A New Suite of Risk Analysis Software for Dam and Levee Safety

C. Haden Smith | Woodrow L. Fields | Nathan J. Snorteland

Abstract

Over the past few years, the US Army Corps of Engineers (USACE) Risk Management Center (RMC) has developed a robust suite of risk analysis software to support dam and levee safety investment decisions. The tools allow engineers to quickly generate quality flood hazard, consequence, and potential failure mode information, and compute risk analysis results. The tools can interact together as a suite or independently as standalone software. The analysis methods contained within each tool are cost-effective and scalable so practitioners can achieve higher quality results from more advanced study using all of the same tools. Many of these tools were recently released on the RMC website (https://www.rmc.usace.army.mil).

Introduction

The US Army Corps of Engineers (USACE), Risk Management Center (RMC), has developed an integrated suite of software and supporting tools to facilitate risk analyses within the USACE

dam and levee safety programs. These tools comply with USACE policy (US Army Corps of Engineers, 2014) and risk analysis best practices (US Bureau of Reclamation & US Army Corps of Engineers, 2019). The available supporting tools include:

• RMC-QRACalcs – A suite of Microsoft Excel spreadsheets to support quantitative risk assessments for dam and levee safety.
• RMC Risk Calculations Suite – A suite of toolboxes to help risk assessors calculate risks for semi-quantitative and some specialty quantitative risk analyses.
• Specialty calculation tools for spillway erosion, breach parameters, overtopping erosion, seismic analysis, structural analysis, internal erosion, and riverine erosion.
• An integrated desktop and web-based software suite to support dam and levee safety.

Many of these supporting tools and software were recently released and can be downloaded from the RMC website (https://www.rmc.usace.army.mil) under the software tab as shown in Figure 1.

The focus of this paper is on the integrated desktop and web-based software suite. Figure 2 shows a schematic of the software suite and how each tool is envisioned to interact together in support of the overall risk analysis. The flood hazard tools are shown as light blue, consequence software as light orange, the various toolboxes that support potential failure model analysis (PFMA) as light green, and the fully integrated risk analysis software (RMC-TotalRisk) as light red.

Starting from the top of Figure 2, the rainfall-runoff frequency tool (RMC-RRFT) is a web-based application that facilitates calculation of flood hazard curves. The tool allows the user to upload a calibrated HEC-HMS hydrologic model of a watershed upstream of a dam or levee of interest. The RRFT will then automate the extraction of NOAA Atlas 14 precipitation frequency information and perform stochastic flood simulation to compute inflow-frequency relationships. The RMC-BestFit program provides a numerical framework for merging flow-based frequency curves (paleoflood data, at-site gage data, and regional skew information) with rainfall-runoff based inflow frequency curves. The reservoir frequency analysis tool (RMC-RFA) then samples starting reservoir conditions, inflow storm patterns, and inflow frequency relationships to assess stage-frequency relationships or other hydrologic characteristics at a dam.

Consequences can be estimated using LifeSim, which is an easily scalable agent-based flood event consequence estimation simulator. LifeSim simulates the warning and evacuation process to determine the population that would be exposed to flooding and calculates potential fatalities conditional on the hydraulic conditions at each agent's location. In addition to estimating potential fatalities, LifeSim also calculates economic damages to buildings, agriculture, and indirect regional impact.

Finally, the RMC-TotalRisk program combines flood hazards, consequences estimates, and potential failure mode analyses (PFMAs) to calculate risk at dams or levees for use in risk

