A robust and efficient stochastic simulation framework for estimating reservoir stage-frequency curves with uncertainty bounds

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The U.S. Army Corps of Engineers (USACE) Risk Management Center (RMC) developed the Reservoir Frequency Analysis software (RMC-RFA) to facilitate, enhance, and expedite flood hazard assessments within the USACE Dam Safety Program. RMC-RFA is a stochastic flood modeling software that employs advanced statistical and computing techniques, allowing a user to perform a screening-level stage-frequency analysis on a desktop PC with runtimes on the order of seconds to a few minutes. RMC-RFA utilizes an inflow volume-based stochastic simulation framework that treats the seasonal occurrence of the flood event, the antecedent reservoir stage, inflow volume, and the inflow flood hydrograph shape as uncertain variables rather than fixed values. In order to construct uncertainty bounds for reservoir stage-frequency estimates, RMC-RFA employs a two looped, nested Monte Carlo methodology. The natural variability of the reservoir stage is simulated in the inner loop defined as a realization, which comprises many thousands of events, while the knowledge uncertainty in the inflow volume-frequency distribution is simulated in the outer loop, which comprises many realizations.

Stage-frequency curves derived with RMC-RFA are compared to those derived with more complex, precipitation-based simulation frameworks, such as the Monte Carlo Reservoir Analysis Model (MCRAM), the Stochastic Event Flood Model (SEFM), and the Watershed Analysis Tool (HEC-WAT). The inflow volume-based framework employed by RMC-RFA produces stage-frequency curves that strongly agree with the more complex, precipitation-based methods. Furthermore, the results from the alternative methods fall within the RMC-RFA uncertainty bounds, demonstrating its robustness. In this sense, the RMC-RFA simulation framework lends itself to a value of information approach to risk management, where knowledge uncertainty can be efficiently quantified at a screening-level assessment, and then the value of performing more complex and sophisticated studies to reduce uncertainty can be considered.

Keywords: Risk assessment, stochastic simulation, flood frequency, uncertainty, value of information

Introduction

For the risk assessment of dams, the annual peak reservoir stage is typically the primary loading parameter considered in evaluating a potential failure mode and the associated risk. Other parameters such as discharge, duration, and velocity are also important. The probability of failure is often conditional on the magnitude of the hydrologic loading. The consequences of failure are also a function of the reservoir stage, outflow, and corresponding reservoir volume. Therefore, the annual probability of exceeding a given reservoir stage, commonly referred to as stage-frequency, is a critical consideration in performing a risk analysis (*Smith et al*, 2018).

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This paper presents the RMC-RFA simulation framework, four case studies where RMC-RFA results are compared with more complex, precipitation-based simulation frameworks, and a discussion on assessing the value of more advanced analysis.

Overview of simulation framework

RMC-RFA utilizes an inflow volume-based stochastic simulation framework that treats the seasonal occurrence of the flood event, the antecedent reservoir stage, inflow volume, and the inflow flood hydrograph shape as uncertain variables rather than fixed values. In order to construct uncertainty bounds for reservoir stage-frequency estimates, RMC-RFA employs a two looped, nested Monte Carlo methodology. The natural variability of the reservoir stage is simulated in the inner loop defined as a realization, which comprises many thousands of events, while the knowledge uncertainty in the inflow volume-frequency distribution is simulated in the outer loop, which comprises many realizations (for more information on the difference between natural variability and knowledge uncertainty, please refer to *Vose* (2008) for general discussion or *Smith et al.* (2018) for application in hydrologic hazards). The model parameters that are treated as random

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variables in RMC-RFA are listed in Table 1. The basic construct of the simulation procedure employed by RMC-RFA is illustrated in Figure 1.

Table 1. Model parameters treated as random variables.

Input Parameter	Dependency	Statistical Distribution	Sampling Approach
Inflow Volume	Independent	Analytical	Importance/Stratified
Inflow Hydrograph Shape	Independent	Empirical	Monte Carlo
Flood Season	Independent	Empirical	Monte Carlo
Reservoir Starting Stage	Flood Season	Empirical	Monte Carlo

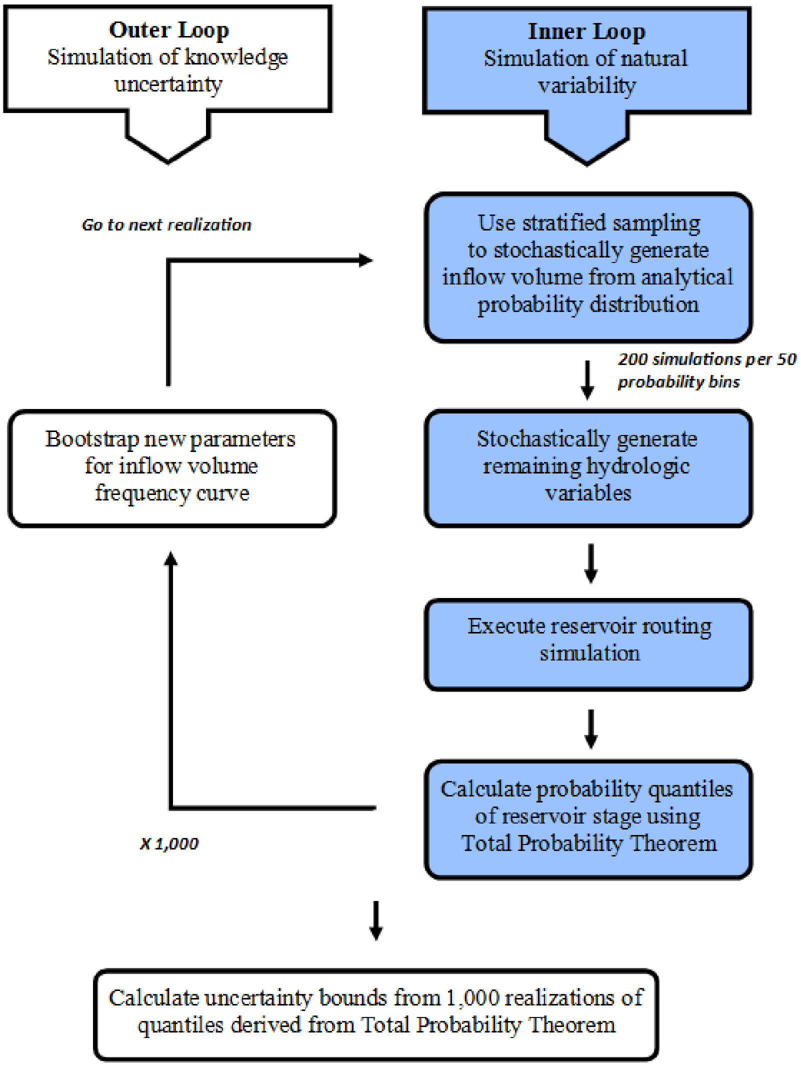

Figure 1. Flowchart of the steps involved in the RMC-RFA simulation.

Model inputs

The model inputs required for a RMC-RFA simulation are listed below. Methodology and guidance for developing model inputs can be found in *Smith et al*. (2018), and a step-by-step guide for setting up a project and simulation is provided in the software user's manual.

1. ***Inflow volume-frequency curve***: The inflow volume-frequency curve must be derived externally using statistical software, such as HEC-SSP. It is recommended that the volume-frequency curve be fit using systematic, historical, regional, and paleoflood data when available. Please see Bulletin 17C (U.S. Geological Survey, 2017) for current U.S. guidance on fitting flood frequency curves.
2. ***Inflow hydrograph shapes***: Inflow hydrographs for major historical events, large events, or synthetic events should be used when available. The shape of the hydrograph is a reflection of the response of the watershed to an event. At least one inflow hydrograph shape is required to perform a simulation. Multiple inflow hydrographs can

be sampled as part of the simulation. The inflow hydrograph shape is scaled up or down based on the sampled inflow volume in the stochastic simulation. Typically, the hydrograph shapes are given equal probability of occurrence since there is normally limited hydrograph data available for large events in the watershed to suggest a different weighting scheme.

