall events through 2018 into the A14 precipitation-frequency estimates. This is a significant improvement from the previous precipitation-frequency analysis, Technical Report 40 (TP-40) dated May 1961. It is important to know when a precipitation-frequency analysis was complete as that will inform whether it includes recent historical rainfall events or not. This means the A14 Volume 11 precipitation-frequency data accounts for a much longer record of rainfall, providing more confidence in the A14 precipitation depths. RRFT was designed to provide an efficient way to develop a stochastic analysis using precipitation-frequency data. The A14 data is readily available in RRFT for a user to easily include in an analysis. For Joe Pool Dam, A14 Volume 11 was selected, and the watershed shapefile loaded into RRFT (Figure 2). From a study of historical hyetographs, most rainfall events that have significant flooding are approximately 48-hour events, therefore the 48-hour duration was selected. Because A14 is a point precipitation dataset, an ARF should be applied for the watershed area size. Joe Pool Dam (224 sq-mi) required a 12.5% reduction from the point to the basin area, therefore a 0.875 was applied to the A14 precipitation-frequency estimates (Figure 2). Given the input data, RRFT quickly pulls the A14 precipitation-frequency data for the mean, upper, and lower curves shown on Figure 9.

RRFT also allows the user to extrapolate the A14 curves using a distribution like GEV, shown on Figure 10. To correctly develop input data for the minimum and maximum AEP values of interest, precipitation depths must be sampled beyond those of interest. For example, A14 only has precipitation depths up to the 1E-03 AEP, which allows for Monte Carlo sampling to be sampled out to 1E-03. For Joe Pool Dam, the precipitation-frequency was extrapolated to 2E-07, and the Monte Carlo sampling used precipitation depths between 2E-01 and 2E-05 (Figure 11).

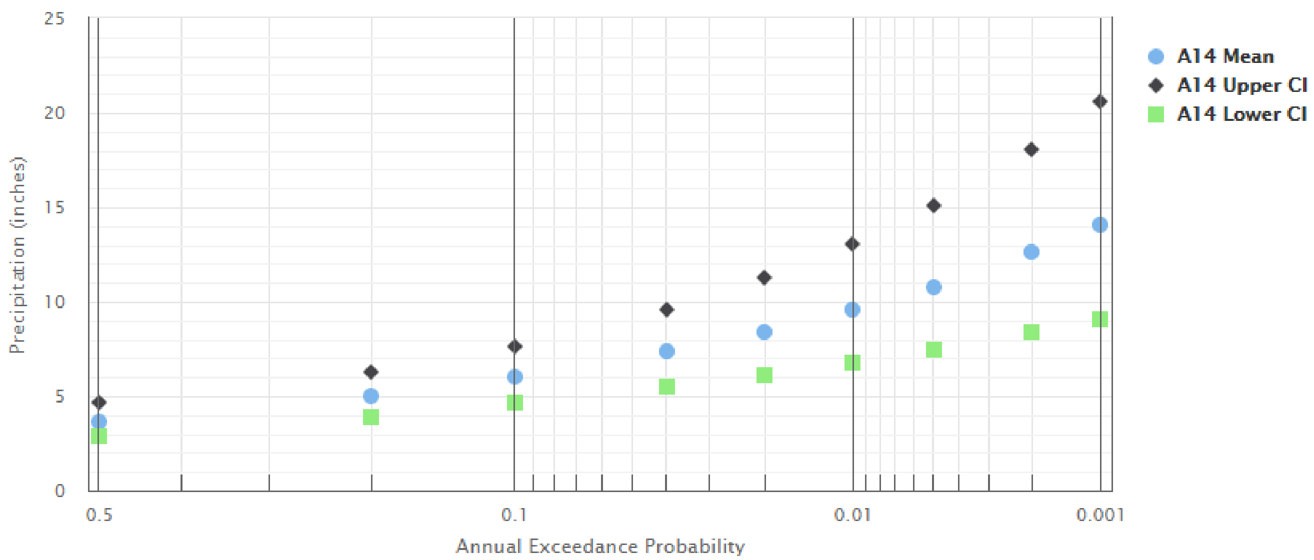


Figure 9: NOAA Atlas 14 Areal-Average Precipitation Frequency Curves for Joe Pool Dam