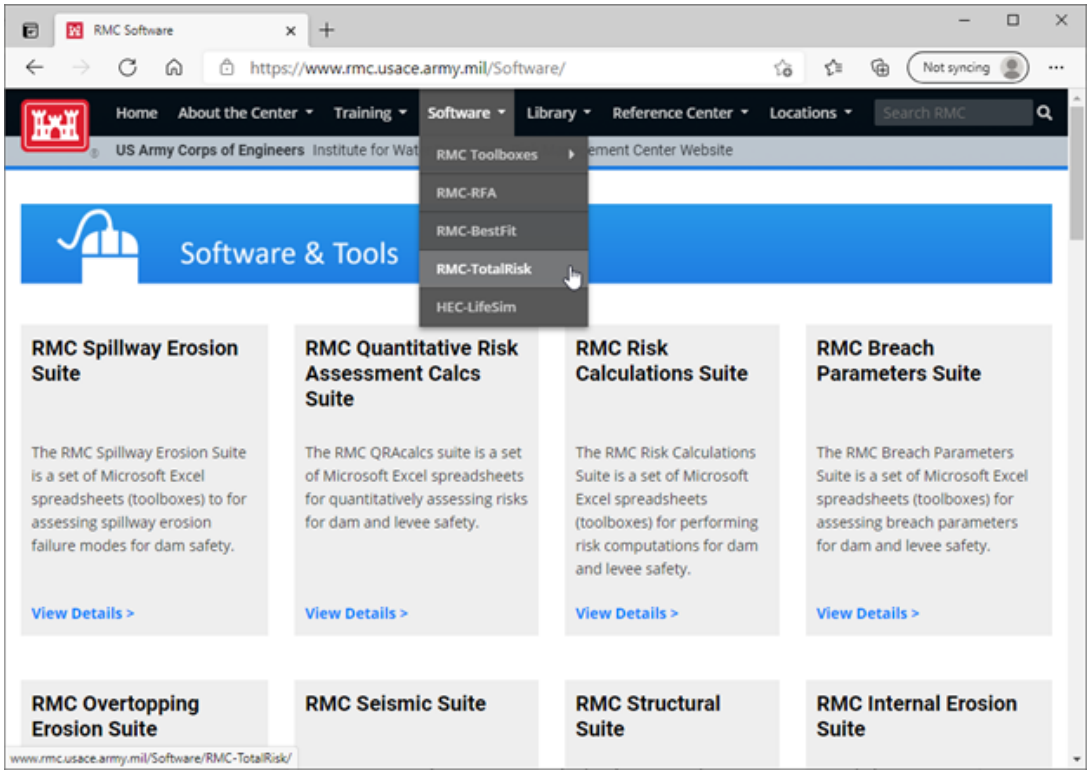

Figure 1. RMC website

informed decision making (RIDM). The long-term vision is to make these tools publicly available to the dam and levee safety community to support RIDM activities throughout the nation.

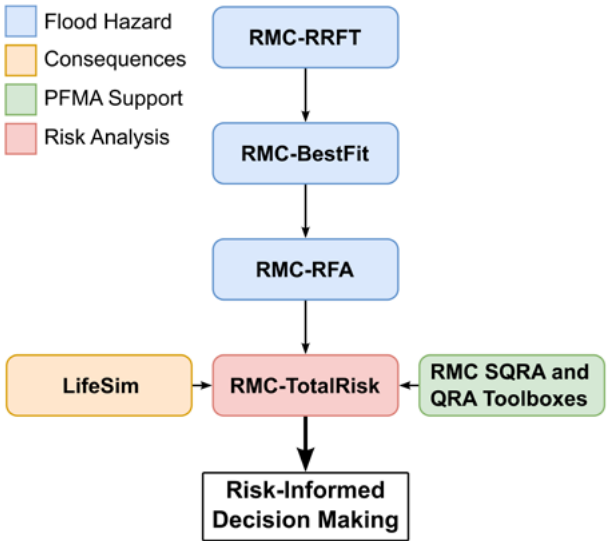

Figure 2. Schematic of the integrated RMC risk analysis software suite

The tools are designed to efficiently generate quality flood hazard, consequence, and risk analysis results. The tools can interact together as a suite or independently as standalone software. The analysis methods contained within each tool are cost-effective and scalable so practitioners can achieve higher quality results from more advanced analyses using all of the same tools. These tools are intended to support our USACE dam and levee safety programs, which includes several hundred dams and levees. However, the tools will work equally well for prioritizing repairs for a single dam owned by a private utility.

The desktop software packages are designed to provide an identical look and feel across software packages, which will reduce the time required to learn new tools. The graphical user interface (GUI) is designed to have a simple workflow with minimal mouse clicks to set up an analysis. The modern design also provides the user with options to customize their workspace. Finally, each software package allows the user to create report quality plots that can be customized, edited, or exported for use in other programs.

The standard desktop GUI consists of a menu bar, tool bar, and four window panes. Starting from the left in Figure 3 and moving clockwise, there is a project explorer (left), document window (center), properties window (right), and the message window (bottom). The documents can be tabbed, grouped, or undocked and moved to another monitor to maximize the user's workspace and increase flexibility.

