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A New Quantitative Risk Analysis Software for Dam and Levee Safety, RMC-TotalRisk

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ABSTRACT

The U.S. Army Corps of Engineers (USACE) Risk Management Center (RMC) introduces RMC-TotalRisk, an advanced risk analysis software designed to facilitate decision-making in dam and levee safety investments. This comprehensive tool streamlines the user experience with an intuitive workflow that guides users through the necessary inputs. It seamlessly integrates flood hazard curves from RMC-BestFit, RMC-RFA, and RMC-RRFT, as well as consequence estimates from LifeSim. Utilizing the built-in event tree tool, RMC-TotalRisk enables the estimation of system response probabilities.

A distinctive feature of RMC-TotalRisk is its capability to conduct a full Monte Carlo analysis, simulating uncertainty in every input. Remarkably, the software achieves this within short runtimes, ranging from a few seconds to minutes. The output includes insightful plots and diagnostics, offering users valuable insights. Furthermore, the software incorporates a sensitivity analysis option, allowing users to discern key inputs and identify primary sources of uncertainty. RMC-TotalRisk stands as a powerful tool that significantly enhances and expedites quantitative risk analyses, ultimately contributing to more informed and effective investment decisions in dam and levee safety.

I. INTRODUCTION

The U.S. Army Corps of Engineers (USACE) Risk Management Center (RMC) developed the quantitative risk analysis software, RMC-TotalRisk, to enhance and expedite risk assessments within the Flood Risk Management, Planning, and Dam and Levee Safety communities of practice.

RMC-TotalRisk is a menu-driven software that performs risk analysis from user-defined hazard, system response, and consequence functions. The software features a fully integrated modeling platform, including a modern graphical user interface, data entry capabilities, and report-quality charts and diagnostics. The RMC-TotalRisk software is part of a comprehensive RMC risk analysis software suite [1]. Figure 1 below illustrates a schematic of the software suite and how each tool is envisioned to interact together in support of a project's overall risk analysis.

Flood hazard information can be estimated with the stochastic rainfall-runoff frequency tool (RRFT), the Bayesian estimation and fitting software (BestFit), and/or the reservoir frequency analysis software (RFA), and then imported into RMC-TotalRisk. These flood hazard tools are designed to work together or independently. For example, results from RRFT can be incorporated into BestFit or entered directly into TotalRisk. Various semi-quantitative (SQRA) or quantitative risk assessment (QRA) toolboxes that support potential failure mode analysis (PFMA) can be used to estimate system response probabilities. Consequences can be estimated with and imported from LifeSim. RMC-TotalRisk then combines the hazard, system response, and consequences to calculate the system risk.

RMC-TotalRisk can perform risk analysis for a single component, such as a dam or levee, or a complex system with multiple components, where each component can have multiple failure modes. While RMC-TotalRisk was primarily developed for dam and levee safety applications, the software is not limited to just flood risk management applications. RMC-TotalRisk is a general-purpose risk analysis software, capable of estimating risk for any system with fewer than 20 components.

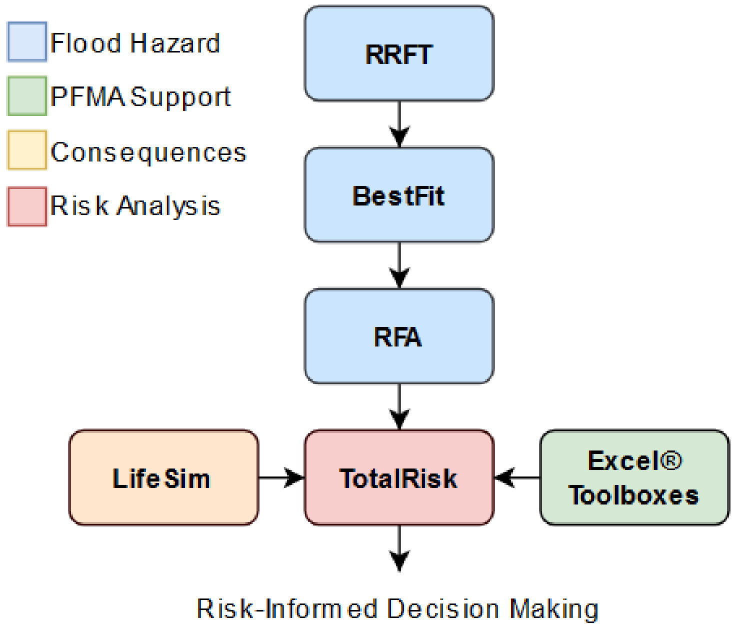

Figure 1. Schematic of the RMC risk analysis software suite.

II. OVERVIEW OF THE RISK ANALYSIS FRAMEWORK

Risk has various definitions and interpretations among different industries, but it is generally understood to be the expected value of the consequences of an uncertain event, $\mathbb{E}[C]$. This expected value is calculated by multiplying the probability of the event occurring by the magnitude of its consequences. Mathematically, it can be expressed as:

$$\mathbb{E}[C] = \sum_i P_i \cdot C_i \tag{1}$$

where P_i is the probability of the i-th event occurring and is the consequence or impact of the i-th event. In dam and levee safety, the risk is often calculated based on discrete hazardous flood or seismic events that serve as external loading conditions on a dam or levee structure. For example, the risk of failure using discrete hazard events is calculated as follows:

$$\mathbb{E}[C_F] = \sum_i P(x_i) \cdot P(F|x_i) \cdot C_F(x_i) \tag{2}$$

where $P(x_i)$ is the probability of the hazard level x_i for the i-th event; $P(F|x_i)$ is the conditional probability of failure given the hazard level; and $C_F(x_i)$ is the consequence of failure given the hazard level. Equation 2 is often written semantically to convey the risk equation as:

$$Risk\ of\ Failure\ = P(Hazard) \times P(Failure|Hazard) \times Consequences\ of Failure \tag{3}$$

where the risk of failure is equal to the probability of the hazard level, $P(Hazard)$, multiplied by the probability of failure given the hazard level, $P(Failure|Hazard)$, multiplied by the consequences of failure at the hazard level, $Consequences\ of Failure$.