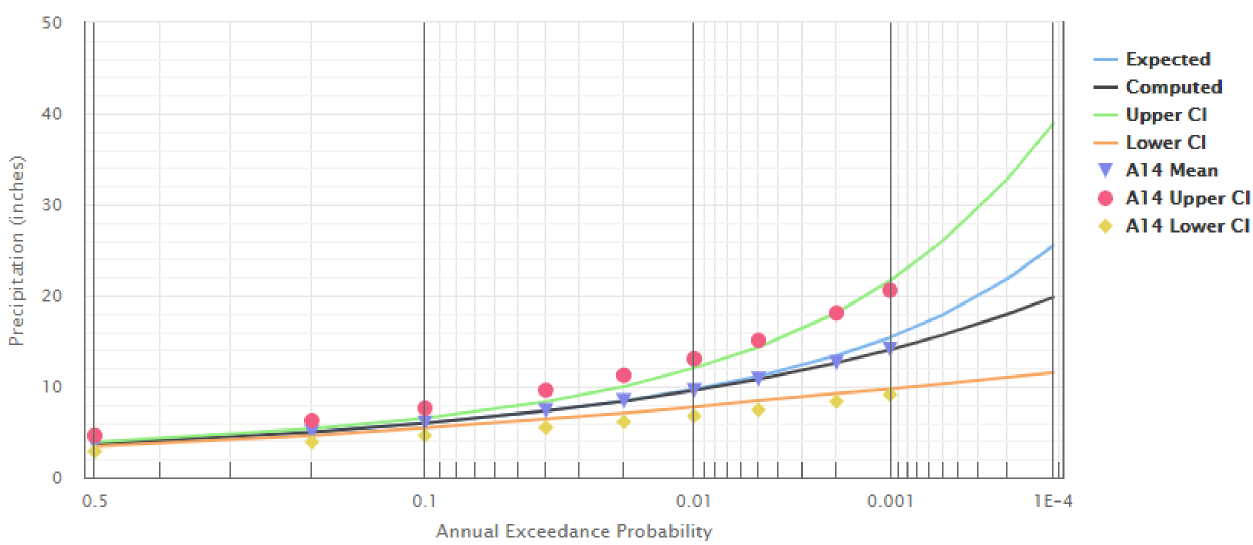


Figure 10: NOAA Atlas 14 Generalized Extreme Value Extrapolated Precipitation-Frequency Curves for Joe Pool Dam