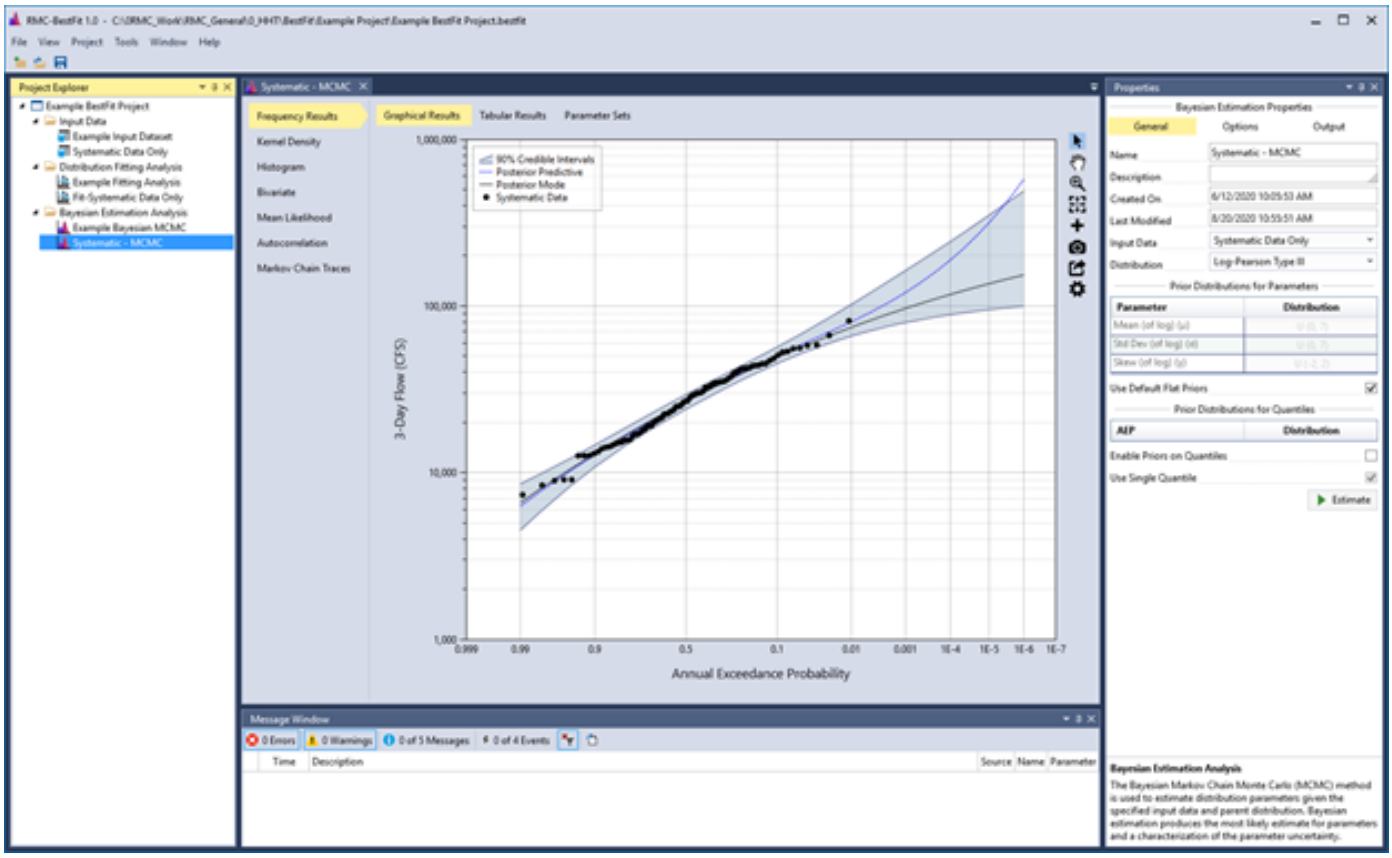

Figure 3. Standard RMC desktop software user interface

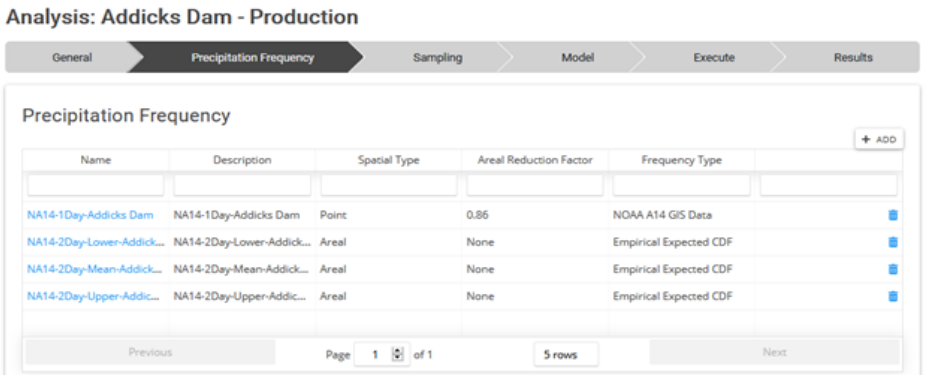

Figure 4. RMC-RRFT interface workflow

The following sections provide an overview of each software tool in the RMC suite and includes a discussion on future developments.

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[1] (Smith et al., 2018). 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.

[1] The RMC-RRFT, -BestFit, and -RFA are software for estimating exceedance probabilities for floods. Probable Maximum Precipitation and Flood (PMP/PMF) information is not used as inputs to the statistical analysis in these tools. However, results from RRFT, BestFit, and RFA can be used to estimate the exceedance probability of the PMP/PMF for a dam or levee. The PMP/PMF are not directly used in risk analysis calculations. However, they are used to rule out potential failure modes. For example, if the dam comfortably passes the PMF, the overtopping failure mode is typically ruled out and considered to be not actionable.

