A New Comprehensive Risk Analysis Software, RMC-TotalRisk

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The U.S. Army Corps of Engineers (USACE) Risk Management Center (RMC) has developed a comprehensive risk analysis software, RMC-TotalRisk, to support dam and levee safety investment decisions. RMC-TotalRisk has an intuitive workflow to step the user through the required inputs, including importing flood hazard curves from RMC-BestFit and consequences estimates from LifeSim. The system response probabilities can be estimated using the built-in event tree tool. 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 and diagnostics, and it also includes a sensitivity analysis option so the user can understand the driving inputs and the largest sources of uncertainty. The RMC-TotalRisk software can greatly enhance and expedite quantitative risk analyses, thereby improving risk-informed investment decisions.

Keywords: Risk assessment, uncertainty analysis, Monte Carlo simulation, software

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, which performs risk analysis from user-defined hazard, system response, and consequence functions. The software features a fully integrated modelling 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 (Smith, Fields, & Snorteland, 2021). Figure 1 shows a schematic of the software suite and how each tool is envisioned to interact together in support of the overall risk analysis.

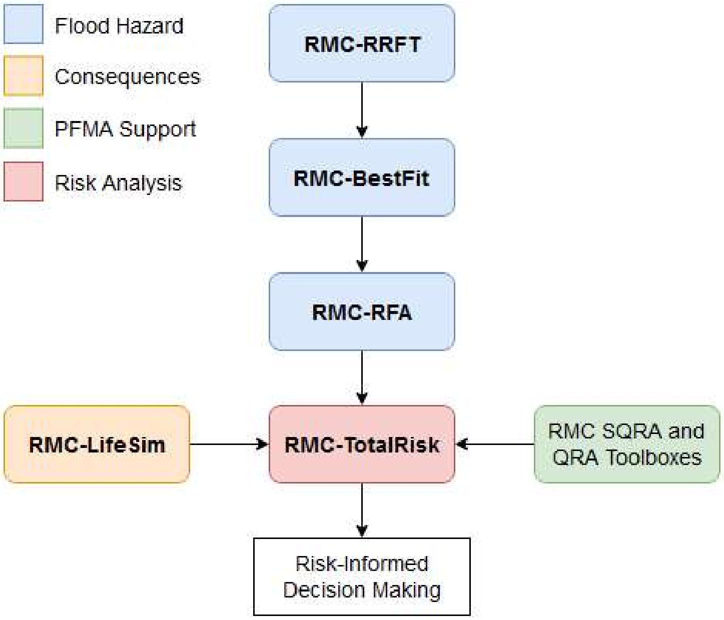

Figure 1 – Schematic of the RMC risk analysis software suite.

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 to 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 support the estimation of 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.

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 TotalRisk was primarily developed for dam and levee safety applications, the software is not limited to just flood risk management applications. RMC-TotalRisk is all-purpose risk analysis software, capable of estimating risk for any system.

Overview of the Risk Analysis Framework

Risk has various definitions and interpretations among different industries, but it is generally understood to describe the probability that some undesirable event occurs, and the corresponding consequences of the event (Committee on Risk-Based Analysis for Flood Damage Reduction, 2000). In the U.S., flood risk management investment decisions are typically made from a *risk neutral*[1] perspective based on average annual net benefits (U.S. Water Resources Council, 1983). As such, flood risk can be formally defined by the expected consequences $\mathbb{E}[C]$, which is calculated as:

$$\mathbb{E}[C] = \int_{-\infty}^{\infty} f\big(C(x)\big) \cdot C(x) \cdot dx \qquad \textbf{Equation 1}$$

where x is the hazard level (e.g., flood discharge or water level); $C(x)$ determines the consequences, such as property damage or life loss, for the hazard level x; and $f\big(C(x)\big)$ is the probability density function (PDF) of the consequences occurring. In practice, risk at a dam or levee is often calculated numerically based on discrete hazardous flood or seismic events. The risk of failure using discrete hazard levels follows from Equation 1 and is defined as:

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

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

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

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 (Smith, Bartles, & Fleming, 2018). Other parameters such as discharge, duration, and velocity can also be important for certain failure modes, such as a spillway erosion failure mode 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. 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 that is estimated using flood-frequency analysis methods. Next, moving to the top right, peak flow is then transformed to 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. And 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 (Smith, Fields, & Margo, 2022). Additional details on risk analysis for flood risk management can be found in (Committee on Risk-Based Analysis for Flood Damage

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[1] An agency with *risk neutral* preferences seeks to maximize the expected net benefits of a project. Whereas a *risk averse* agency would be willing to accept net benefits which are smaller than the expected value.