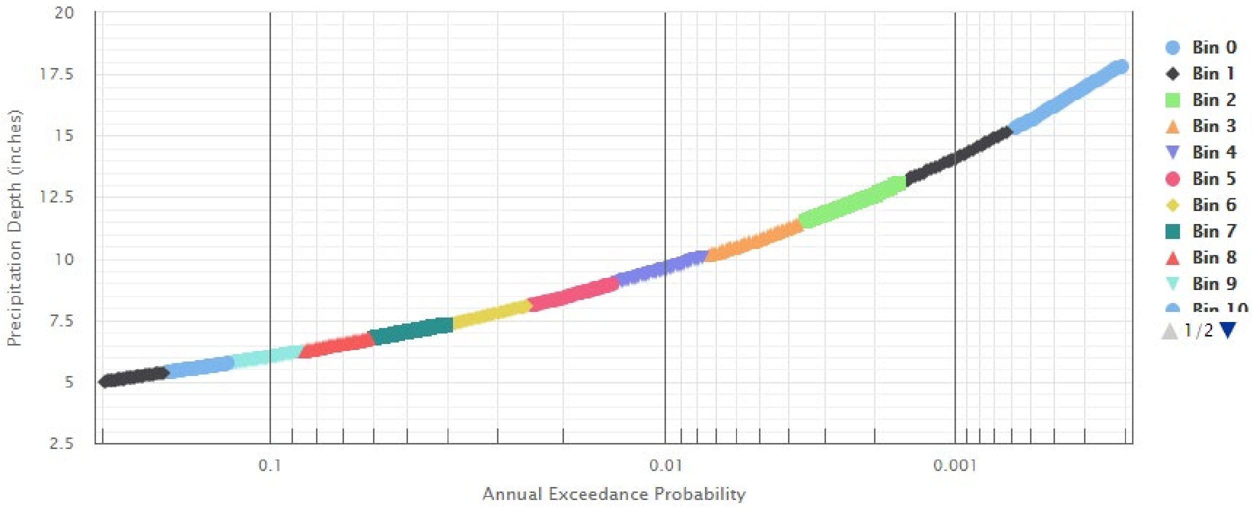


Figure 11: Monte Carlo Sampled Precipitation Depth based on the Extrapolated GEV Competed Precipitation Curve

Then in RRFT, with the Monte Carlo sampling plan just mentioned, the Joe Pool Dam calibrated HEC-HMS model was uploaded, and a stochastic simulation was created and computed. RRFT can produce reservoir inflow, outflow, and stage-frequency curves for use in flood risk analyses. For this analysis, only the 2-day inflow volumes were needed to pass information to BestFit to complete the 2-day flow-frequency analysis. Figure 12 shows the results from the stochastic execution run using the GEV extrapolated computed curve (Figure 5). Unlike Dam 47, RRFT results will be transferred to BestFit, which produces the expected (Posterior Predictive) flow-frequency curve. Therefore, only the GEV computed curve is required to develop the BestFit prior quantile values. This analysis also included another 300 samples for the upper and lower GEV extrapolated curves. RRFT can produce 10 sample results to millions depending on the level required for a study. The 300 samples were enough to inform the Joe Pool Dam analysis.