In the risk analysis of dams and levees, the annual maximum water surface elevation (WSE) is typically the primary loading parameter for evaluating a potential failure mode (PFM) [2]. Other parameters such as discharge, duration, and velocity can also be important for certain failure modes, such as spillway erosion failure for a dam. The probability of failure is often conditional on the magnitude of the WSE, typically referred to as the hydrologic loading or flood hazard level. The consequences of failure are also a function of the WSE at the time of failure, the breach outflow, and the corresponding reservoir volume or river flood volume.

A typical risk analysis process for a levee is shown in Figure 2 below. Beginning in the top left of the figure, the flood hazard is a peak flow-frequency distribution estimated using flood-frequency analysis methods. Next, moving to the top right, peak flow is transformed into a WSE using a stage-discharge rating curve, which is estimated using a hydraulic model. Then, moving to the bottom right, the probability of failure given WSE is estimated, often derived from engineering analysis and expert elicitation methods. Finally, moving to the bottom left, the consequences given failure are estimated as a function of WSE. The expected annual consequences are computed by integrating over these functions, following equation 2. Greater details on the mathematics of risk analysis are provided in the technical reference manual [3]. Additional details on risk analysis for flood risk management can be found in [4], [5], and [6].

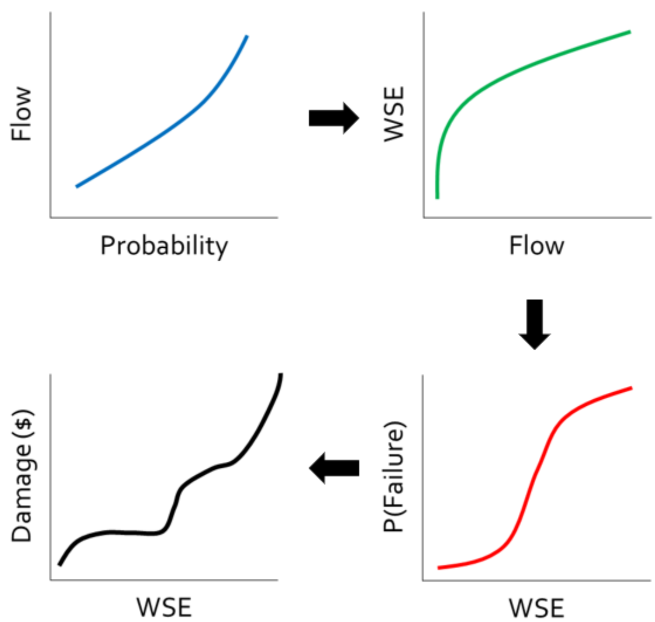

Figure 2. Levee risk analysis process for a single failure mode and a single system component.

III. MODEL INPUTS

Figure 2 illustrates the key inputs for a single failure mode for a single system component, in this case, a levee. These inputs are as follows: 1) hazard function (top left), 2) transform function (top right), 3) system response function (bottom right), and 4) consequence function (bottom left). In RMC-TotalRisk, the input functions can be defined with either parametric or nonparametric methods. Additionally, these functions can be specified with or without uncertainty. The following subsections provide details on the inputs and the available options for each. Complete details are provided in [3] and [7].

A. Hazard Functions

A hazard function is a probability distribution that describes the exceedance probabilities of various hazard levels, commonly referred to as frequency curves. Examples include peak flow-frequency, reservoir pool stage-frequency, and seismic hazard curves. There are several ways to create a hazard function in RMC-TotalRisk:

- **RMC-BestFit**: A parametric probability distribution with uncertainty can be imported from the Bayesian estimation and fitting software, RMC-BestFit. In USACE, BestFit is routinely used for estimating flow-frequency curves because it can incorporate multiple sources of hydrologic information into the fit, such as systematic records, historical and paleoflood data, regional information, and causal rainfall-runoff results. More details on BestFit can be found in [8] and [9].

- **RMC-RFA**: A nonparametric distribution, with or without uncertainty, can be imported from the reservoir frequency analysis software, RMC-RFA. In USACE, RFA is routinely used for estimating reservoir pool stage-frequency curves. More details on RFA can be found in [2] and [10].
- **Parametric**: A parametric distribution can be selected with user-defined parameters, with or without uncertainty. In the latter case, the parametric bootstrap [11] is used to model uncertainty in the parametric hazard function. There are several distributions to choose from, including Generalized Extreme Value (GEV) and Log-Pearson Type III (LPIII). The parametric hazard function option is ideal for importing results from external frequency analysis software, such as HEC-SSP[1]. A plot of a parametric hazard function with uncertainty is shown in Figure 3 below.
- **Nonparametric**: A nonparametric distribution can be defined following the same procedures provided in the flood damage reduction analysis software, HEC-FDA [12]. This option is meant to be backward compatible with legacy software in USACE.
- **Tabular**: A hazard function can be defined with a tabular (or nonparametric) relationship of hazard levels and exceedance probabilities. In many cases, nonparametric flood hazard functions will be derived from external simulation software, such as RRFT, RFA, or SEFM[2]. For seismic hazards, nonparametric functions are often derived from a probabilistic seismic hazard analysis (PSHA) [6]. These externally modelled hazard results can then be entered as tabular data into TotalRisk. Uncertainty in either the hazard level or the exceedance probability can be defined at every ordinate in the table.
- **Composite**: A composite hazard function can be created by assigning weights (or likelihoods) to a list of hazard functions. This option is useful for combining hazard functions for various gate failure or debris blockage scenarios. Alternatively, a composite hazard function can be created where the selected hazard functions compete to produce the maximum event. This option is useful for combining hazard functions when flood events arise from distinctly different and independent processes, such as rainfall and snowmelt.