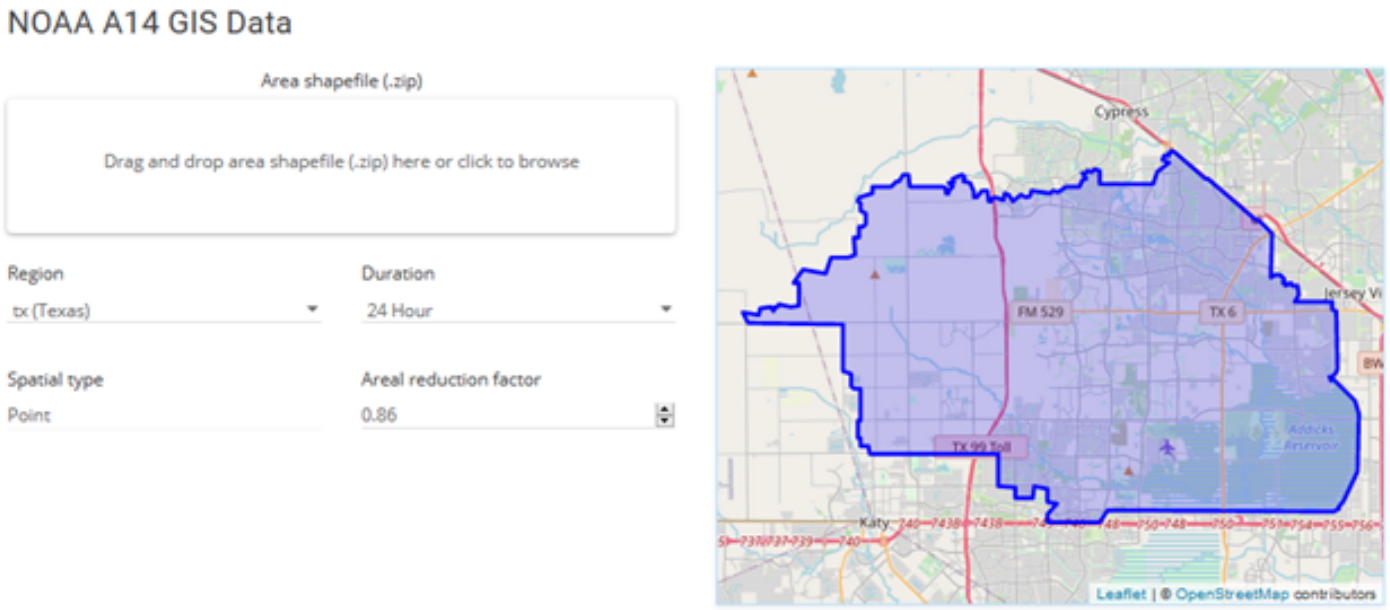

Figure 5. RMC-RRFT interface for processing NOAA Atlas 14 point precipitation-frequency data

To address these challenges, the RMC developed the rainfall-runoff frequency tool (RMC-RRFT), which is a web-based stochastic flood modeling software for developing flood hazard curves. The RRFT provides an intuitive step-by-step process for flood hazard curve development, as shown in Figure 4. At the top of the screen, the user is provided with arrowed tabs that walk them through the process.

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[2] 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 5. 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.

Next, the user can select a Monte Carlo sampling plan, upload their calibrated HEC-HMS model, and then execute the stochastic simulation. The RRFT can produce reservoir inflow, outflow, and stage-frequency curves for use in risk analyses. In addition, the results from RMC-RRFT can also be combined with RMC-BestFit and RMC-RFA to improve the estimated flood hazard curves at the dam, as will be discussed in the following sections. For greater details on the RRFT workflow please see (Denno & Smith, 2021).

The RRFT represents a considerable advancement in flood hazard analysis technology. We can now perform large scale stochastic simulations 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.

In January 2021, version 1.0 of RRFT was released internally within USACE. The goal is for the RRFT to be available to other organizations, both public and private, by the end of 2022. In the near term, enhancements are being made to improve the runtimes and the interaction with the Hydrologic Engineering Center's (HEC) software libraries for better error management. Other planned enhancements include additional uncertainty analysis capabilities and improved visualization of results.

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

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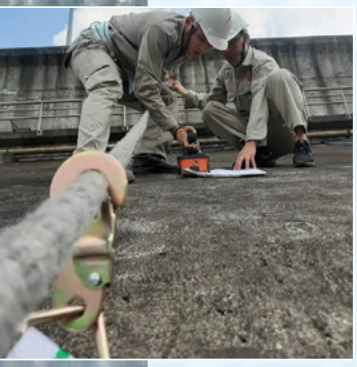