Reduction, 2000), (U.S. Army Corps of Engineers, 1996), and (U.S. Bureau of Reclamation & U.S. Army Corps of Engineers, 2019).

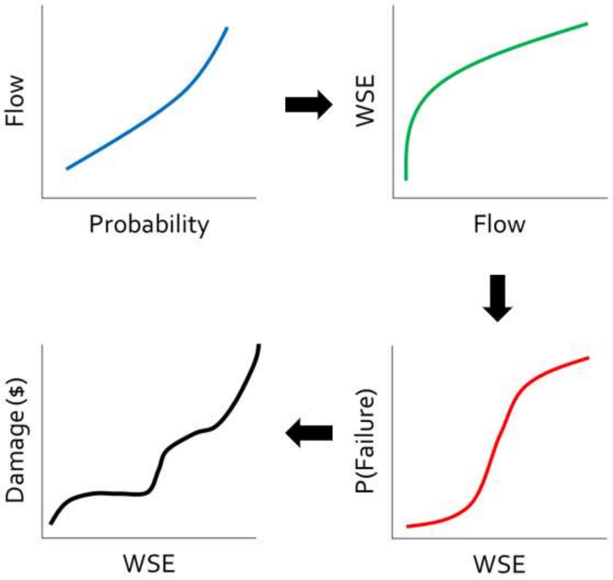

Figure 2 - Levee risk analysis process for a single failure mode and a single system component.

Model Inputs

Figure 2 illustrates the key inputs for a single failure mode for a single system component, which in this case is 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. In addition, these functions can be defined with or without uncertainty. The following subsections provide details on the inputs, and the available options for each. Complete details are provided in (Smith, Fields, & Margo, 2022) and (Fields & Smith, 2022).

Hazard Functions

A hazard function is a probability distribution that describes the exceedance probabilities of various hazard levels. Hazard functions are also 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 different 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 found in (Smith & Skahill, 2019) and (Smith & Doughty, 2020).
- ***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 (Smith, Bartles, & Fleming, 2018) and (Smith, 2018).
- ***Parametric***: A parametric distribution can be selected with user-defined parameters, with or without uncertainty. In the latter case, the parametric bootstrap (Efron & Hastie, 2016) is used to model uncertainty in the parametric hazard function. The user must enter an effective record length (ERL), which is a measure of information content in the fit of the distribution. 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[2] or FLIKE[3]. 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 (U.S. Army Corps of Engineers, 2016). 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, RORB[4], or SEFM[5]. Or in the case of seismic hazards, nonparametric functions are often derived from a probabilistic seismic hazard analysis (PSHA) (U.S. Bureau of Reclamation & U.S. Army Corps of Engineers, 2019). 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 tabular data.
- ***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. Or alternatively, rather than using weights, a composite hazard function can be created by combining a list of hazard functions using the probability of union, assuming statistical independence between functions. This option is useful for combining hazard functions when flood events arise from distinctly different and independent processes, such as rainfall and snowmelt.

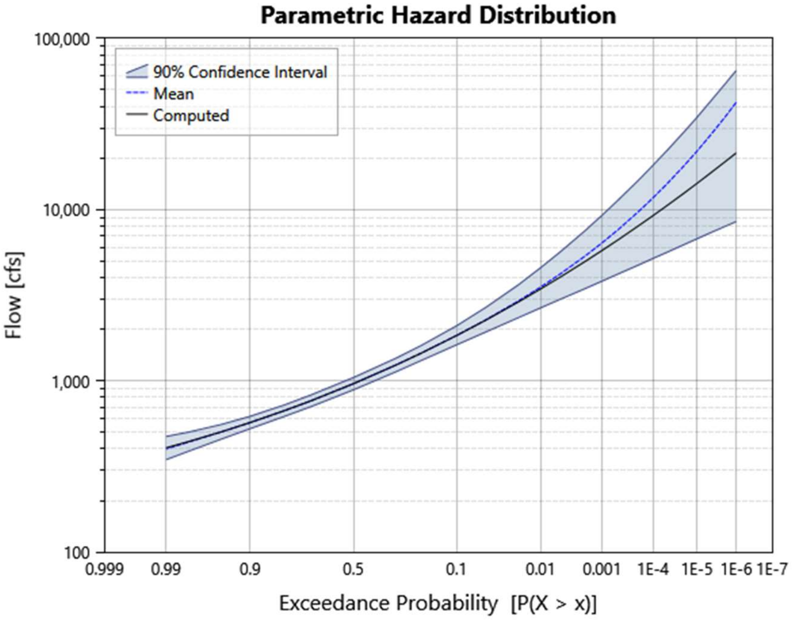

Figure 3 - Example of a parametric hazard function.