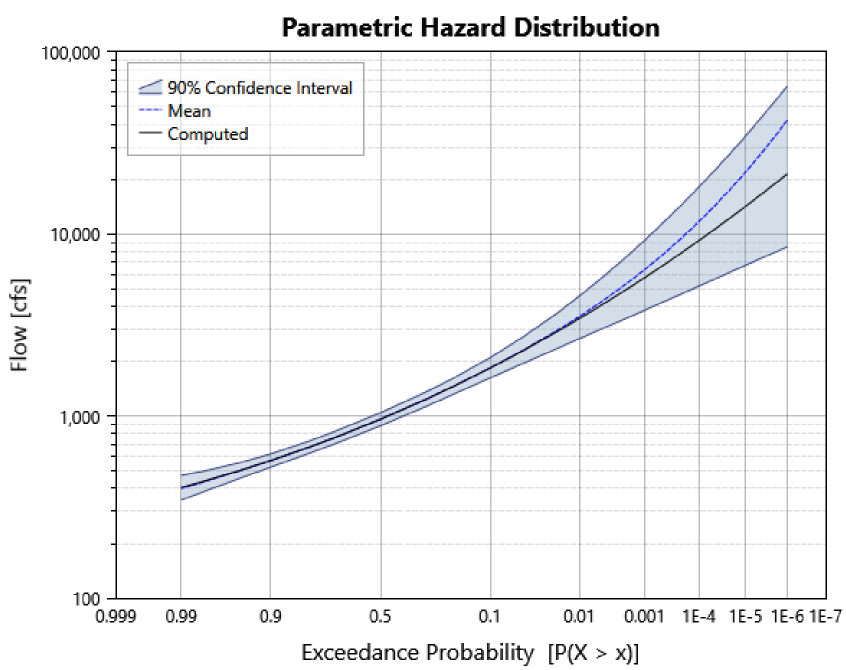

Figure 3. Example of a parametric hazard function.

[1] The Hydrologic Engineering Center Statistical Software Package, HEC-SSP (https://www.hec.usace.army.mil/software/)

[2] The stochastic event flood model (https://mgsengr.com/sefm/)

B. Transform Functions

A transform function can be used to convert hazard levels from one type of function to another. For example, a peak flow-frequency function can be transformed into a stage-frequency function using a flow-to-stage rating curve. Transform functions are not necessary to define a failure mode in RMC-TotalRisk and are optional inputs. The following transform function options are available:

- **Linear**: A transform function can be defined using a simple linear equation. Uncertainty can be defined with an additive error.
- **Power**: A transform function can be defined using a power equation. Rating curves are commonly defined with power functions. Uncertainty can be defined with a multiplicative error.
- **Tabular**: A transform function can be defined using a tabular (or nonparametric) relationship of hazard levels and transformed hazard levels. A flow-stage rating curve will typically be derived by a hydraulic model, such as HEC-RAS. The modeled flow-vs-stage results can then be entered as tabular data into TotalRisk. Uncertainty is defined in the same manner as the tabular hazard function.

C. System Response Functions

A system response function describes the conditional probability of failure for various hazard levels, such as water surface elevations, and is commonly referred to as fragility curves. The system response function defines the failure mode in RMC-TotalRisk.

- **Event Tree**: A response function can be defined using an event tree. Event tree analyses depict how an initiating event, like a flood or earthquake, can lead to various types of failure and damage [13]. An example of an event tree for a seismic failure mode is shown in Figure 4 below. Chance nodes have user-defined probabilities typically estimated through expert elicitation. Users can reference other chance nodes within the same tree, other full event trees, or any other response function in the analysis, allowing for the creation of complex and interdependent event trees.
- **Parametric**: A response function can be defined with a parametric probability distribution, similar to a parametric hazard function.
- **Tabular**: A response function can be defined using a tabular (or nonparametric) relationship of hazard levels and conditional probabilities of failure. Uncertainty can be defined in the same manner as the tabular hazard function.
- **Bivariate**: A bivariate response function provides a way to define a tabular response function that is conditional on two hazards. For example, seismic failure modes for dams are often conditional on the water surface elevation in the reservoir when the earthquake occurs and the peak ground acceleration (PGA) of the earthquake.
- **Composite**: A composite response function can be created by assigning weights (or likelihoods) to a list of response functions. Alternatively, a composite function can be created where the response functions compete to fail first. This option is useful for combining potential failure modes when each has the same consequences.

D. Consequence Functions

A consequence function describes the consequences of failure or non-failure for various hazard levels, such as water surface elevations, and is commonly referred to as damage functions.