2. ***Flood seasonality and stage duration analyses***: Flood seasonality and seasonally dependent stage duration analysis options are included in the RMC-RFA software. The flood seasonality describes the frequency of occurrence of floods on a seasonal basis. In the simulation, the seasonal occurrence of the flood is randomly sampled, and the starting stage for the reservoir model is sampled based on the seasonal stage duration relationships.
3. ***Reservoir Model***: Reservoir routing in RMC-RFA is based on a deterministic "hydrologic method", which is concentrated on the concept of storage for the flood water and does not directly include effects of resistance to the flow. Specifically, RMC-RFA uses the *Modified Puls* routing method, also known as storage-indication routing or level-pool routing. RMC-RFA requires a stage-storage-discharge function to define the reservoir model input.

Simulation efficiency

Standard Monte Carlo sampling procedures are computationally inefficient. The bulk of the computational burden is expended on sampling frequent flood events in the range of exceedance probabilities that are not typically important in risk assessments. If flood events greater than 100 year are of primary interest, which is common in dam safety risk analysis, then 99% of the Monte Carlo samples provide little to no useful information. Consequently, to ensure computational effort is focused on extreme flood events, RMC-RFA uses an *importance* and *stratified sampling* approach based on procedures outlined in *Nathan and Weinmann* (2013) and *Nathan et al*. (2016), which involves dividing the inflow volume-frequency curve into uniformly spaced bins over the Extreme Value Type I (EVI) probability domain. As a result, accurate reservoir stage-frequency results in the range of extreme exceedance probabilities can be attained with significantly less computational effort than standard Monte Carlo methods. In order to accurately quantify knowledge uncertainty in stage-frequency results, RMC-RFA employs the *parametric bootstrap*, which was originally introduced in 1979 as a computer-based method for estimating standard errors (see *Efron & Tibshirani* (1998) for more discussion on bootstrap applications). Finally, the full stochastic simulation, which utilizes the importance and stratified sampling approach and the parametric bootstrap, is parallelized so that realizations can be carried out simultaneously on a multi-core computer processor.

RMC-RFA contains many additional features that allow for much more efficient model development and analysis of reservoir frequency relationships. RMC-RFA is a Windows desktop application written with the .NET Framework that is designed for interactive use in a multi-tasking environment. The software features a fully integrated modeling platform, featuring a graphical user interface (shown in Figure 3), input data entry capabilities, statistical analysis components, reservoir routing models, stochastic simulation, and results reporting tools.

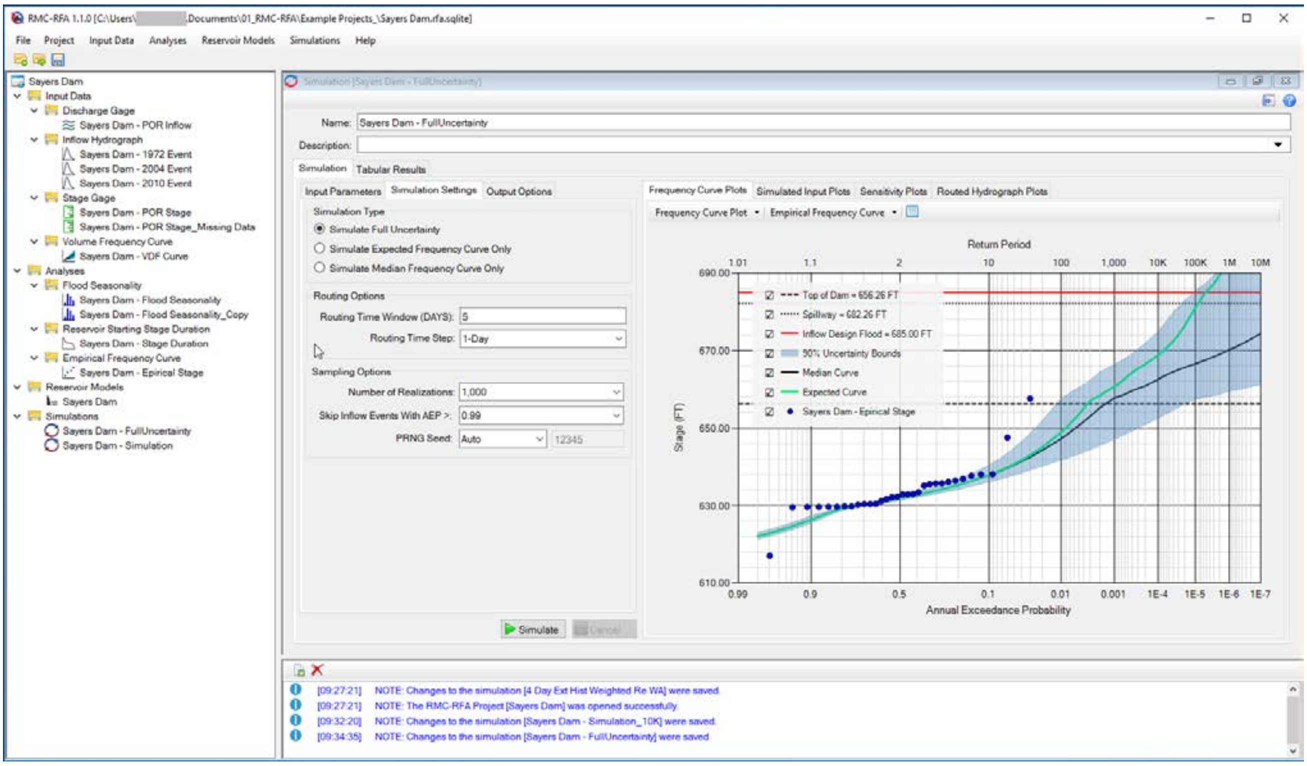

Figure 2. RMC-RFA graphical user interface.

In RMC-RFA, the user can select from three simulation options: 1) Simulate full uncertainty; 2) Simulate expected frequency curve only; and 3) Simulate median frequency curve only. The latter two options only require 10 seconds in runtime[2], permitting the user to rapidly perform sensitivity analysis and explore a more extensive variety of possible flood and operational scenarios at the reservoir as compared to more traditional platforms. The full uncertainty option with 1,000 realizations requires approximately 15 minutes in runtime[3]. In RMC-RFA, inflow volume-frequency relationships can be defined using the Log Normal, Log Gumbel, Log Pearson Type III, or Log Generalized Extreme Value distribution, allowing the user to also assess the range of uncertainty and sensitivity in reservoir stage-frequency due to statistical model selection. There are also multiple frequency curve output options, including peak stage-frequency, reservoir peak outflow-frequency, and reservoir outflow-volume-frequency curves, allowing the user to characterize hydrologic hazards for various potential failure modes, such as overtopping and spillway erosion.

Limitations

Every stochastic simulation system has limitations due to the choices made in the design and development of the software. Stochastic simulation with RMC-RFA permits the exploration of an extensive variety of possible flood scenarios for reservoirs as compared to more traditional deterministic approaches. However, it is important to understand the limitations associated with the stochastic simulation methods employed by RMC-RFA. The primary limitations are as follows:

1. ***Observed flow records***: RMC-RFA utilizes an inflow volume-based stochastic simulation framework, which, of course, requires observed inflow records for the project of interest. If there are no recorded inflow data, then it is recommended to route precipitation-frequency events using a rainfall-runoff model that is parameterized using standard approaches for ungauged watersheds.
2. ***Knowledge uncertainty***: In RMC-RFA, knowledge uncertainty in the form of sampling uncertainty is estimated using the parametric bootstrap. However, there are other sources of knowledge uncertainty that are not accounted for in RMC-RFA, such as measurement error, model uncertainty, reservoir operational uncertainty, and others.
3. ***Reservoir routing***: The current version of RMC-RFA utilizes the Modified Puls method for reservoir routing, and only requires a stage-storage-discharge relationship as model input. Therefore, RMC-RFA cannot simulate complex reservoir operations, such as those that require seasonal guide curves, complex rules, or downstream constraints on releases. Consequently, RMC-RFA should only be used as a screening level tool for those reservoirs requiring complex operations. However, for most dams in the USACE portfolio, including those with very complex operations, RMC-RFA has been shown to provide valid stage-frequency estimates above the spillway invert to beyond the top of dam elevation. In this elevation range, many reservoirs have uncontrolled spillway flow, which can be modeled accurately using only a stage-storage-discharge relationship. Future versions of the software will provide more flexibility in simulating complex reservoir operations. Experience to date suggests that extreme flood events requiring seemingly complex reservoir operations can often be modeled using relatively simple stage-storage-outflow relationships.