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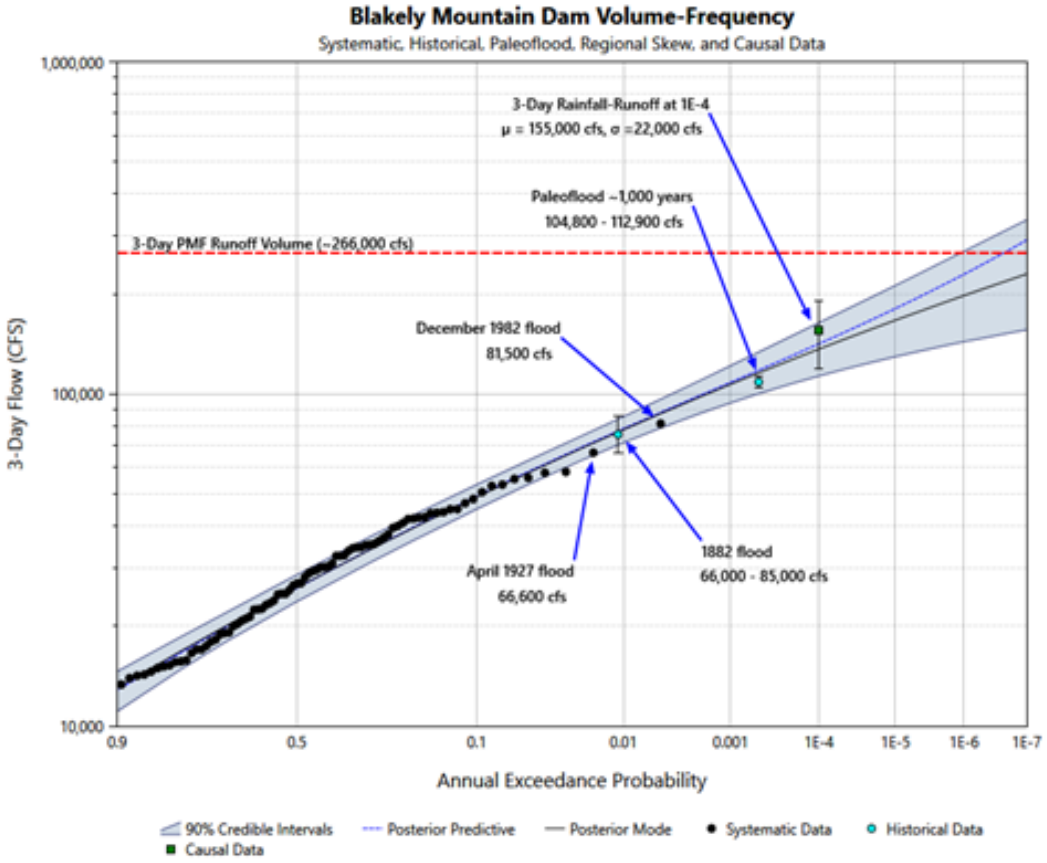

Figure 6. An example flood frequency curve from RMC-BestFit software

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. BestFit is a menu-driven software package, which performs distribution fitting and uncertainty analysis from a choice of thirteen probability distributions.

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 gage data, and record extension. With BestFit, we can also reduce uncertainty by specifying our prior knowledge on the parameters through expert elicitation, rainfall-runoff modelling, or regional analysis.

Figure 6 shows an example of a flood frequency analysis that combines at-site data, historical data, regional skew information, and rainfall-runoff results from RMC-RRFT. The resulting frequency curve provided high confidence in our estimates of exceedance probabilities for the design flood and the overtopping failure mode at the dam. With the use of BestFit, we were able to assess that the risk of failure at the dam was below tolerable risk guidelines. For more detailed discussion on combining data with RMC-BestFit, please see (Smith & Skahill, 2019).

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 (US Geological Survey, 1982) and Bulletin 17C (US Geological Survey, 2018).

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.

Version 1.0 of RMC-BestFit was officially released in September of 2020, and it is already seeing widespread use within the dam safety community of practice. The software has been shared with the international community as well, and has been used in Canada, Netherlands, and Australia. Future versions of RMC-BestFit will be able to estimate joint distributions, account for land-use changes and climate change, and assess model selection uncertainty.

RMC-RFA

The RMC developed the Reservoir Frequency Analysis software (RMC-RFA) with the primary purpose of estimating reservoir pool stage-frequency curves to support risk assessments in the 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 reservoir stage-frequency analysis on a desktop PC with simulation runtimes on the order of seconds to a few minutes. 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.

RFA utilizes an inflow volume-based simulation framework that treats the seasonal occurrence of the flood, the antecedent reservoir stage, inflow volume, and the inflow flood hydrograph shape as uncertain variables rather than fixed values (Smith et al., 2018; Smith & England, 2017).

The inflow volume-based simulation framework employed by RFA produces stage-frequency curves that strongly agree with the more complex and sophisticated precipitation-based methods, as shown in (Smith, 2018). 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.

Since RMC-RFA was first released in 2017, it has been used to model over 300 dams in USACE, including USACE's largest reservoir, Garrison Dam in North (Melliger et al., 2021). It has also been used by the US Bureau of Reclamation for evaluating the flood hazard at Shasta Dam in California, which is one of the tallest dams in the nation (Dworak et al., 2019).