- **LifeSim** A consequence function, with or without uncertainty, can be imported from LifeSim, a software for estimating life loss and economic damages. More details on LifeSim can found in [14] and [15].
- **Tabular**: A consequence function can be defined using a tabular (or nonparametric) relationship of hazard levels and consequences. Uncertainty can be defined in the same manner as the tabular hazard function.
- **Composite**: A composite consequence function can be created by assigning weights (or likelihoods) to a list of consequence functions. This option is useful for combining different types of consequences, such as daytime and nighttime impacts, as shown in Figure 5 below. Alternatively, a composite function can be created by summing across a list of consequence functions.

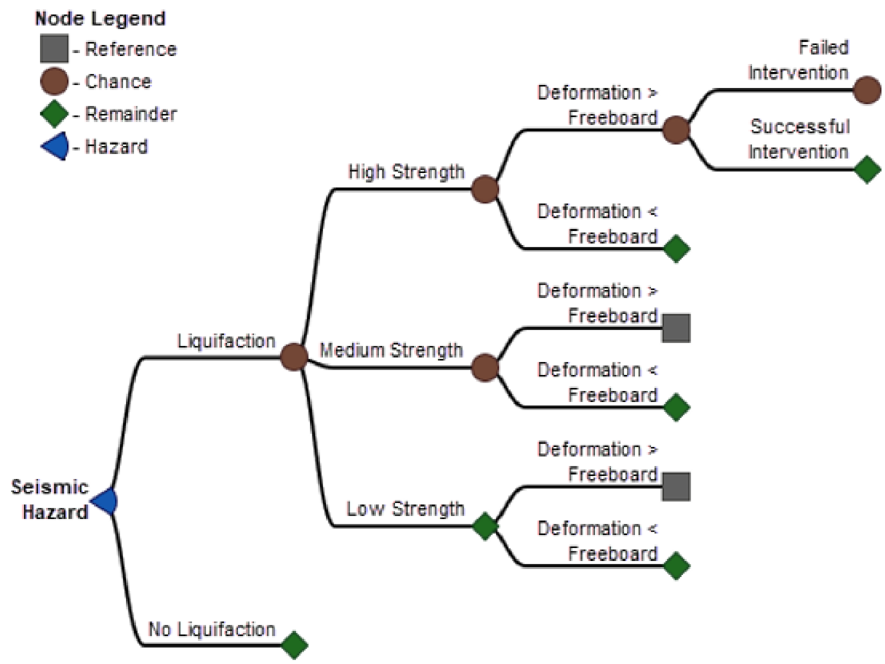

Figure 4. Example of an event tree for a seismic potential failure mode.

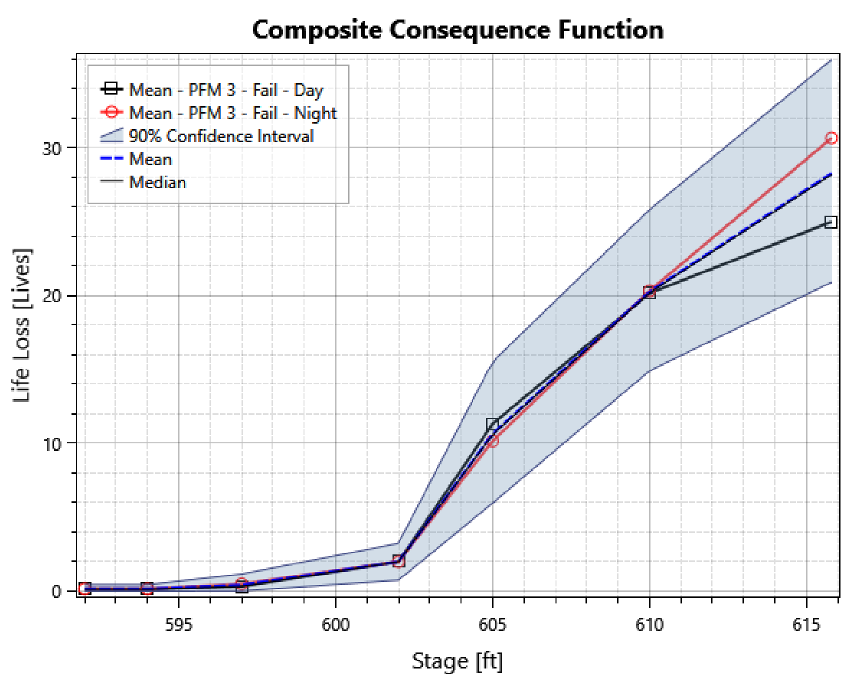

Figure 5. Example of a composite consequence function for day and night losses.

IV. RISK ANALYSIS

A risk analysis in RMC-TotalRisk is defined through a diagram as shown in Figure 6 below. The diagram offers an intuitive approach to create and connect the various components of the modeled system. Figure 6 depicts a single system component for a dam safety risk analysis.

At the top of the diagram in Figure 6, a non-failure mode connects the hazard function to non-failure consequences using a purple connector. This mode assesses scenarios where the dam remains operational but still has consequences, such as activating emergency spillways during major flood events to prevent downstream flooding.

The diagram includes two failure modes:

1. **PFM 1 - Internal Erosion**: Positioned centrally, it connects the stage-frequency hazard at Dam A to the PFM 1 response function and subsequent consequences.
2. **PFM 2 - Overtopping**: Located at the bottom, it is similarly connected to its respective response function and consequences.