For more information on the RMC-RFA methodology, example applications, and discussion on limitations, please see *Smith* (2017), *Smith & England* (2017), and *Smith et al*. (2018). To request a free copy of the software please contact the author.

Case studies

Four case studies are presented where reservoir stage-frequency curves derived with RMC-RFA are compared to those derived with more complex and advance precipitation-based simulation frameworks, such as the Monte Carlo Reservoir Analysis Model (MCRAM), the Stochastic Event Flood Model (SEFM), and the Watershed Analysis Tool (HEC-WAT). Dams from across the United States with varying climate and flood driving mechanisms are evaluated. These include the Lake Okeechobee watershed in Florida, the American River and the Whittier Narrows watersheds in California, and the Willamette Basin in Oregon.

Lake Okeechobee

Lake Okeechobee is located in south central Florida, near the Everglades. The watershed is large and complex, spanning approximately 13,600 km^2, including the lake surface of Okeechobee, which covers over 1,800 km^2. A map of the watershed delineation is provided in Figure 4. Although the drainage basin is contained within the Coastal Plain physiographic province, surface and groundwater characteristics can vary significantly through the basin. Over the last several decades, the basin has experienced significant alteration for irrigation, navigation, water supply, and flood damage reduction.

In 2015, the RMC performed a comprehensive hydrologic hazard assessment for Lake Okeechobee in order to support the estimation of risks and inform dam safety modification decisions (see *Smith et al* (2015) for a full technical report). A stochastic hydrologic modeling software, referred to as the Monte Carlo Reservoir Analysis Model (MCRAM), was

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[2] Runtimes are based on the following computer specifications: Intel Core i7-4900MQ CPU @ 2.80 GHz (4 cores – 8 threads) and 32 GB of RAM. Runtimes will vary depending on the computer, as well as the selected routing time window, time step, and size of the routing stage-storage-discharge table.

[3] Runtimes can be expected to increase linearly with addition realizations. For example, if 1,000 realizations take 15 minutes to run, then it can be expected that 10,000 realizations will require 150 minutes (or 2.5 hours) of runtime.

developed by the RMC to specifically meet the needs of the analysis. MCRAM continuously simulated hydrologic conditions at a daily time step for thousands of synthetic years. Stochastic precipitation events were generated for the watershed by randomly sampling daily basin-average precipitation. The daily precipitation was then spatially disaggregated using historical storm patterns. Tropical storm events were handled as a special case of weather generation to capture the effects of the mixed population in meteorology. Additionally, synthetic tropical storm wind fields were used to create a coupled hydrologic and wind-driven hydrodynamic simulation (see *Smith & Karlovits* (2015) for more details on the MCRAM simulation framework). The results of this study increased confidence in the characterization of the hydrologic hazards for Lake Okeechobee to a level that was commensurate with the needs of the risk assessment and the dam safety modification decisions at the time.

An RMC-RFA model was developed for Lake Okeechobee for the purposes of this paper. RMC-RFA inputs were developed using available data from the 2015 study. Using Bulletin 17C procedures (U.S. Geological Survey, 2017), an inflow volume-frequency curve for the 30-day critical inflow duration was developed using the Log Pearson Type III distribution fit to systematic flow records from 1972 to 2013 and historical data back to 1928. A simple reservoir stage-discharge relationship was developed using the RUN-25 regulation schedule.

The comparison of stage-frequency[4] results for Lake Okeechobee using RMC-RFA and MCRAM is provided in Figure 5. As can be seen, the results from the two models are agreeable. RMC-RFA predicts a top of dam exceedance probability that is one order of magnitude more frequent. However, the precipitation-frequency based results from MCRAM fall well within the RMC-RFA uncertainty bounds. It is important to note that Lake Okeechobee reservoir operations are very complex, and rely on a decision tree to guide operations for flood control, water supply, environmental, and downstream constraints. Nevertheless, RMC-RFA is still capable of producing a stage-frequency curve that agrees well with both the observed data and the more sophisticated MCRAM results.

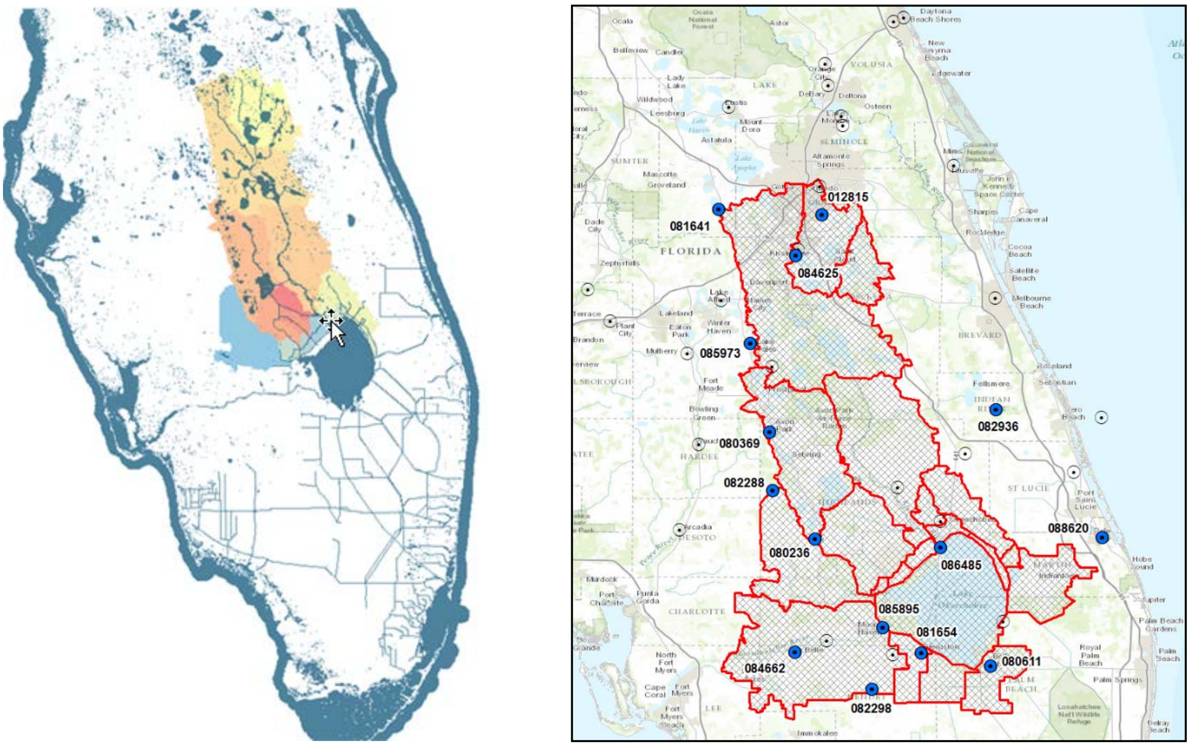

Figure 3. Lake Okeechobee watershed delineation (Smith et al (2015)). The lake is located in the southeast corner of the watershed.

[4] USACE policy is that frequency curves used in risk assessment must reflect the expected probability (U.S. Army Corps of Engineers, 1994). For simplicity, only the 90% confidence intervals (uncertainty bounds) and the expected probability curves for the case studies are shown for comparison in this paper.