Version 2.0 of RMC-RFA is currently under development. The next version will be able to import results from RMC-BestFit, transform unregulated inflows, simulate complex reservoir operations, and evaluate levee stage-frequency to support the levee safety program.

LifeSim

The RMC in association with HEC developed a modern implementation of LifeSim for the primary purpose of estimating life loss and economic damages from flood events. The key component of the LifeSim methodology is that the magnitude of life loss depends on whether people evacuate successfully and whether those who fail to evacuate can find adequate shelter (Aboelata et al., 2003). LifeSim explicitly models the warning and evacuation of people during a flood and predicts the spatial distribution of fatalities within buildings and on roads. It uses an agent-based approach to track individuals throughout the warning and evacuation process. Although LifeSim was developed for dam and levee safety analyses, the software is not limited to breach flood hazards (US Army Corps of Engineers, 2018).

LifeSim employs Monte Carlo sampling techniques to capture uncertainty in various parameters that influence loss of life from flooding resulting in a distribution of potential outcomes (Figure 7). Many model parameters can be defined with uncertainty, including but not limited to structure stability criteria, hazard identification time, hazard communication time, warning diffusion speed, protective action initiation timelines, and fatality rates for those that are inundated. Details on the methodologies applied in LifeSim can be found in the ***LifeSim Technical Reference Manual*** (US Army Corps of Engineers, 2020).

The LifeSim UI is designed to quickly build an analysis with powerful editing and result viewing capabilities. LifeSim can leverage nationwide datasets such as the National Structure Inventory and OpenStreetMap for rapid model development. It has a built-in GIS map window that can animate the traffic and flood throughout the evacuation process. LifeSim has been

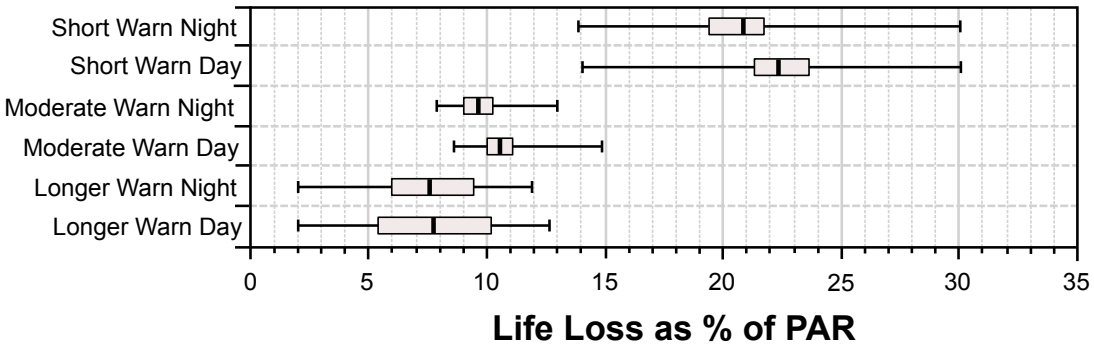

Figure 7. Results from LifeSim showing a distribution of life loss as a percentage of population at risk (PAR) for various warning scenarios

validated against real world events (Needham et al., 2020). Version 2.0 has been Corps certified for use in planning for both life loss and economic damage estimates. LifeSim Version 3.0 will be fully integrated with the RMC desktop suite. Every risk assessment beyond screening-level in the USACE uses LifeSim to estimate consequences. It continues to be used by other US, state, and international agencies.

RMC-TotalRisk

The RMC has developed a comprehensive risk analysis software (RMC-TotalRisk) to support the dam and levee safety programs. RMC-TotalRisk has an intuitive workflow to step the user through the required inputs, including importing flood hazard curves and consequence estimates from RMC-RFA and LifeSim (Figure 2).

Figure 8 shows the RMC-TotalRisk project explorer, which steps the user through the development of a risk analysis. First, the user can manually enter or import flood hazard results from RMC-RFFT, -BestFit, or -RFA. Next, the user can choose to transform the hazard function, which can be useful when the hazard frequency function does not match the system response. For example, the user might want to transform peak flow-frequency to river stage-frequency using a stage-discharge rating curve. Next, the user can develop the system response function using tabular data or the built-in event tree control shown in Figure 9. Finally, users can manually enter or import consequence results from LifeSim.