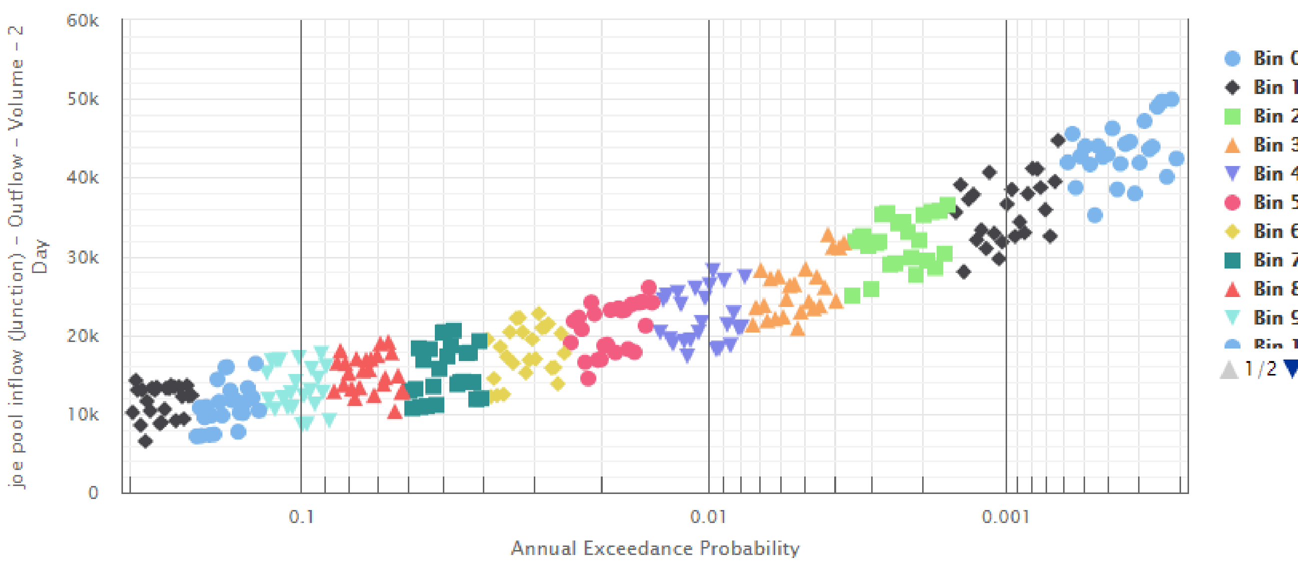


Figure 12: 2-day Inflow Volume RRFT Results for Joe Pool Dam

RRFT also produces the total probability giving all the sample results. The Joe Pool Dam computed, upper, and lower 2-day flow-frequency total probability curves are shown on Figure 13 (black curves). These curves represent the precipitation sampling plans routed through the HEC-HMS model which accounts for watershed runoff response. These total probability curves are compared to the original A14 extrapolated curves converted to 2-day flow volumes assuming no losses (blue curves). As expected, the rainfall-runoff results for the flow-frequency curves plot lower than the A14 curves because RRFT accounts for the hydrologic losses in the system. The flow-frequency results cannot exceed the precipitation-frequency results as that would mean the HEC-HMS model is producing runoff volumes greater than precipitation depths assuming no losses.

Another point of interest with the RRFT is the ability to simulate results in the range of the probable maximum flood (PMF) and estimate an AEP. Figure 13 shows the 2-day PMF runoff volume, the extrapolated A14 computed curve, and the RRFT computed total probability curve merge at an AEP of approximate 1E-06. Because both the extrapolated A14 precipitation-frequency curve and the rainfall-runoff total probability curves both cross the 2-day PMF volume at about the same AEP, it is a good indication of the possible AEP of the PMF elevation. In most cases, it would not be expected that the PMF elevation would vary much from the PMF runoff volume AEP. Therefore, RRFT can provide a reasonable AEP estimate for the PMF elevation or at a minimum provide a quality check to the AEP of the PMF elevation. The PMF elevation cannot be more frequent than the precipitation-frequency or flow-frequency curves because the flow-frequency would still have to be routed through a reservoir model before estimating the stage-frequency. This routing process will result in a PMF AEP the same as the flow-frequency or less frequent.

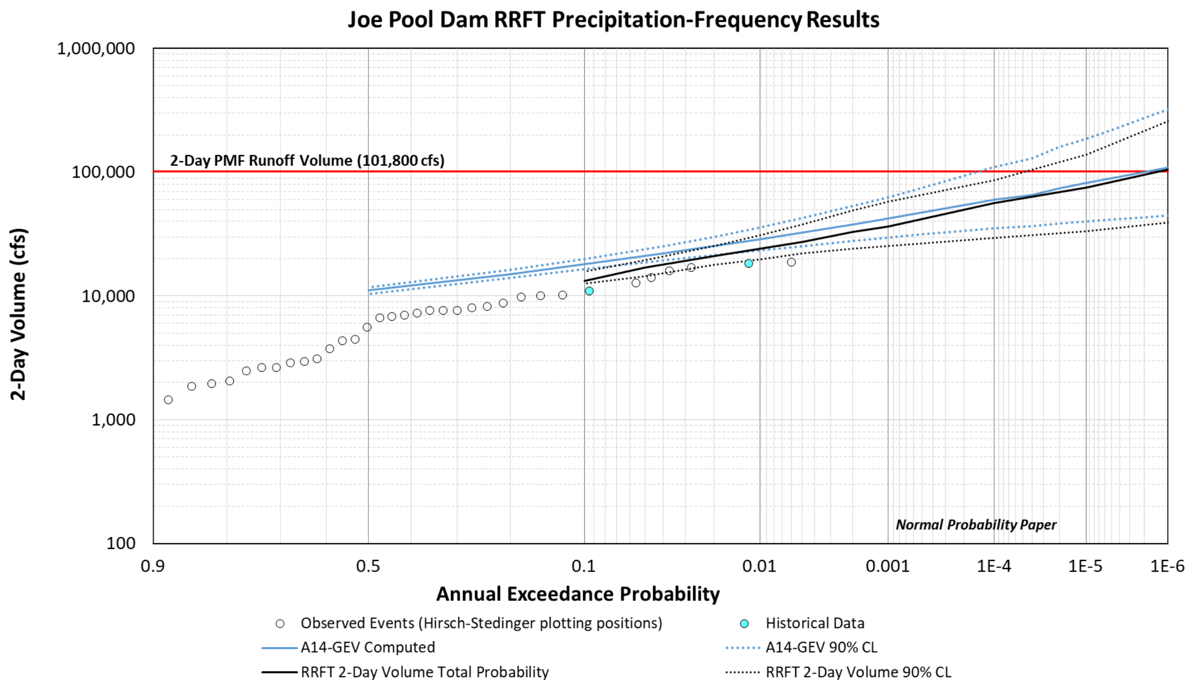
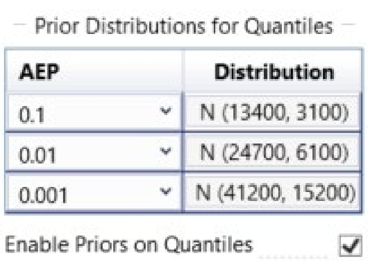