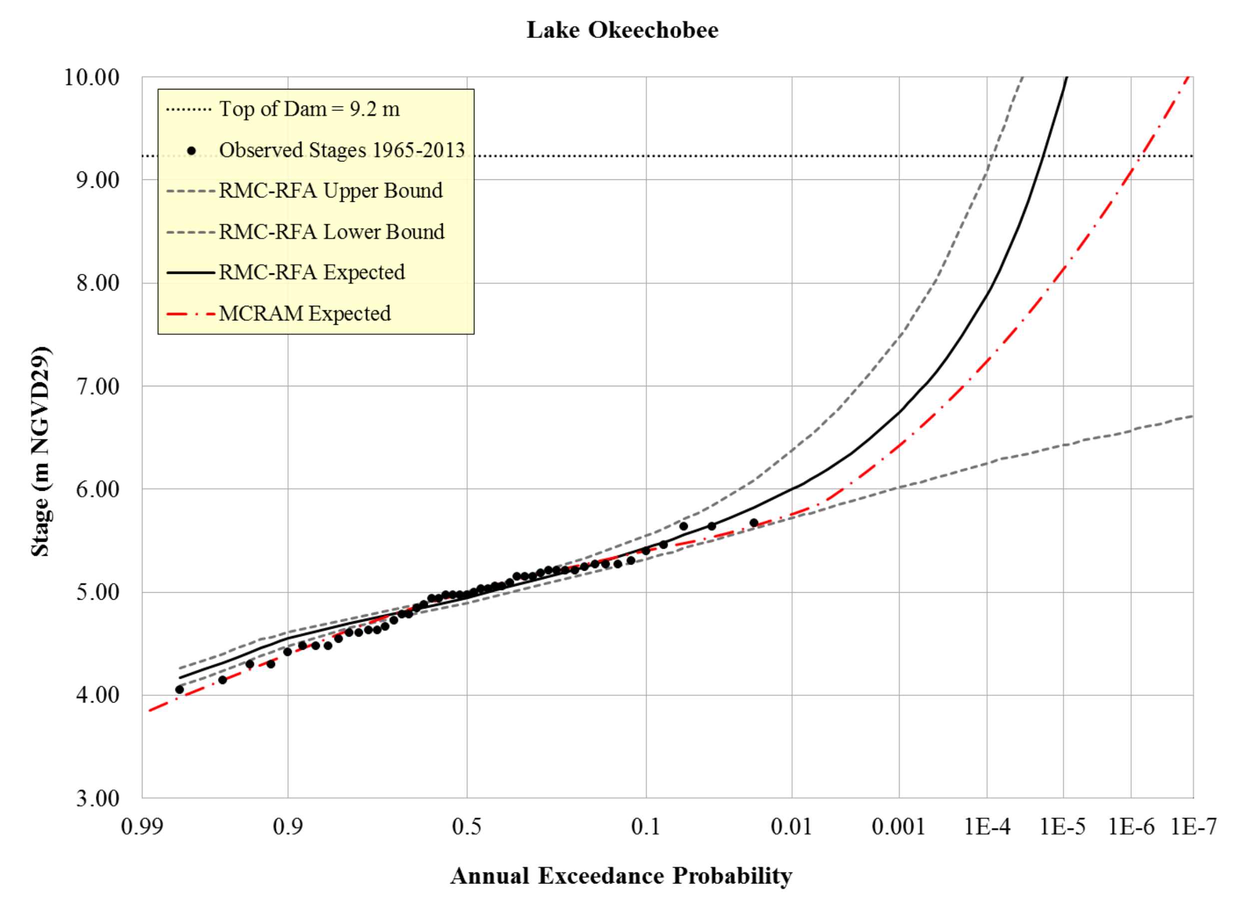

Figure 4. Comparison of stage-frequency results for Lake Okeechobee using RMC-RFA and MCRAM. The figure shows the 90% confidence intervals and the expected and median frequency curves produced by RMC-RFA. Only the expected curve is shown from MCRAM. All probability plots use a normal probability scale.

Folsom Dam

Folsom Dam is located on the American River in northern California. Folsom Dam was constructed by USACE and later transferred to the U.S. Bureau of Reclamation (USBR). The dam is a multipurpose project, providing flood control, hydropower, and water supply. The American River watershed, shown in Figure 6, covers approximately 4,820 km^2.

In 2005, MGS Engineering Consultants, Inc. developed a stochastic event flood model (SEFM) for the American River watershed tributary to Folsom Dam for use in estimating exceedance probability for extreme floods. SEFM utilized a deterministic flood computation model (HEC-1 at the time of the study) and treated the hydrometeorological input parameters as variables instead of fixed values. Monte Carlo sampling procedures were used to allow the climatic and storm related input parameters to vary in accordance with that observed in nature. Hydrometeorological inputs that were treated as variables included: seasonality of storm occurrence: magnitude of extreme storm; temporal and spatial distribution of storms; temporal temperature pattern during the storm; sea-level and freezing level temperatures during the storm; antecedent precipitation; antecedent snowpack; antecedent soil moisture; initial storage in major upstream reservoirs; and initial storage in Folsom Lake. For more information on the Folsom Dam study and the SEFM methodology, please see *MGS Engineering Consultants, Inc*. (2005) and *MGS Engineering Consultants, Inc*. (2009).

An RMC-RFA model was developed for Folsom Dam using inputs that were previously developed in the SEFM study. In addition, the inflow volume-frequency curve was developed for RMC-RFA using paleoflood data and Log Pearson Type III parameters derived for a flood hazard analysis in 2002 (U.S. Bureau of Reclamation, 2002). Since the SEFM analysis focused on the rainy winter season, starting pools were restricted to only occur between the months of October to April. The reservoir stage-discharge relationship was developed using the same rule curves as done in the SEFM analysis.

The comparison of stage-frequency results for Folsom Dam using RMC-RFA and SEFM is provided in Figure 7. As can be seen, the results from the two models are nearly identical. In the SEFM study, the 72-hour basin-average precipitation-frequency relationship was developed through regional analyses. Using the SEFM model, the peak flow of the probable maximum flood (PMF) had an estimated annual exceedance probability (AEP) of 4.5×10^{-5} (1:22,000). However, the paleoflood frequency analysis estimated the AEP of the PMF as 1×10^{-4} (1:10,000). Therefore, as can be seen in Figure 7, the expected stage-frequency curve from RMC-RFA is slightly more frequent than the best estimate curve derived from SEFM.

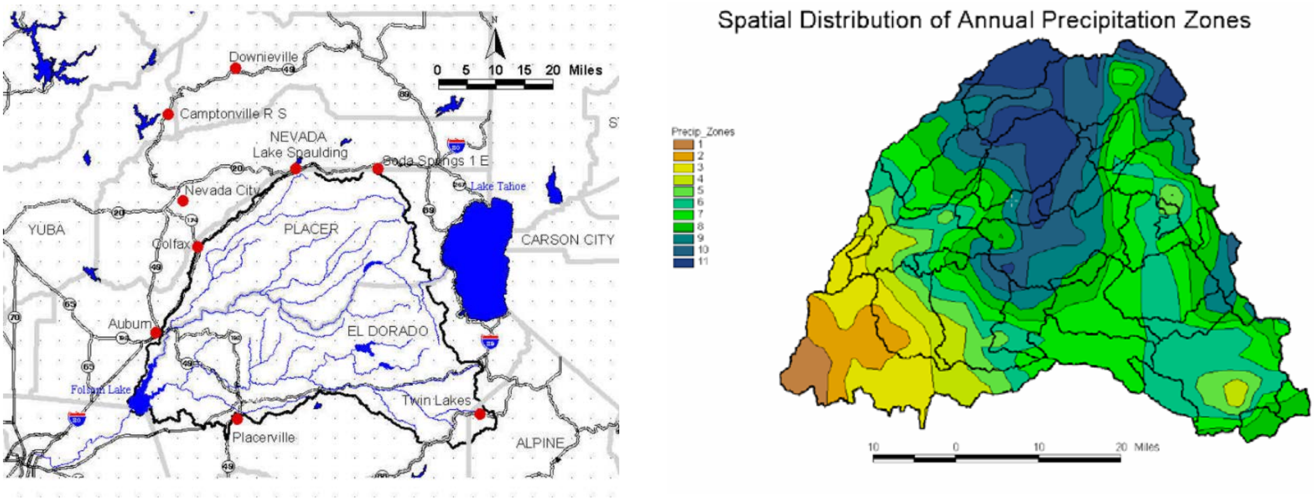

Figure 5. American River Watershed above Folsom Dam and surrounding area (MGS Engineering Consultants, Inc. (2005)). Basin delineation and spatial distribution of precipitation is shown to the right.

