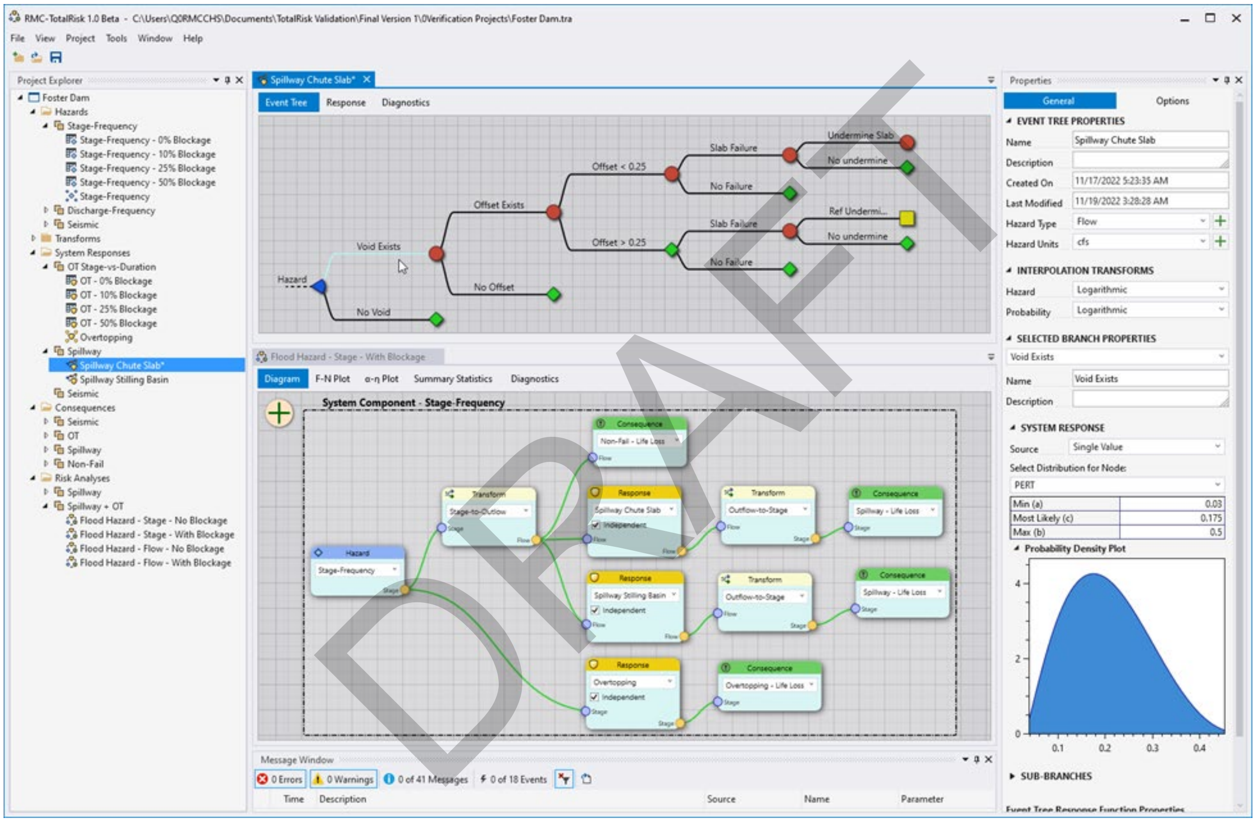
RMC-TotalRisk User Guide

RMC-TR-2023-XX



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14. ABSTRACT
The U.S. Army Corps of Engineers TotalRisk software (RMC-TotalRisk) performs quantitative risk calculations for a system from a set of hazard, system response, and consequence functions. RMC-TotalRisk is part of an integrated software suite designed to support risk assessments. The software features a fully integrated modeling platform, including a modern graphical user interface, data entry, report quality charts, and diagnostic tools. RMC-TotalRisk can evaluate risk for a single component with multiple failure modes and a complex system comprised of multiple components. This document provides a guide for developing a quantitative risk analysis with RMC-TotalRisk.

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Welcome to RMC-TotalRisk

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 USACE 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. TotalRisk can perform multi-failure risk analysis for a single dam or levee or for a complex system with multiple components.

Why you should use RMC-TotalRisk

RMC-TotalRisk is a powerful risk analysis software package with an intuitive and easy to use interface. RMC-TotalRisk reduces complexity in risk assessments by connecting the components of risk (hazard, response, and consequences) through an intuitive risk diagram. The software can generate various aspects of risk including Incremental, Background, Total, Failure, Non-Failure risk [1]. Every component of the software can be defined with uncertainty. The risk analysis supports modelling multiple locations each with their own failure modes as separate system components, making system level risk analysis easy.

When should you use RMC-TotalRisk? Any time you perform a risk analysis, you can and should use RMC-TotalRisk. Typical applications in science and engineering include structural flood mitigation risk but can apply to any application that has a hazard and a consequence.

Examples related to flood risk for dams and levees are provided throughout this document. However, 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 a variety of complex systems.