Transform Functions

A transform function can be used to transform (or convert) the hazard levels from one type of function to another. For example, a peak flow-frequency function can be transformed to 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:

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

[3] The flood frequency analysis toolkit recommended by the Australian Rainfall and Runoff (ARR) guidance (https://www.tuflow.com/products/flike/)

[4] An Australian rainfall-runoff software used regularly for stochastic simulation (https://www.monash.edu/engineering/departments/civil/research/themes/water/rorb)

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

- ***Linear***: A transform function can be defined from a simple linear equation. Uncertainty can be defined with an additive error.
- ***Power***: A transform function can be defined from 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 modelled 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.

System Response Functions

A system response function describes the conditional probability of failure for various hazard levels, such as water surface elevations. System response functions are 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 represent the logic of how an initiating event, like a flood or earthquake, can lead to various types of failure and damage (Hartford & Baecher, 2004). An example of an event tree for a seismic failure mode is shown in Figure 4. Chance nodes have user-defined probabilities that are typically estimated with expert elicitation. In addition, users can reference other chance nodes within the same tree, other full event trees, or any other response function in the analysis. This provides flexibility to create very complex and interdependent event trees.
- ***Parametric***: A response function can be defined with a parametric probability distribution in the same way as 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. A plot of a tabular response function with uncertainty is shown in Figure 5.
- ***Bivariate***: A bivariate response function provides a simple 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 WSE 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. Or alternatively, rather than using weights, a composite function can be created by combining a list of response functions using the probability of union, assuming statistical independence between functions. This option is useful for combining potential failure modes when each have the same consequences.

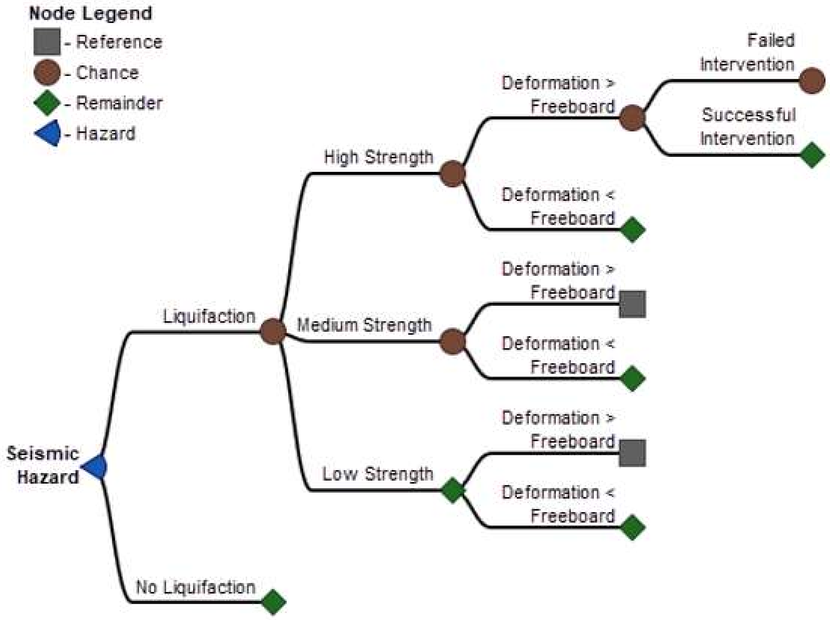


Figure 4 - Example of an event tree for a seismic potential failure mode.