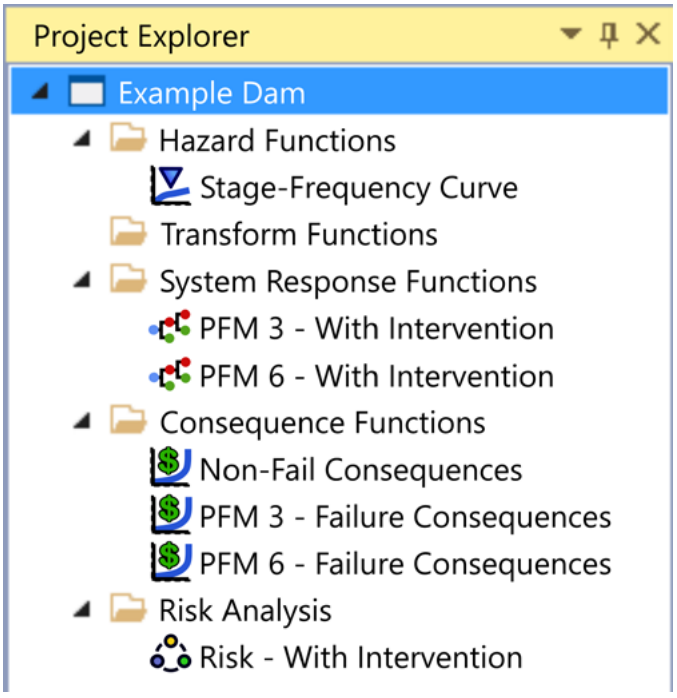

Figure 8. RMC-TotalRisk project explorer

The risk analysis component has an intuitive design that allows the user to quickly add and evaluate the risk of potential failure modes. RMC-TotalRisk is also capable of running a full Monte Carlo analysis, simulating uncertainty in every input, with runtimes on the order of a few seconds to minutes. The software includes several useful output plots, including f-N and F-N plots with tolerable risk reference lines from several different agencies, and other diagnostic plots. And it also includes a sensitivity analysis option so the user can understand the driving inputs and the largest sources of uncertainty.

Conclusions

USACE has developed a robust suite of risk analysis software to support dam and levee safety investment decisions. The tools allow engineers to quickly generate quality flood hazard, consequence, and risk analysis results. The tools can interact together as a suite or independently as standalone software. The analysis methods contained within each tool are scalable, so practitioners can achieve higher quality results from more advanced analyses, using all the same tools.

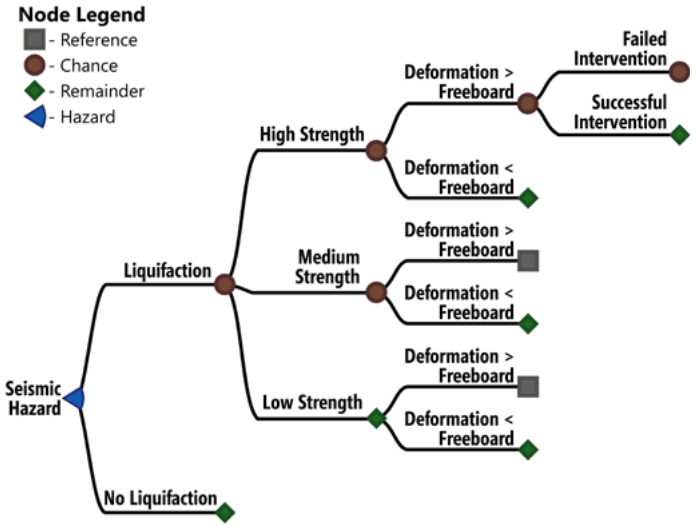

Figure 9. RMC-TotalRisk event tree

There are additional tools in the works as well. The RMC is developing a hydraulic structures design software, RMC-Hydra, to support dam and levee safety modification studies. The timeline of current and future software development is shown in Figure 10.

This software and the accompanying software training courses will be made available to the public. The RRFT is currently under development and for internal use only on USACE servers. However, in the future it will be made available. RMC-BestFit and RMC-RFA have been used for flood hazard analysis by