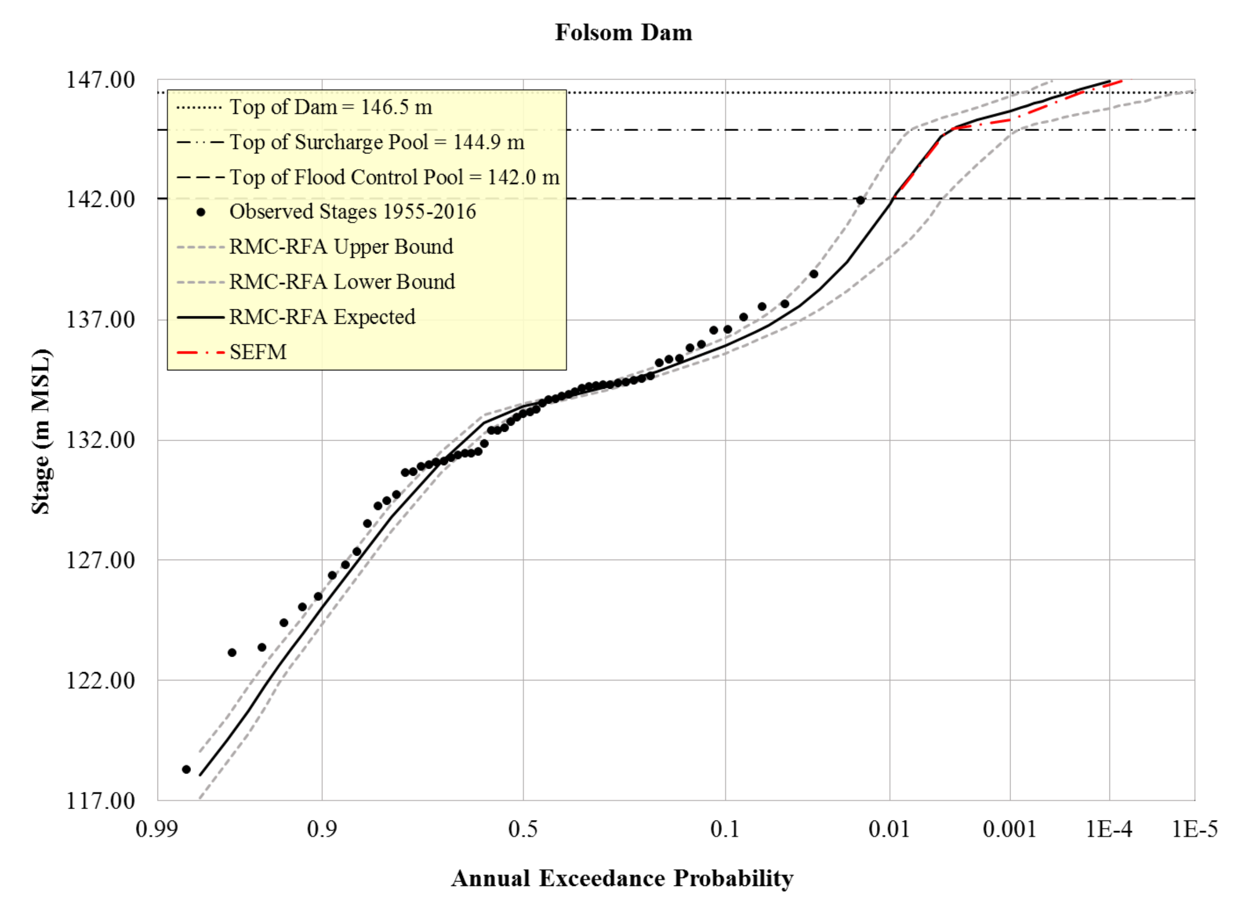

Figure 6. Comparison of stage-frequency results for Folsom Dam using RMC-RFA and SEFM. The figure shows the 90% confidence intervals and the expected probability curve produced by RMC-RFA. Only the best estimate curve from SEFM is shown. The plotted observed stages are annual maximums from only the winter months of January to March.

Whittier Narrows Dam

Whittier Narrows Dam is a USACE dam located at a natural gap in the hills that forms the southern limit of the San Gabriel Valley, approximately 16 kilometres east of downtown Los Angeles, California. The Rio Hondo River and San Gabriel River flow through that natural gap and are both impounded by the dam. The Whittier Narrows Dam watershed is approximately 1,465 km^2 and contains extremely varied regions ranging from remote mountains to highly urban. Whittier Narrows Dam is a high hazard dam, central to the Los Angeles County flood control system, and is currently being evaluated in a modification study.

As a result of the urban development, a significant portion of the valley is impervious to rainfall infiltration and storm runoff infiltration. Unusually high flood peaks of short duration characterized the runoff from the drainage area. High rainfall intensities, combined with the effects of shallow surface soils underlain by impervious bedrock, fan-shaped collecting systems, occasional denudation by fire, and steepness of gradients, produce floods heavily laden with debris below the canyon mouths. Most streams in the drainage area are intermittent. During normal dry weather the regulated outflow from dams in the mountains increases the discharge of many streams.

A basin-average precipitation-frequency curve for the 24-hour critical duration was developed using existing National Oceanic and Atmospheric Administration (NOAA) Atlas 14 data, and is limited to the period of record at each station available at the time of publishing Atlas 14 Volume 6, version 2.3 (Perica, et al., 2014). Regionalization was performed with the goal of creating a large, homogeneous region useful for extrapolating to remote probabilities by increasing the available number of station-years of observations as much as possible while maintaining regional homogeneity. A single depth-area-duration relationship was used for converting a point precipitation frequency analysis to the estimated Whittier Narrows Dam Watershed.

The precipitation-frequency events were then routed using an "AEP neutral" approach (*Nathan & Bowles*, 1997) where median values of hydrometeorological conditions were used for storm seasonality, antecedent soil moisture, soil loss rates, and the initial reservoir stage.