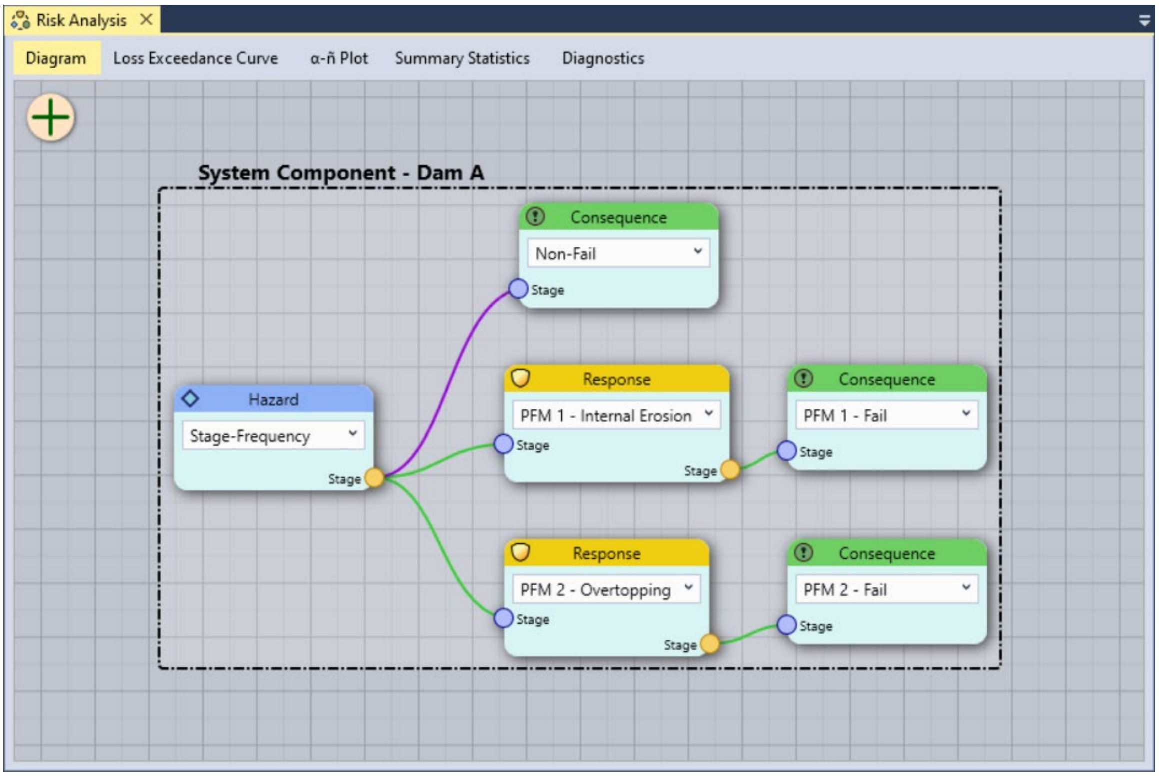

Figure 6. RMC-TotalRisk risk diagram.

Failure modes within each system component are labeled based on the chosen response functions. Multiple failure modes can be combined using one of four numerical options:

1. **Joint Failures**: Multiple failure modes can occur simultaneously during the same event. A joint consequence rule must be selected to specify how the consequences of joint failures are treated. By default, the maximum of the joint consequences is recorded when joint failures occur in the simulation.
2. **Competing Failures**: Multiple failure modes compete to fail first. Joint failures cannot occur during the same event. The system component fails when the first of the competing failure modes reaches a failure state.
3. **Common Cause Failures**: Multiple failure modes are initiated by a common cause, but joint failures cannot occur. This method maintains compatibility with existing risk analysis software.
4. **Mutually Exclusive Failures**: Multiple failure modes are assumed to be mutually exclusive, so joint failures cannot occur. Failure probabilities that sum greater than 1 at a given hazard level are normalized during the risk analysis.

When using the joint failures or competing failures methods, up to 20 failure modes are allowed. However, with the common cause or mutually exclusive options, RMC-TotalRisk permits an unlimited number of failure modes per component. A single system in TotalRisk is limited to 20 components due to virtual memory and computer runtime constraints. For example, complex systems like a watershed comprising up to 20 dams, each with 20 failure modes, can be evaluated.

Dependency between failure modes and system component hazard functions can be defined in TotalRisk, including options for perfectly independent, positively dependent, negatively dependent, or user-defined correlation matrices.

After selecting inputs and dependency options, RMC-TotalRisk computes the risk for each failure mode, the system component, and the overall system. The overall risk and Monte Carlo simulation framework employed by RMC-TotalRisk is illustrated in Figure *7* below. For comprehensive details on the risk analysis framework and simulation options, please refer to the technical reference manual [3].