Figure 13: RRFT GEV Precipitation-Frequency Converted to 2-Day Volumes

Results from the Joe Pool Dam RRFT stochastic analyses were compiled to produce three rainfall-runoff values for the 1E-01, 1E-02, and 1E-03 AEP. The mean and standard deviation from the RRFT results were input into the prior quantile table in BestFit (Figure 14), which is how the regional precipitation-frequency is combine with the at-site data [2], [3].


Prior Distributions for Quantiles

AEP	Distribution
0.1	N (13400, 3100)
0.01	N (24700, 6100)
0.001	N (41200, 15200)

Enable Priors on Quantiles

Figure 14: BestFit Prior Distribution for Quantile Table

Joe Pool Dam flow-frequency curve using systematic inflow record, historical events, and threshold flows had already been entered into BestFit (Figure 8), providing the full extent of knowledge available from the at-site gauge. After the completion of the Joe Pool Dam RRFT stochastic rainfall-runoff modeling and the prior distributions for the three quantiles were calculated, the regional information was entered into the BestFit analysis (Figure 14).

Figure 15 shows the BestFit analysis using only the at-site gauge information. Based on this analysis for Joe Pool Dam, using only the at-site information, the 2-day probable maximum flood (PMF) volume of 101,800 cfs, has an AEP of approximately 5.8E-06 or is a 172,000-year event according to the Posterior Predictive curve (blue dashed curve on Figure 15). Note that when the Posterior Predictive curve exceeds the upper bound, it is not an error or bug. However, it is an indication that more data or information is needed to better inform and reduce the uncertainty of the flow-frequency.