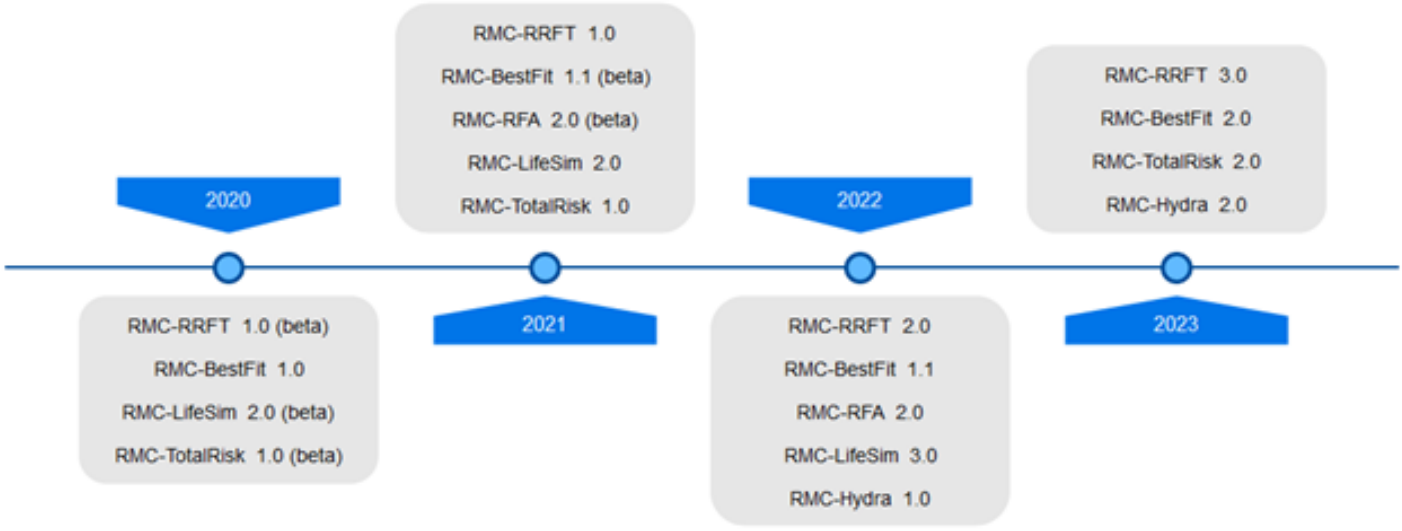

Figure 10. Timeline of software development for calendar years 2020-2023

USACE, USBR, TVA and accepted for use by FERC (Federal Energy Regulatory Commission, 2016). LifeSim is expected to be widely used, both in an outside of the public sector. RMC-TotalRisk is also expected to be widely used in the community of practice once it is officially released.

Acknowledgements

The RMC risk analysis software suite would not exist without support of RMC leadership, in particular the RMC Director, Nathan J. Snorteland, and the RMC lead engineers David Margo and John England. The RMC-BestFit software has been developed in collaboration with Brian Skahill (ERDC-CHL), who has made significant contributions within USACE toward the advancement of Bayesian estimation methods and tools. The development team would like to also recognize Ruben Jongejan (Risk Management Consulting B.V.), who performed an external peer review of the USACE methodology for assessing hydrologic uncertainty (Jongejan, 2018). His recommendations have served as a catalyst for the development and continued advancement of the risk analysis software suite. The development team is also very grateful to others who have helped contribute to the software.

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C. Haden Smith

Senior Hydrologic Engineer, USACE IWR-RMC

12596 W. Bayaud Ave. Suite 400 • Lakewood, CO 80228 • 303-963-4575 • cole.h.smith@usace.army.mil

Haden Smith is a senior hydrologic engineer with the USACE Risk Management Center. His experience in this position includes developing and advancing risk methodology, performing flood hazard assessments for high priority dams and levees, and developing risk analysis software such as RMC-BestFit, -RFA, and -TotalRisk. Mr. Smith obtained a Bachelor of Science degree in civil engineering from the University of Memphis, a Master of Science degree in risk management from Notre Dame of Maryland University, and is finishing a Master of Science degree in economics from Colorado School of Mines.

Woodrow Lee Fields

Consequence Specialist, USACE IWR-RMC

609 2nd St Davis, CA 95616 • 530-302-3731 • Woodrow.L.Fields@usace.army.mil

Woodrow Lee Fields is a consequence specialist with the USACE Risk Management Center. Woodrow is the lead developer of LifeSim, which is a detailed consequence modelling system for estimating economic damages and life loss through simulated warning and evacuation combined with flood wave propagation. Woodrow obtained a Bachelor of Science degree in environmental science from Portland State University in 2005 and a Master of Science degree in civil & environmental engineering from the University of California, Davis in 2009.

Nathan J. "Nate" Snorteland, M.S., P.E.

Director, USACE IWR-RMC

12596 W. Bayaud Ave. Ste.400 • Lakewood, CO 80228 • (303) 963-4573 • nathan.snorteland@usace.army.mil

Nate Snorteland has been with the Corps of Engineers as the director of the Risk Management Center since 2009. In this role, Mr. Snorteland is responsible for managing risks for the Corps of Engineers portfolio of more than 740 dams and 15,000+ miles of levees. Mr. Snorteland's background includes experience designing and constructing a wide variety of dams across the United States. He has experience with grouting, RCC, seismic analysis, and embankment dam construction, culminating with being a designer and construction engineer for Ridges Basin Dam, a 275-foot-high pump-storage dam in Southwest Colorado. Following his work as a designer and construction engineer, he worked in the dam safety program for the Bureau of Reclamation in a variety of roles. He was Reclamation's project manager and lead engineer for the Joint Federal Project, a $1.6 Billion flood risk management and dam safety project at Folsom Dam in California. He specializes in risk assessment and risk management and developed risk management strategies for both Reclamation and the Corps of Engineers. Since coming to the Corps of Engineers, he has led efforts related to risk, risk analysis, risk management, portfolio management, design standards, and risk-informed design. He sits on the Dam and Levee Safety committees for USSD and the Journal Committee for ASDSO. He holds a B.S. in civil engineering from the University of Colorado, Denver and a M.S. in geotechnical engineering from Virginia Tech. He is a registered professional engineer in the State of Colorado.

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