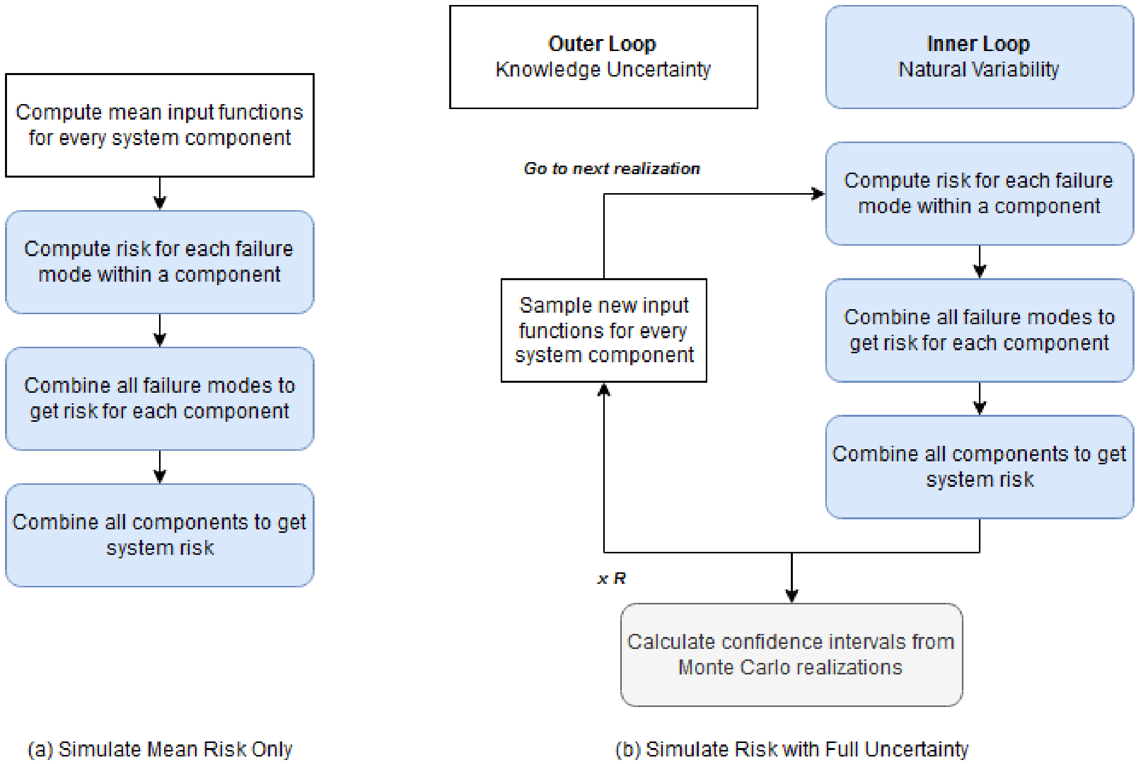

Figure 7. Flowchart of the TotalRisk simulation options: (a) Simulate mean risk only, and (b) Simulate risk with full uncertainty.

E. Risk Results

RMC-TotalRisk estimates five different types of risk: background risk, incremental risk, total risk, failure risk, and non-failure risk. These risk types are crucial for evaluating trade-offs in risk reduction alternatives for dam and levee safety studies. Additionally, TotalRisk provides several more risk measures to support informed investment decisions.

There are three main ways to view the risk results:

1. **Loss Exceedance Curve (LEC)**: This plot shows the exceedance probabilities for a range of consequences, as shown in Figure 8 below. This type of plot is also referred to as a survival function or F-N curve. In a LEC plot, the uncertainty is portrayed as shaded confidence intervals.
2. **$\boldsymbol{\alpha \cdot \tilde{n}}$ Plot**: A more commonly used plot in the USACE dam and levee safety programs is the $\alpha \cdot \tilde{n}$ plot (shown in Figure 9), which plots the conditional expected consequences ($\tilde{n}$) against the probability of failure (α). The diagonal of the $\alpha \cdot \tilde{n}$ plot is equal to the product of α and $\tilde{n}$, which is the expected value of consequences, $\mathbb{E}[\mathrm{N}] = \alpha \cdot \tilde{n}$. In an $\alpha \cdot \tilde{n}$ plot the uncertainty is portrayed as a scatter cloud.

3. **Summary Statistics**: Summary statistics are provided for each risk type being evaluated, as shown in Figure 10. Statistics are provided for each failure mode for each system component, as well as for the full system. The probability of failure for the dam and each failure mode is provided in the column labeled “Probability, α” in Figure 10. The average consequences given failure are provided in the “Conditional Mean, $\tilde{n}$” column. Finally, the average annual consequences are provided in the “Mean, E[N]” column.

Customizable tolerable risk limits (or guidelines) can be displayed on both the LEC and $\alpha \cdot \tilde{n}$ plots. In Figure 9, both failure modes plot below the tolerable risk limits; however, the overall system risk plots above the limit guideline. This is because the variance of the two failure modes increases the conditional expected consequences ($\tilde{n}$) of the overall system risk. Reducing the risk of the overtopping failure mode, PFM 2, which plots in the bottom right, will do the most to reduce the conditional expected consequences and overall risk at the dam.