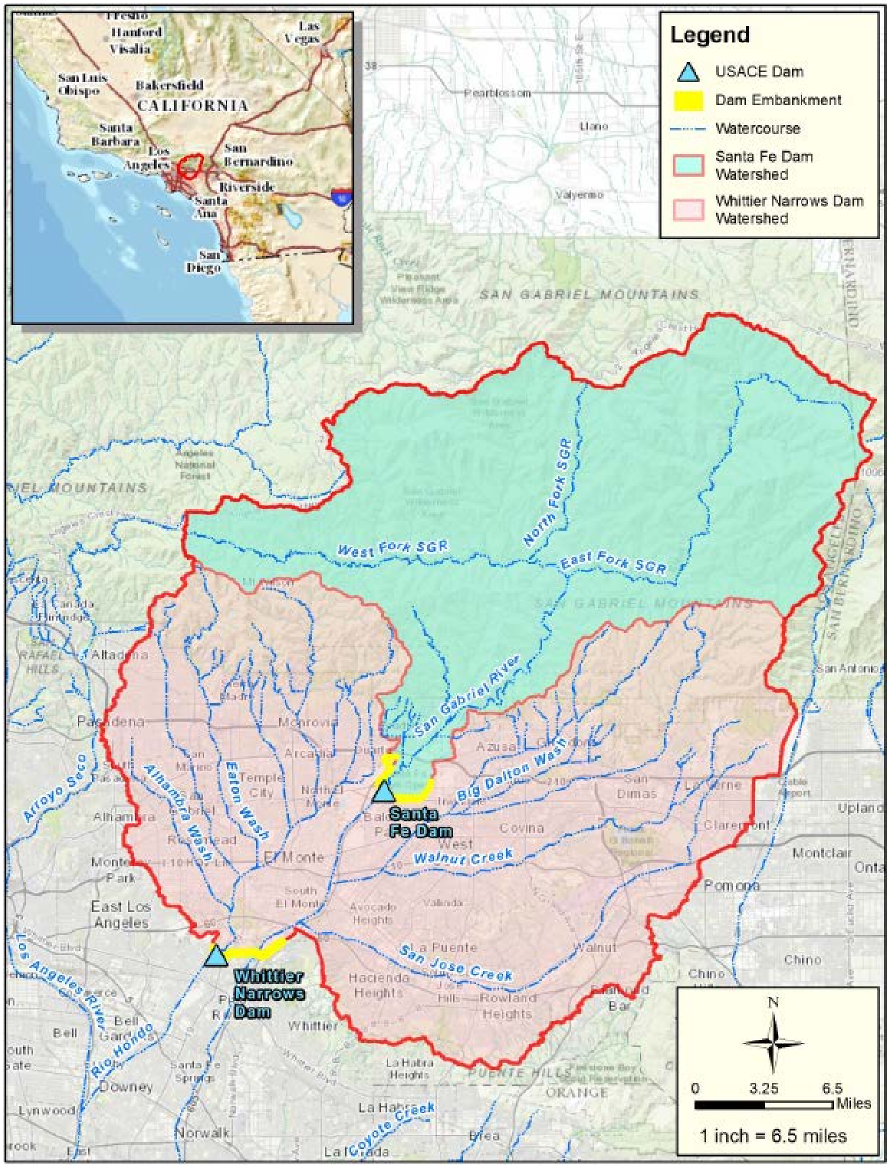

Figure 7. Whittier Narrows Dam watershed.

To appropriately account for the nonlinearity in the rainfall-runoff response in the highly urban and mountainous Whittier Narrows watershed, precipitation-frequency events were routing using a combination of HEC-HMS and HEC-RAS 2D. More specifically, HEC-HMS was used to determine the excess rainfall-volume from the frequency-based rainfall. Then, HEC-RAS 2D was used to hydrodynamically route the excess rainfall-volume and baseflow to the reservoir. Figure 9 depicts the workflow for estimating the reservoir stage-frequency curve for Whittier Narrows Dam. For more information on the Whittier Narrows Dam study, please see *Smith et al.* (2018).

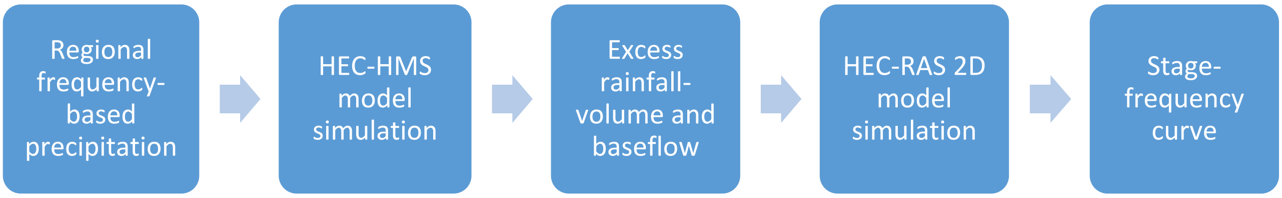

Figure 8. Workflow for estimating the reservoir stage-frequency curve for Whittier Narrows Dam.

An RMC-RFA model was developed as part of the Whittier Narrows Dam study. The inflow volume-frequency curve was developed using systematic records from 1956 to 2016. The 1938 and 1943 historical flood events were included using Bulletin 17C procedures (U.S. Geological Survey, 2017). In addition, regional skew information (U.S. Geological Survey, 2011) was used to weight the at-site skew estimate. The same reservoir stage-discharge relationship as used in the HEC-HMS and HEC-RAS models was used in RMC-RFA.

The comparison of stage-frequency results for Whittier Narrows Dam using RMC-RFA and the aforementioned precipitation-frequency based method is provided in Figure 10. The inflow volume-based expected stage-frequency curve and the expected precipitation-based frequency curve are nearly identical to one another. When the stage-frequency curves exceed the top of dam, the volume-based expected stage-frequency curve becomes more frequent than the precipitation-based curve.

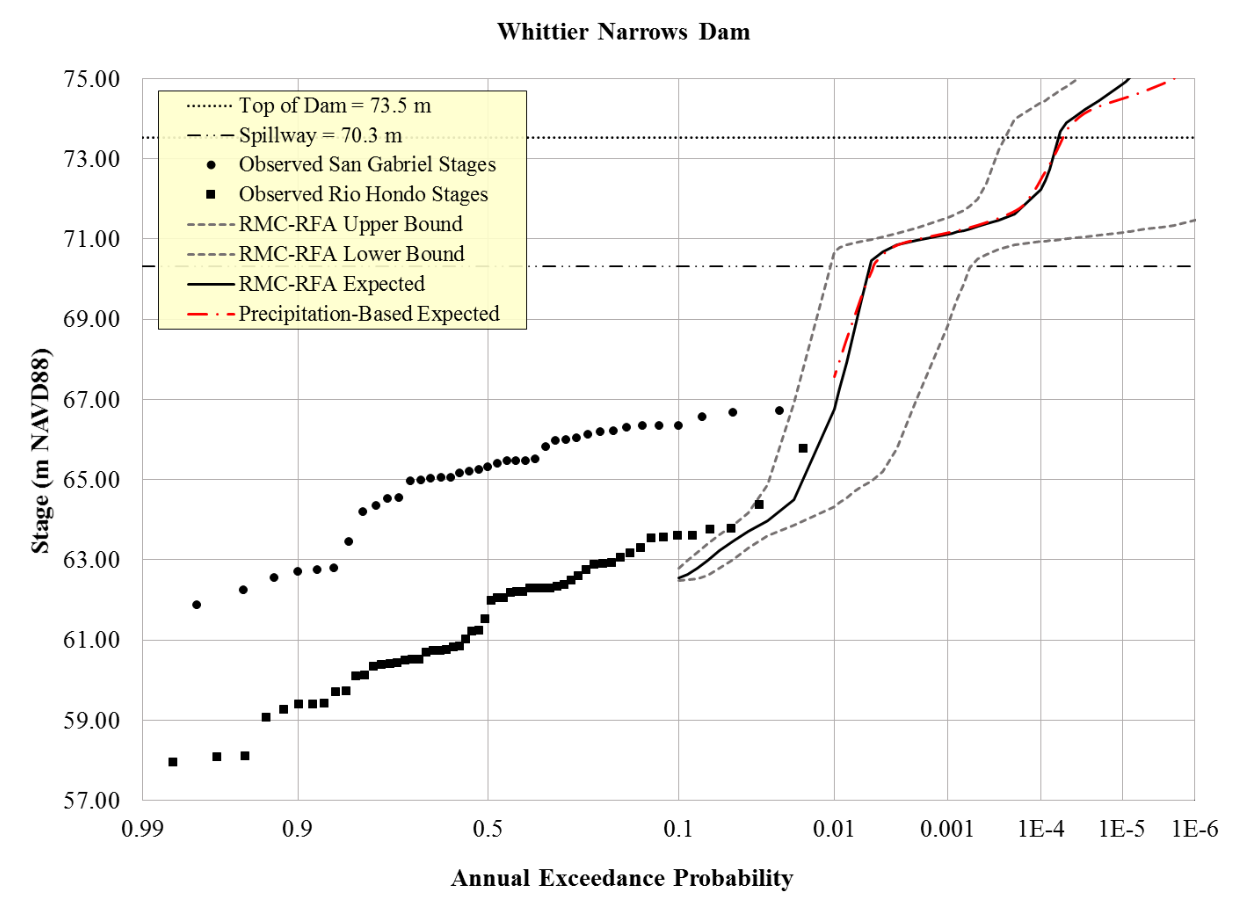

Figure 9. Comparison of stage-frequency results for Whittier Narrows Dam using RMC-RFA and regional precipitation-frequency analysis. The figure shows the 90% confidence intervals and the expected probability curve produced by RMC-RFA. Only the expected curve from precipitation-frequency based results is shown.