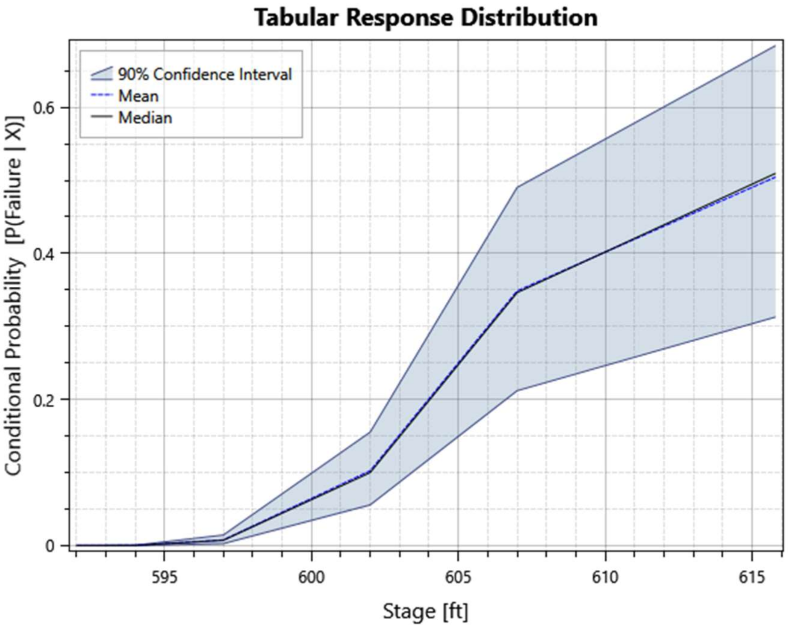


Figure 5 - Example of a tabular response function.

Consequence Functions

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

- ***LifeSim***: A consequence function with or without uncertainty can be imported from the consequence estimation software, LifeSim. Life loss and economic damages can be estimated with LifeSim. More details on LifeSim can found in (U.S. Army Corps of Engineers, 2018) and (U.S. Army Corps of Engineers, 2020).
- ***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 daytime and night-time consequences as shown in Figure 6 below. Alternatively, a composite function can be created by summing across a list of consequence functions.

Risk Analysis

A risk analysis in RMC-TotalRisk is defined through a diagram as shown in Figure 7 below. The diagram provides an intuitive way to create and connect the various components of the modelled system. Figure 7 shows a single system component for a dam safety risk analysis. There is a non-failure mode, shown at the top of the diagram, that connects the hazard function to the non-failure consequences, without any system response. For many dams, there will often be consequences even if the structure does not fail. For example, during a major flood event, a dam could activate the emergency spillway, preventing the dam from reducing downstream flooding. The non-failure mode is used to model the risk of non-failure. There are two failure modes: 1) An internal erosion failure mode, labelled PFM 1, shown in the center of the diagram connects the hazard at Dam A to the PFM 1 response function and the PFM 1 consequences; and 2) An overtopping failure mode, labelled PFM 2, shown in the bottom of the diagram with the same respective connections.

The system components are identified and labelled by the selected hazard function. The failure modes within a component are identified and labelled by the selected response functions. RMC-TotalRisk permits an unlimited number of failure modes per component. However, a single system is limited to 20 components due to virtual memory and computer runtime limitations. For example, the system risk of a watershed comprising up to 20 dams, each with 20 failure modes, can be assessed.

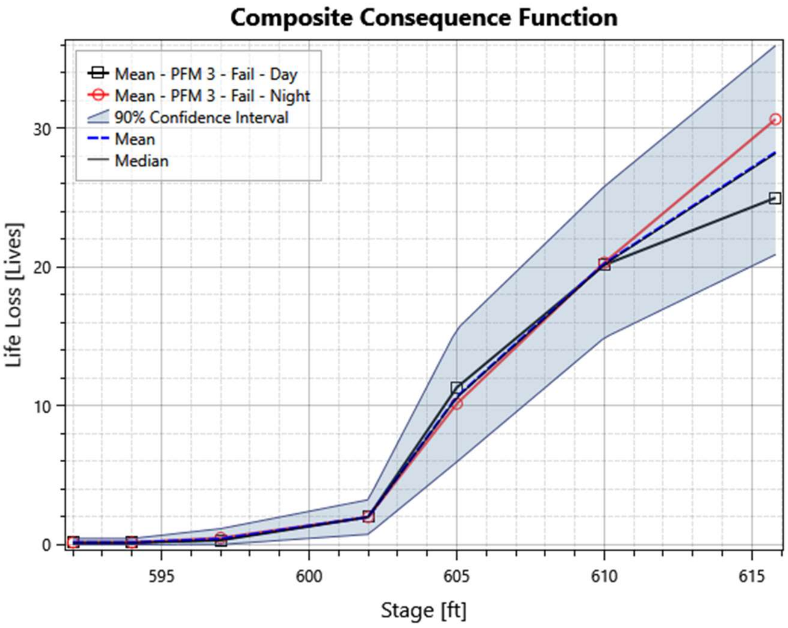


Figure 6 - Example of a composite consequence function for day and night losses.

Dependency between failure modes and system components can be defined in TotalRisk. There is rarely enough data to estimate the true joint probability between failure modes. Instead, failure modes can be modelled as perfectly independent, or perfectly negatively dependent. Perfect independence is an upper bound when failure modes are positively correlated. Whereas perfect negative dependency is an upper bound when failure modes are negatively correlated (Ang & Tang, 1984). Likewise, dependency between system components can be set as perfectly independent, positive, or negatively dependent. There is also an option to set the dependency between system components with a user defined correlation matrix.