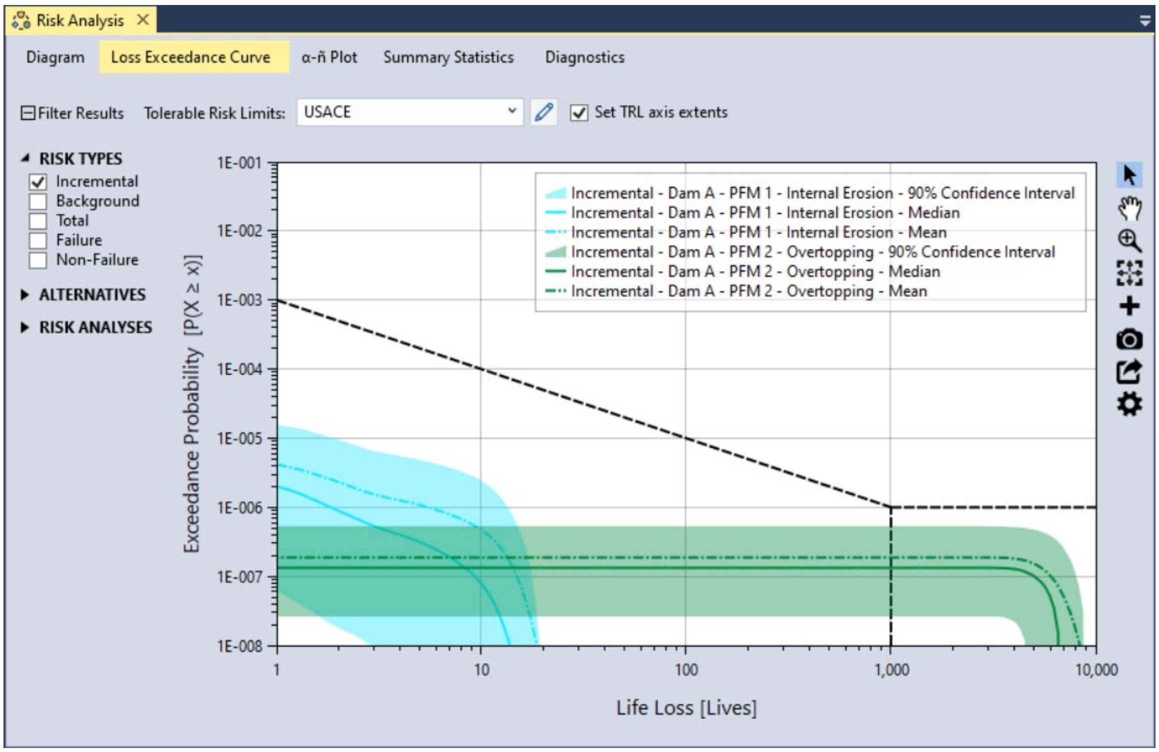

Figure 8. RMC-TotalRisk output loss exceedance curves for PFM 1 and 2.

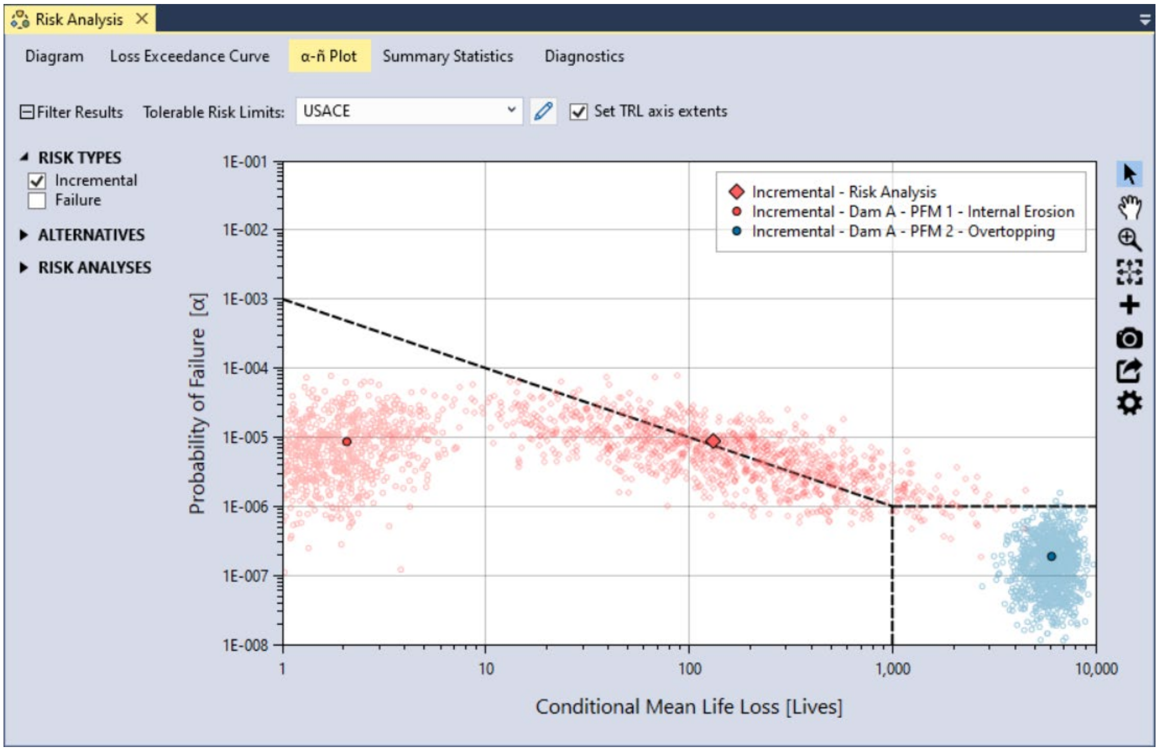

Figure 9. RMC-TotalRisk output α-ñ scatter plot for risk results.

Component	Risk Type	Probability	Conditional Mean, ñ	Mean, E[N]	Std Deviation, σ
Dam A	Incremental	8.8002E-006	131.5019	1.1572E-003	2.3986E+000
Dam A - PFM 1 - Internal Erosion	Incremental	8.6123E-006	2.0742	1.7863E-005	8.2366E-003
Dam A - PFM 2 - Overtopping	Incremental	1.8795E-007	6,062.1303	1.1394E-003	2.3986E+000

Figure 10. RMC-TotalRisk summary statistics for risk results.