Willamette River Basin

The Willamette River Basin is located in Oregon. The Willamette River and its watershed lie in the greater Cascades Geological Province, which extends from British Columbia to northern California. The river has a watershed area of approximately 29,730 km^2. The watershed runoff fluctuates dramatically with heavy precipitation in the winter months, snowmelt in the spring months, and relatively rain-free summers. The Willamette River Basin contains 13 USACE dams and reservoirs, which provide flood damage reduction, hydropower, water supply, navigation, recreational, and environmental benefits. The flood control reservoirs are operated as a system to provide storage during the rainy winter months of November to February. A map of the watershed showing the locations of USACE dams is provided in Figure 11.

Stage-frequency curves were developed for seven high priority dams located in the Willamette River Basin: Blue River, Cougar, Fall Creek, Foster, Green Peter, Hills Creek, and Lookout Point Dams. Each dam is located on a major tributary to the Willamette River, which flows from south to north to meet the Columbia River near Portland, Oregon (Figure 11).

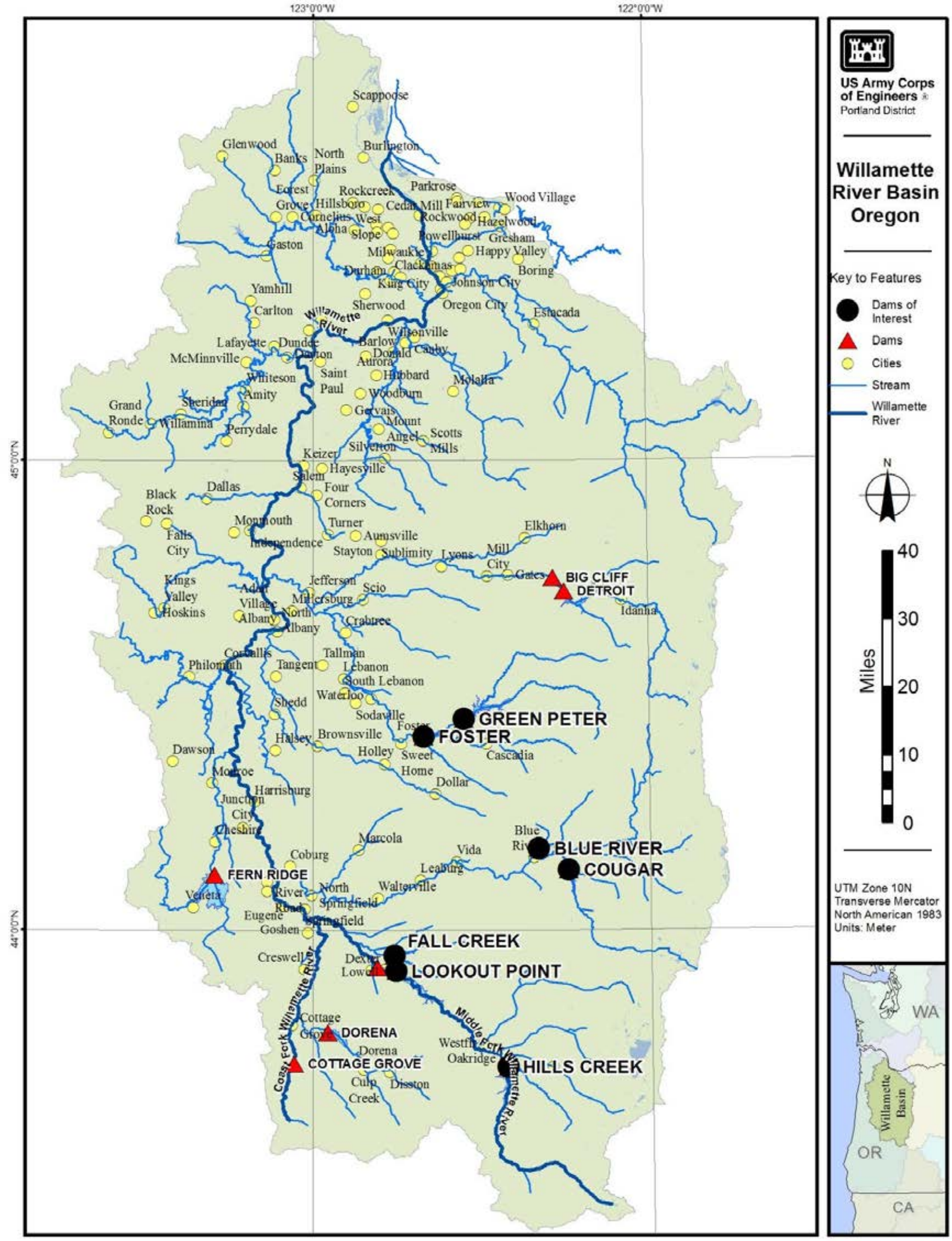

Figure 10. Willamette River Basin

To accurately model the runoff response in the watershed, the hydrologic hazard was modeled using a system-wide stochastic rainfall-runoff approach using the Watershed Analysis Tool (HEC-WAT). HEC-WAT is a software application that can be used to "link" software together in a user-defined compute sequence. The Flood Risk Analysis (FRA) compute option in HEC-WAT uses a similar stochastic simulation framework as RMC-RFA: natural variability is simulated in the inner loop defined as a realization, which comprises many thousands of events, while the knowledge uncertainty is simulated in the outer loop, which comprises many realizations.

For the stage-frequency curve analysis, stochastic precipitation events were sampled using the FRA compute option and routed using the rainfall-runoff model, HEC-HMS. Runoff hydrographs were passed from HEC-HMS to the reservoir simulation model, HEC-ResSim, which then routed the inflow while making reservoir release decisions based upon the complex operational rules. In the HEC-WAT study, the basin-average precipitation-frequency relationship was developed through regional analyses. For more information on the Willamette Basin study, please see *Duren et al.* (2018).

An RMC-RFA model was developed for all seven reservoirs as part of the Willamette Basin study. The inflow volume-frequency curve was developed using systematic records from 1928 to 2008. Since the HEC-WAT analysis focused on the rainy winter season, starting pools were restricted to only occur between the months of November to February. The reservoir stage-discharge relationship was developed using the existing HEC-ResSim models.

The comparison of stage-frequency results for Green Peter Dam[5] are provided in Figure 12. As can be seen, the RMC-RFA model is capable of matching the trend of the observed stages. However, RMC-RFA predicts spillway and top of dam exceedance probabilities that are two orders of magnitude more frequent than the HEC-WAT results. Though, the HEC-WAT results are still within the RMC-RFA uncertainty bounds. It is important to note that the inflow volume-frequency curve had an effective record length of 80 years. Whereas, the regional precipitation-frequency analysis resulted in nearly 500 years of effective record length. Consequently, the HEC-WAT results provide confidence that the overtopping exceedance probability is less than 1 x 10^{-6}. The comparison for the remaining six dams are similar to Green Peter Dam, in that the HEC-WAT results are less frequent that RMC-RFA, but contained within in the uncertainty bounds.