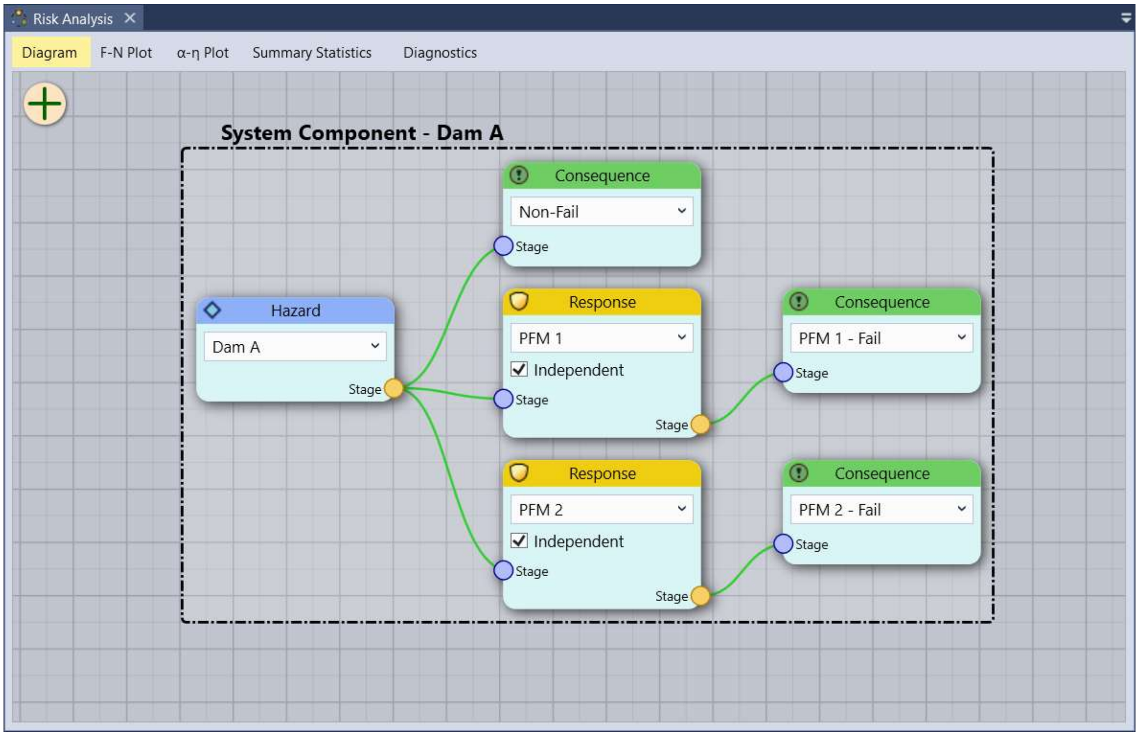


Figure 7 - RMC-TotalRisk risk diagram.

After the inputs and dependency options have been selected, the risk for each individual failure mode, the system component, and the overall system can be computed. The overall risk and Monte Carlo simulation framework employed by RMC-TotalRisk is illustrated in Figure 8.