F. Diagnostics

RMC-TotalRisk provides several diagnostic options for exploring Monte Carlo simulation results for a risk analysis. If no uncertainty has been defined in the risk analysis inputs, the diagnostic tools provide limited value. However, if uncertainty has been included, some of the diagnostic features include the following:

- **Kernel Density Plot:** Understand the shape and distribution of various risk measures.
- **Risk Profile:** Plots the cumulative expected consequences against increasing hazard levels. This plot is useful for identifying critical hazard levels where risk sharply increases.
- **Tornado Plot:** Shows how sensitive the risk results are to the input functions at each hazard level. The inputs are ranked from most sensitive at the top to least sensitive at the bottom, as shown in Figure 11 below.
- **X-Y Plot:** Assesses the correlation between the system risk results and an individual input component, such as a failure mode.
- **Tabular Results:** Presents a column for each system component and a row for each Monte Carlo realization. The data in this table can be exported, copied, or analyzed using the table column tools.

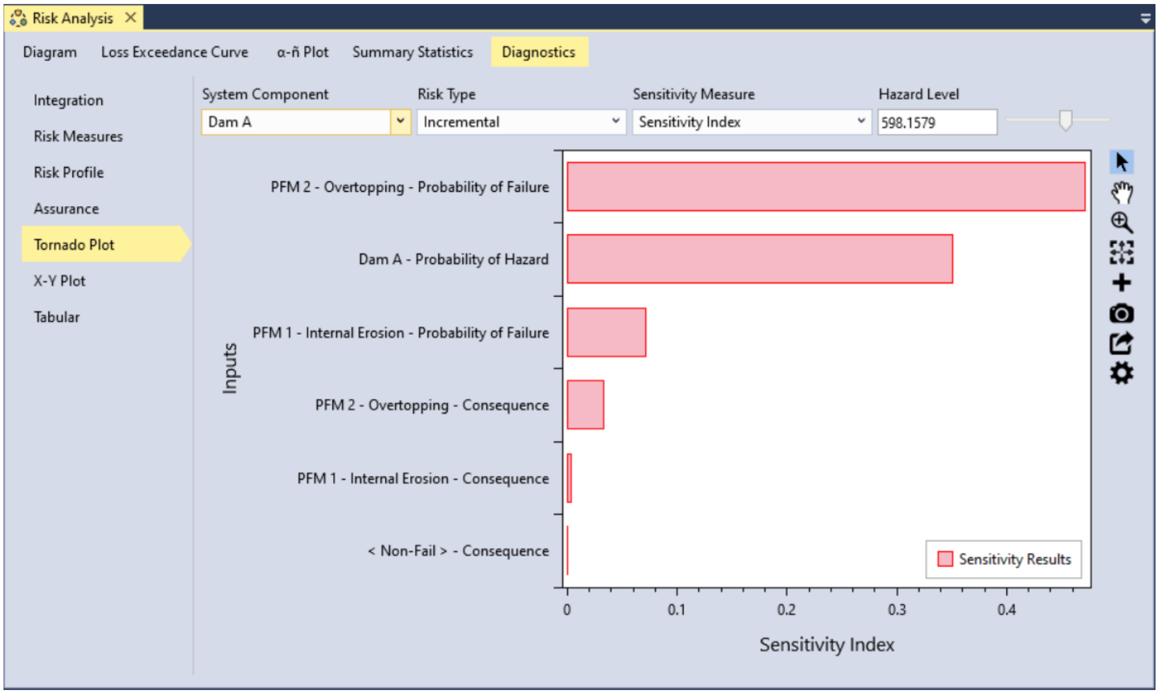

Figure 11. Tornado plot sensitivity diagnostic plot in RMC-TotalRisk.

V. CONCLUSIONS

RMC-TotalRisk is a powerful and versatile tool for conducting comprehensive risk analyses of dam and levee systems. By incorporating various types of risk (background, incremental, total, failure, and non-failure) TotalRisk provides a nuanced and detailed understanding of potential hazards and their consequences. The software's ability to integrate both parametric and nonparametric input functions, coupled with its advanced Monte Carlo simulation capabilities, allows for robust modeling of complex systems with multiple failure modes.

The flexibility in defining hazard functions, transform functions, system response functions, and consequence functions ensures that RMC-TotalRisk can be tailored to meet the specific needs of any risk assessment scenario. This adaptability is crucial for evaluating trade-offs in risk reduction alternatives, making RMC-TotalRisk an invaluable resource for dam and levee safety studies.

A distinctive feature of RMC-TotalRisk is its capability to conduct full Monte Carlo analyses, simulating uncertainty across all inputs. Remarkably, the software achieves this within short runtimes, ranging from a few seconds to minutes. The outputs include insightful plots and diagnostics, offering users valuable insights into the risk landscape. Additionally, the software's sensitivity analysis option allows users to discern key inputs and identify primary sources of uncertainty, thereby enhancing the precision and reliability of the risk assessment.

RMC-TotalRisk provides several diagnostic tools for exploring Monte Carlo simulation results, including kernel density plots to understand the shape and distribution of various risk measures, risk profiles to identify critical hazard levels, tornado plots to rank the sensitivity of input functions, and X-Y plots to assess correlations between system risk results and individual input components. These diagnostics support informed decision-making and effective risk management strategies.

In conclusion, RMC-TotalRisk significantly enhances and expedites quantitative risk analyses, ultimately contributing to more informed and effective investment decisions in dam and levee safety. The software's comprehensive features and capabilities will make it an indispensable tool for practitioners and stakeholders involved in infrastructure risk management. Moreover, RMC-TotalRisk is freely available to the public and can be downloaded from the RMC website (https://www.rmc.usace.army.mil), ensuring broad accessibility within the dam and levee safety community and facilitating its integration into safety and investment planning processes.

VI. ACKNOWLEDGEMENTS

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