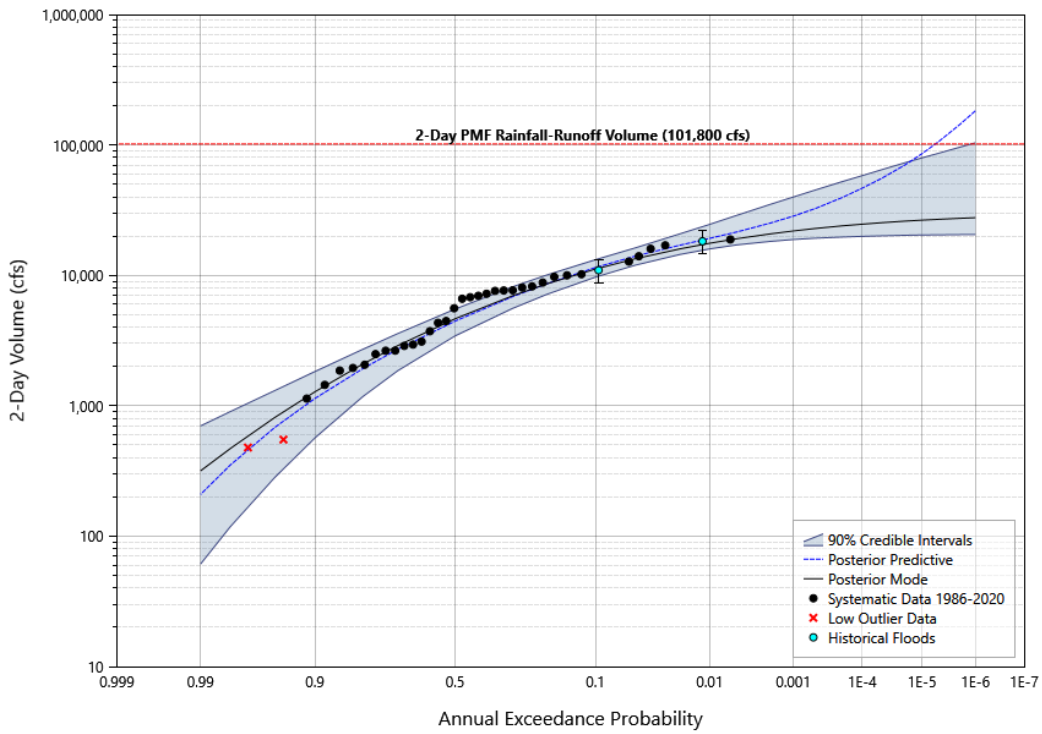


Figure 15: BestFit Analysis using at-site gauge information only for Joe Pool Dam

Adding regional information to an at-site gauge location increases the effective record length by substituting regional space for time. At Joe Pool Dam, adding the RRFT results to the BestFit doubles the ERL from 50-years to 100-years. Figure 16 below shows the three RRFT results entered (red squares) into the BestFit analysis. The addition of the RRFT results did not noticeably change the posterior mode (black line), however because the ERL doubled, the 2-day PMF runoff volume shifted about a half order magnitude to the right resulting in an AEP of 1.7E-06 or is a 588,000-year event.