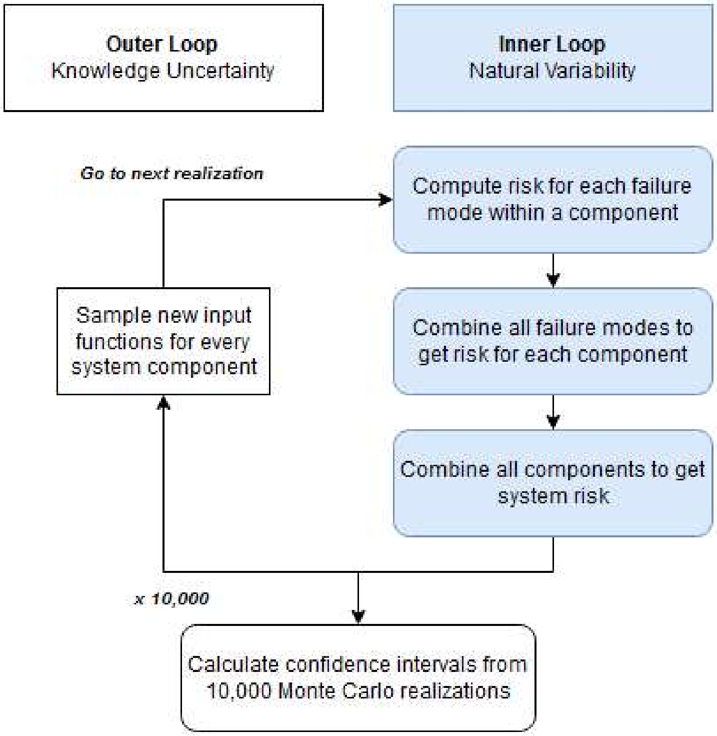


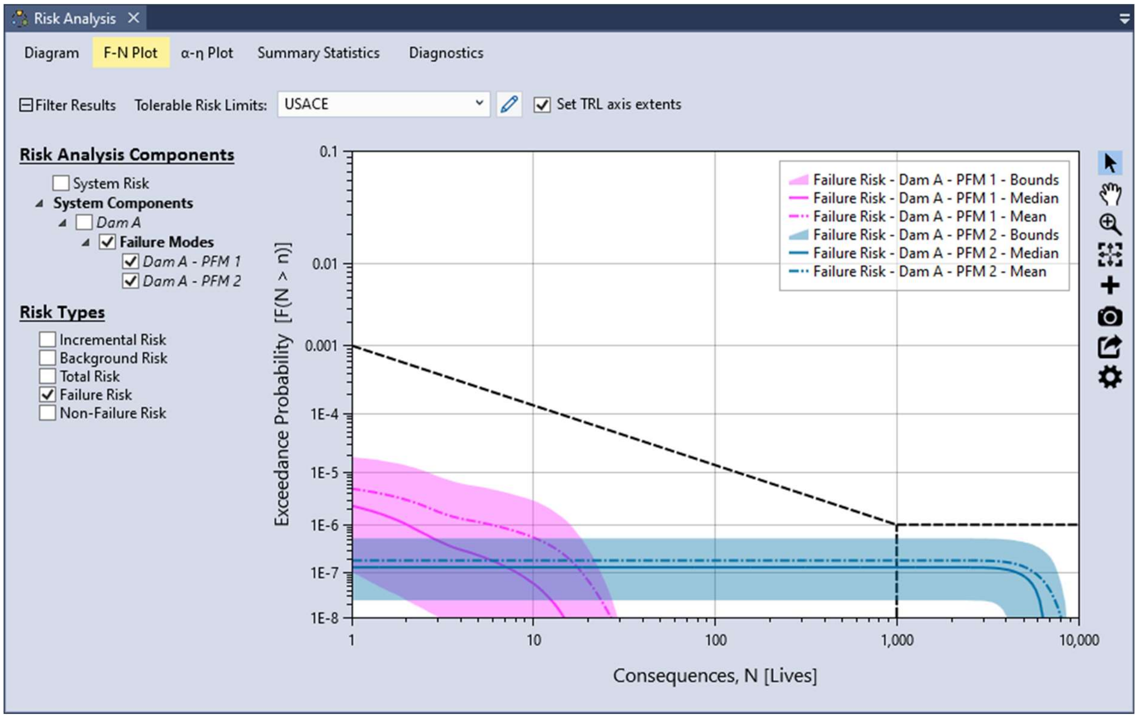
Figure 8 - Flowchart of the RMC-TotalRisk risk and Monte Carlo simulation framework.

Risk Results

There are three main ways to view the risk results. An F-N plot shows the exceedance probabilities (F) for consequences (N) (Figure 9). This type of plot is referred to as a *survival function*. A more commonly used plot in the USACE dam and levee safety programs is the α-η plot (Figure 10), which plots the conditional expected consequences (η) against the exceedance probability (α). The diagonal of the α-η plot is equal to the product of α and η, which is the expected value of consequences, $\mathbb{E}[\mathrm{N}] = \alpha \cdot \eta$. In an F-N plot, the uncertainty is portrayed as confidence intervals, whereas in an α-η plot, the uncertainty is portrayed as a scatter cloud.

Customizable tolerable risk limits (or guidelines) can be displayed on both the F-N and α-η plots. In Figure 10, both failure modes plot below the tolerable risk limits, however, the overall system risk plots above the limit. This is because the variance between the two failure modes increases the conditional expected consequences (η) of the component. 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.

Summary statistics are provided for each risk type being evaluated as shown in Figure 11. 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 labelled “Ex. Probability, α” in Figure 11. The average consequences given failure are provided in the “Conditional Mean, η” column. Finally, the average annual consequences are provided in the “Mean, E[N]” column.