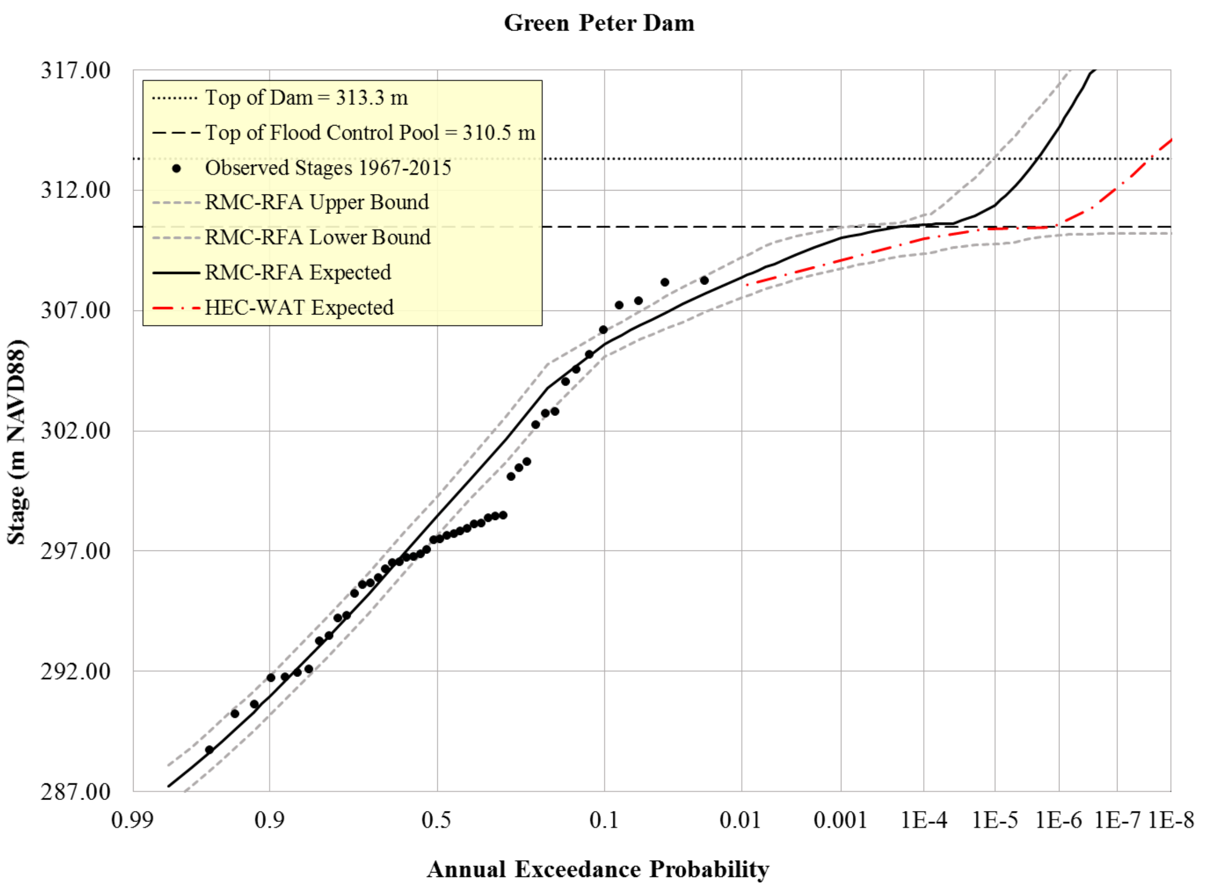

Figure 11. Comparison of stage-frequency results for Green Peter Dam using RMC-RFA and HEC-WAT. The figure shows the 90% confidence intervals and the expected probability curve produced by RMC-RFA. Only the expected curve from the HEC-WAT results is shown.

[5] The Willamette River Basin study was still ongoing when this paper was written. As such, the results presented herein are subject to change. For a final draft of the Willamette River Basin report, please contact the author.

Assessing the value of more advanced analysis

Table 2 lists the estimated study duration (in hours) required to perform a typical stage-frequency analysis using RMC-RFA (*Smith et al.* 2018). The time estimates reflect the effort required for both production and documentation. It is assumed that the hydrologic engineers performing the tasks have a background and training in flood hydrology, hydrologic statistics, and hydrologic modeling. When input data is readily available, study duration and cost can be significantly reduced from the estimates listed below.

Table 2. Estimated study duration to perform a stage-frequency analysis using RMC-RFA

Task	Duration (Hours)
Data acquisition	16
Data quality control	8
Empirical stage-frequency analysis	2
Critical inflow duration analysis	4
Inflow volume-frequency analysis	30
Flood seasonality analysis	4
Reservoir starting pool duration analysis	4
Reservoir model development	20
Reservoir stage-frequency analysis with RMC-RFA	30
Peer review	16
Agency review	16
Total:	**150**

As the case studies demonstrate, the inflow volume-based stochastic simulation framework employed by RMC-RFA produces stage-frequency curves that agree well with the more complex and sophisticated precipitation-based methods. The precipitation-based studies presented in the case studies typically require several months to years to complete, and typically cost hundreds of thousands of dollars (USD). This paper shows that comparable results can be achieved for much less effort using RMC-RFA. Furthermore, the results from the precipitation-based methods fall within the RMC-RFA uncertainty bounds, demonstrating the robustness of the simulation framework.

For the purposes of RMC-RFA, natural variability cannot be reduced with more or better information. Whereas, knowledge uncertainty can be reduced with more and better information through means of additional measurement, more detailed studies, data collection, data quality control, filling gaps in missing gage data, and record extension through the inclusion of historical and paleoflood data, or regional analysis, which increases record length by effectively trading space for time.

With this in mind, the RMC-RFA simulation framework lends itself to a value of information approach to risk management, where knowledge uncertainty can be efficiently quantified at a screening-level assessment. Then, the value of performing more complex and sophisticated studies to reduce uncertainty can be evaluated. For example, consider the following risk management scenario:

> *A screening-level assessment using RMC-RFA indicates there is an actionable overtopping failure mode. The cost of an overtopping modification is estimated to be 50 million USD. The inflow record used in the RMC-RFA analysis is limited and only 50 years in length, which results in wide uncertainty bounds that heavily influence the risk estimates. Therefore, to reduce uncertainty in the estimated top of dam exceedance probabilities, regional precipitation-frequency analysis and stochastic rainfall-runoff modeling is recommended. The cost of the advanced study is estimated to be 2 million USD. Experts predict that there is a 10% chance that the advanced study will show that the proposed modification is unnecessary, Thus, the expected value of the advanced study is estimated to be 3 million USD (5 million minus the cost of the advanced study).*

As the example illustrates, quantifying uncertainty in stage-frequency at a screening-level could potentially result in significant cost savings by avoiding unnecessary modifications as well as unwarranted additional studies.

The level of detail of an advanced study will depend on time, budget, and organizational constraints. As such, it is recommended that advanced studies should have a scalable level of effort. For example, incorporating historical, regional, and paleoflood information into the inflow volume-frequency analysis is relatively inexpensive, but can yield a sizeable reduction in knowledge uncertainty. Regional precipitation-frequency analysis coupled with a stochastic rainfall-runoff model, such SEFM or HEC-WAT, can significantly reduce knowledge uncertainty; however, these sorts of advanced modeling efforts require considerable time and resources, especially for large watersheds. These studies will become much more viable as the stakes get higher, at which point the cost of modification often exceed the cost of more study by several orders of magnitude (*Jongejan*, 2018).

It is important to note that it is often not possible to objectively assess whether a more detailed study is likely to change the decision. Therefore, it is recommended that a panel of hydrologic engineering experts provide their subjective, expert opinions concerning the value of more advanced analysis.

Conclusions

The inflow volume-based stochastic simulation framework employed by RMC-RFA produces stage-frequency curves that strongly agree with the more complex and sophisticated precipitation-based methods. The stochastic simulation framework employed by RMC-RFA provides reliable and robust results with extremely fast run times, on the order of seconds to a few minutes on a desktop PC. This is a dramatic improvement over existing software options which have run times on the order of hours to days and require cloud computing or super computers. The ability of RMC-RFA to provide reliable and accurate flood hazard estimates, combined with its cost saving efficiency, is providing tangible benefits to the USACE safety program.

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