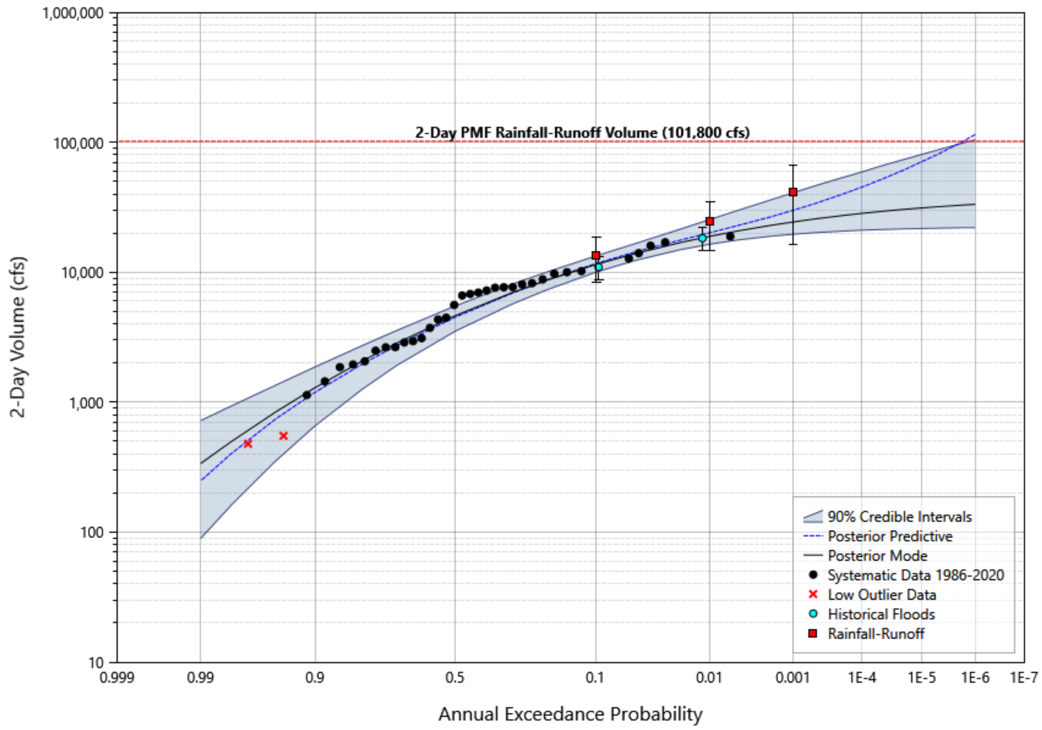


Figure 16: BestFit Analysis using all available information for Joe Pool Dam

For most dam safety studies, often a stage-frequency curve is needed for a risk assessment. The results from BestFit supplies the flow-frequency Log Pearson Type III (LPIII) distribution parameters to RMC-RFA to complete the final stage-frequency curve. Figure 17 shows the change in the final stage-frequency curve going from the at-site gauge information only (black dashed line) to the addition of the RRFT analysis (blue dashed line). The expected curve shifts approximately an order of magnitude less frequent. The PMF shifts from 4,300,000 to 43,000,000-year event (2.3E-07 to 2.3E-08).

Overall, for Joe Pool Dam, the goal was to decrease the knowledge uncertainty in the final stage-frequency curve to provide the best possible information for the dam safety risk assessment. With very little at-site information and no way to include paleoflood or regional skew information, RRFT and BestFit allowed the incorporation of regional precipitation-frequency data into the at-site flow-frequency analysis. This process extended the ERL and provide the best possible flow-frequency analysis for the available information. This information was utilized as an input in RMC-RFA which calculates the stage-frequency curve with uncertainty bounds.

RMC-RFA produces that stage-frequency curve with uncertainty bounds utilizing a deterministic routing model while treating the inflow volume, the inflow hydrograph shapes, the seasonal occurrence, and the antecedent reservoir stage as uncertainty variables [5]. The inflow volume is sampled from the flow-frequency information brought over from BestFit. RMC-RFA samples from the flow-frequency distribution and routes many thousands of flood events. That process is repeated many thousands of times to produces the stage-frequency curve with uncertainty bounds. The ERL and flow-frequency distribution have a large influence on the stage-frequency curve, so it is always important to include as much available data as possible when developing the flow-frequency curve.