Tolerable Risk Limits: USACE

☑ Set TRL axis extents

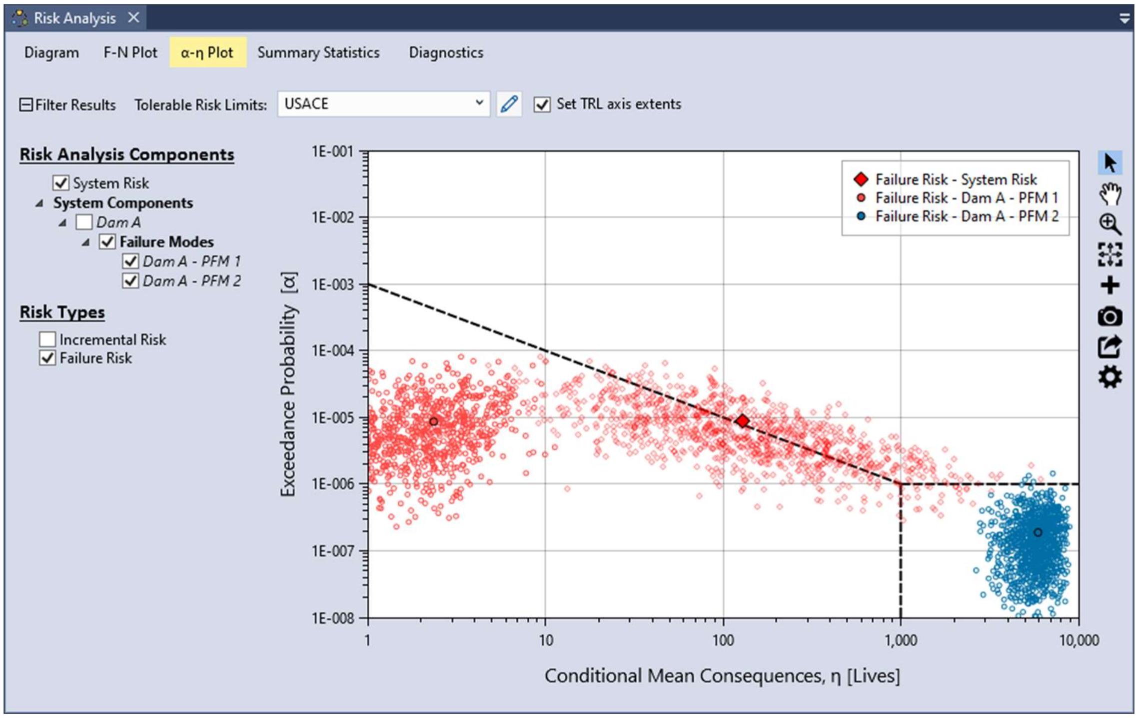
Risk Analysis Components

☐ System Risk
System Components
  ☐ Dam A
    ☑ **Failure Modes**
      ☑ Dam A - PFM 1
      ☑ Dam A - PFM 2

Risk Types

☐ Incremental Risk
☐ Background Risk
☐ Total Risk
☑ Failure Risk
☐ Non-Failure Risk

Figure 9 - F-N results for PFM 1 and 2.



Tolerable Risk Limits: USACE

☑ Set TRL axis extents

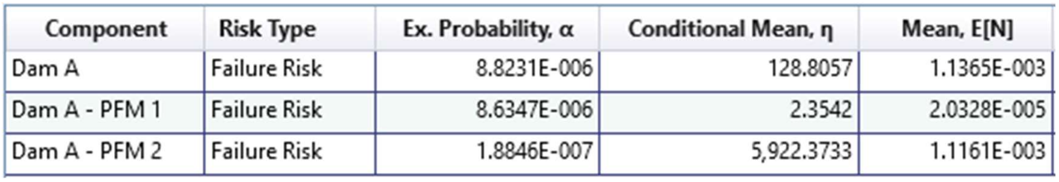
Risk Analysis Components

☑ System Risk
System Components
  ☐ Dam A
    ☑ **Failure Modes**
      ☑ Dam A - PFM 1
      ☑ Dam A - PFM 2

Risk Types

☐ Incremental Risk
☑ Failure Risk

Figure 10 - α-η scatter plot for risk results.



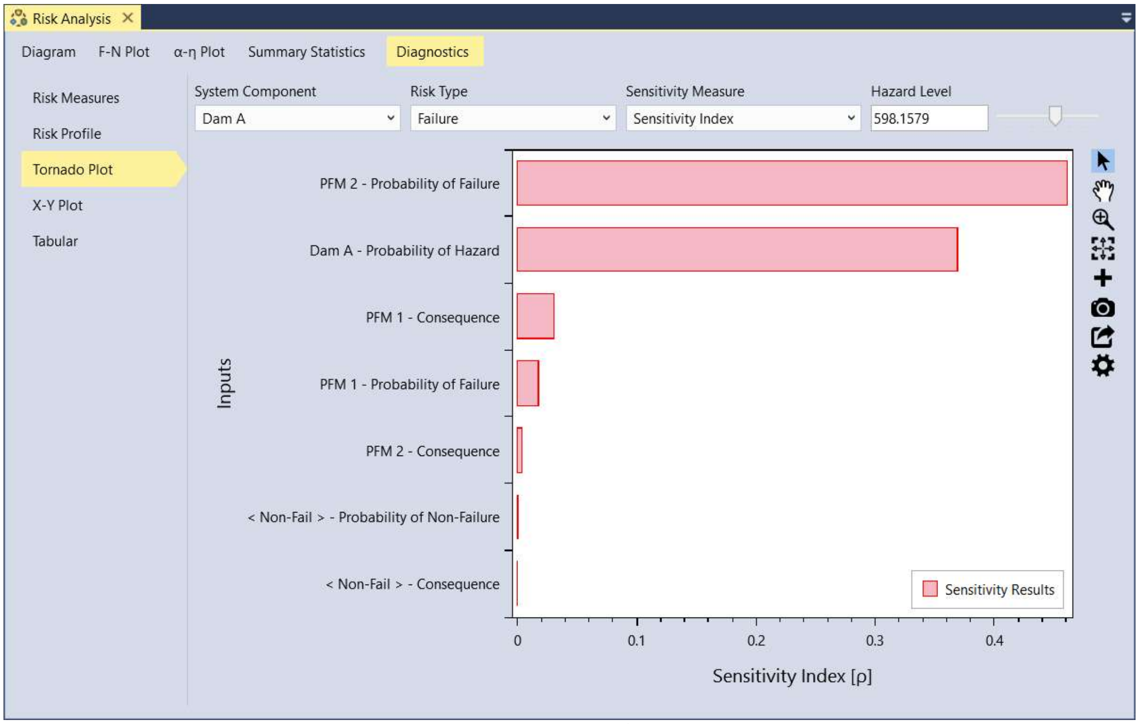
Component	Risk Type	Ex. Probability, α	Conditional Mean, η	Mean, E[N]
Dam A	Failure Risk	8.8231E-006	128.8057	1.1365E-003
Dam A - PFM 1	Failure Risk	8.6347E-006	2.3542	2.0328E-005
Dam A - PFM 2	Failure Risk	1.8846E-007	5,922.3733	1.1161E-003

Figure 11 - Summary statistics for risk results.

Diagnostics

RMC-TotalRisk provides several diagnostics 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, the diagnostic features include the following:

- A kernel density plot to understand the shape and distribution of various risk measures.
- A risk profile that plots the cumulative expected consequences against increasing hazard levels. This plot is useful for identifying critical hazard levels where risk sharply increases.
- A tornado plot that 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 12.
- The X-Y plot for assessing the correlation between the system risk results and an individual input component, such as a failure mode.
- Tabular results where there is a column for each system component and a row for each Monte Carlo realization. The data in this table can be exported, copied, or analysed using the table column tools.



System Component: Dam A
Risk Type: Failure
Sensitivity Measure: Sensitivity Index
Hazard Level: 598.1579

Figure 12 – Tornado plot sensitivity diagnostic plot in RMC-TotalRisk.

Discussion and Conclusions

The RMC-TotalRisk software provides many features that can greatly enhance and expedite quantitative risk analyses, thereby improving investment decisions. The software is part of the comprehensive RMC risk analysis software suite, which includes RRFT, BestFit, RFA, and LifeSim. TotalRisk can also incorporate hazard data from other software tools that support the Australian Rainfall and Runoff guidance, such as FLIKE and RORB.

The effects of climate change on flood hazards can be modelled in the supporting software, such as BestFit and RFA, and then imported and propagated through TotalRisk. Likewise, the effects of land use changes on consequences can be modelled in LifeSim and then imported and propagated through TotalRisk. These features provide a comprehensive framework for assessing the risk of dams and levees under consideration of climate change.

In addition, this software can evaluate the risk of a single dam or levee, or a complex system with many components. TotalRisk also provides several risk measures that can better support the evaluation of risk reduction alternatives.

In conclusion, the RMC-TotalRisk software provides many features that will enhance dam and levee safety activities and improve investment decisions. RMC-TotalRisk is freely available to the public and downloadable from the RMC website (https://www.rmc.usace.army.mil).

Acknowledgements

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