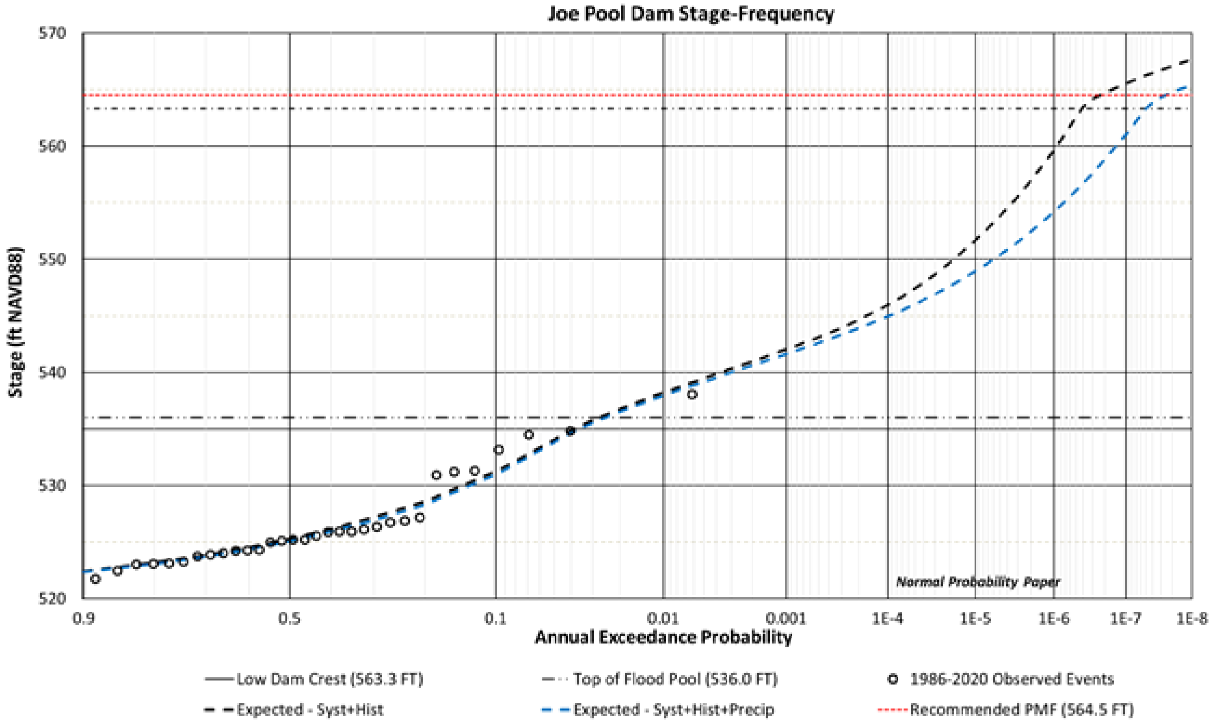


Figure 17: Stage-Frequency Curve Comparison between At-Site Data only and Incorporating Regional Precipitation-Frequency Information

V. Future Improvements

There are many enhancements in the works for RRFT that aim to greatly increase the usability of the tool. Currently, RRFT is only available to USACE RMC staff, however, future versions could be made available for public use. Additional improvements to RRFT include updating the user interface, adding the ability to account for the variability in initial conditions and other parameters, decreased run times by improving the communication with HEC libraries, and enhance the results analysis and data visualization. Also, RRFT will also benefit from the continued improvements in HEC-HMS, such as the ability to model complex reservoir operations.

To date, RRFT has not been used to estimate the inflow volume resulting from a PMP event. To estimate the PMF inflow volume in the current version, a GEV curve must be fit to the A14 data and extrapolated above the PMP depth. Future versions of the tool will allow users to enter site specific PMP information to directly calculate the PMF volume.

VI. Conclusion

It is important for dam safety risk assessments to incorporate as much available data as possible to reduce the uncertainty in understanding of the flood frequency relationship. RRFT provides a considerable advancement in flood hazard analysis technology by offering the ability to simulate large scale stochastic modeling in a cost-effective manner. RRFT offers an intuitive step-by-step process for developing rainfall-runoff stochastic results that can be used to inform at-site flow- and stage-frequency results. BestFit provides a means for combining all the at-site date (systematic, historical, and threshold flows) along with regional information, like regional skew or precipitation-frequency, into the flow-frequency curves. In some cases, flow data might not be available for a dam; RRFT provides a means for performing a stochastic analysis that results in a stage-frequency with confidence intervals that can be used in dam safety risk assessments.

This paper showed two typical cases were using RRFT by itself or RRFT in combination with BestFit can improve the overall dam safety risk assessment process. With the first case, there was no inflow information available. Without RRFT, a stage-frequency curve would need to be developed using discrete hydrologic modeling results, which does not provide any knowledge uncertainty and thus cannot provide confidence intervals. RRFT provided a way to use stochastic modeling to account for the uncertainty in the regional rainfall analysis and hydrologic rainfall-runoff parameters in one analysis, resulting in a stage-frequency curve with confidence intervals. The stage-frequency curve used in the risk assessment now had the best available data to make informed risk decisions.

The second case was an example of a dam in a highly urbanized area where dam safety risk decisions have large impacts to the community. Only limited at-site inflow data was available and the regional skew information and paleoflood analysis were not applicable to the watershed. To decrease the uncertainty in the flood hazard curves, RRFT was used in combination with BestFit to provide regional rainfall-runoff results that increased the effective record length, decreasing uncertainty in the at-site flow- and stage-frequency curves for the dam. This provided a way to incorporate all available data, allowing for the risk assessment to make the most informative decisions giving the data limitations.

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IX. Author Biographies

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