System Requirements

The RMC-TotalRisk program and all dependent libraries were developed using the .NET Framework 4.8. As such, the program is currently only available for the Microsoft Windows operating system. The recommended system configuration for RMC-TotalRisk includes:

- 64-bit Windows Operating System (Windows 7 or newer)
- 512MB of RAM at a minimum
- 2GB of free disk space at a minimum
- Quad-Core CPU with 2.7GHz (or faster) clock speed
- 1280x1024 screen resolution or higher (and at least a 17" monitor)

Installing RMC-TotalRisk

RMC-TotalRisk version 1.0 is available as a portable package (.zip). Installing a portable package does not require administrative rights. Simply extract all contents of the portable package to the desired computer location. After extraction, the package contents will look as shown in Figure 1. Simply double-click the executable **RMC-TotalRisk.exe** to get started. For easy access to the program, you can create a desktop shortcut and pin the program to your Windows taskbar.

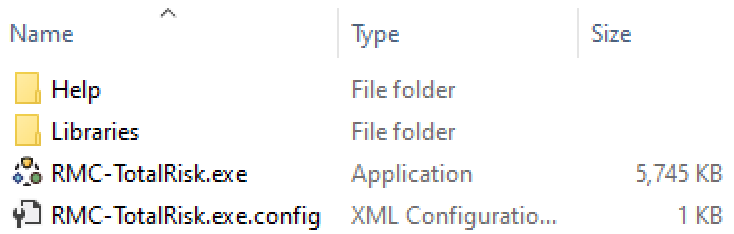

Figure 1 –RMC-TotalRisk executable file in the RMC-TotalRisk portable .zip directory.

Setting the File Association in Windows

RMC-TotalRisk files have the "**.tra**" file extension. To have Windows automatically open **.tra** files with RMC-TotalRisk, first right-click a **.tra** project file. Select **Open with…** from the resulting menu.

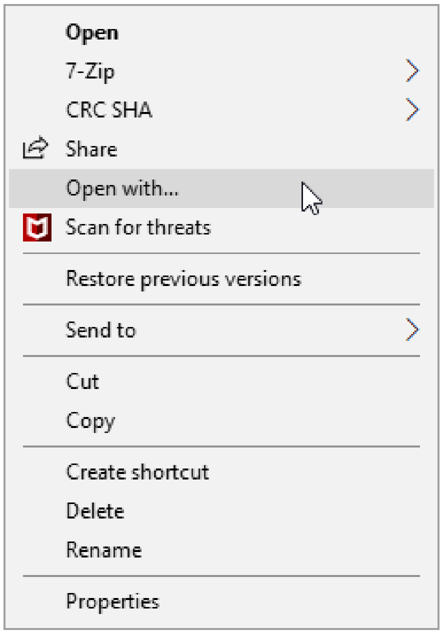

Figure 2 – Right-Click Menu for Project File in Windows.

Then, from the menu that appears when you select **Open with...**, click **Try an app on this PC** for an expanded list of already installed applications. If you do not see RMC-TotalRisk, scroll to the bottom and select **Look for another app on this PC**. This will open a Windows Explorer dialog. Navigate to and select the executable **RMC-TotalRisk.exe**, then click **Open.** When you've found RMC-TotalRisk and it has been selected, check the box labeled **Always use this app to open [.tra] files** before you click the **OK** button. Now **.tra** files will appear in Windows Explorer with the RMC-TotalRisk icon. You can now double-click a project file to automatically open it with RMC-TotalRisk.

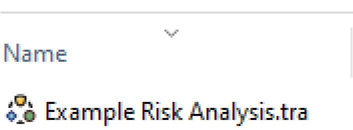

Figure 3 – RMC-TotalRisk Project with File Association in Windows.

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The United States Government, US Army Corps of Engineers, Risk Management Center ("RMC") grants to the user the rights to install RMC-TotalRisk "the Software" (either from a copy obtained from RMC, a distributor or another user or by downloading it from a network) and to use, copy and/or distribute copies of the Software to other users, subject to the following Terms and Conditions of Use:

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As a voluntary user of RMC-TotalRisk you agree to indemnify and hold the United States Government, and its agencies, officials, representatives, and employees, including its contractors and suppliers, harmless from any claim or demand, including reasonable attorneys' fees, made by any third party due to or arising out of your use of RMC-TotalRisk or breach of this Agreement or your violation of any law or the rights of a third party.

Assent

By using this program you voluntarily accept these terms and conditions. If you do not agree to these terms and conditions, uninstall the program and return any program materials to RMC (If you downloaded the program and do not have disk media, please delete all copies, and cease using the program).

Graphical User Interface

RMC-TotalRisk is a menu-driven software package that performs risk analyses. The software features a fully integrated modeling platform, including a modern graphical user interface, data entry capabilities, multi-failure risk analysis, and report quality charts.

The graphical user interface consists of a **Menu Bar**, **Tool Bar**, and four window panes (Figure 4). The panes will be referred to as the **Project Explorer**, the **Tabbed Documents**, the **Properties**, and the **Message Window**. You may move, dock, hide, or close the window panes as desired.

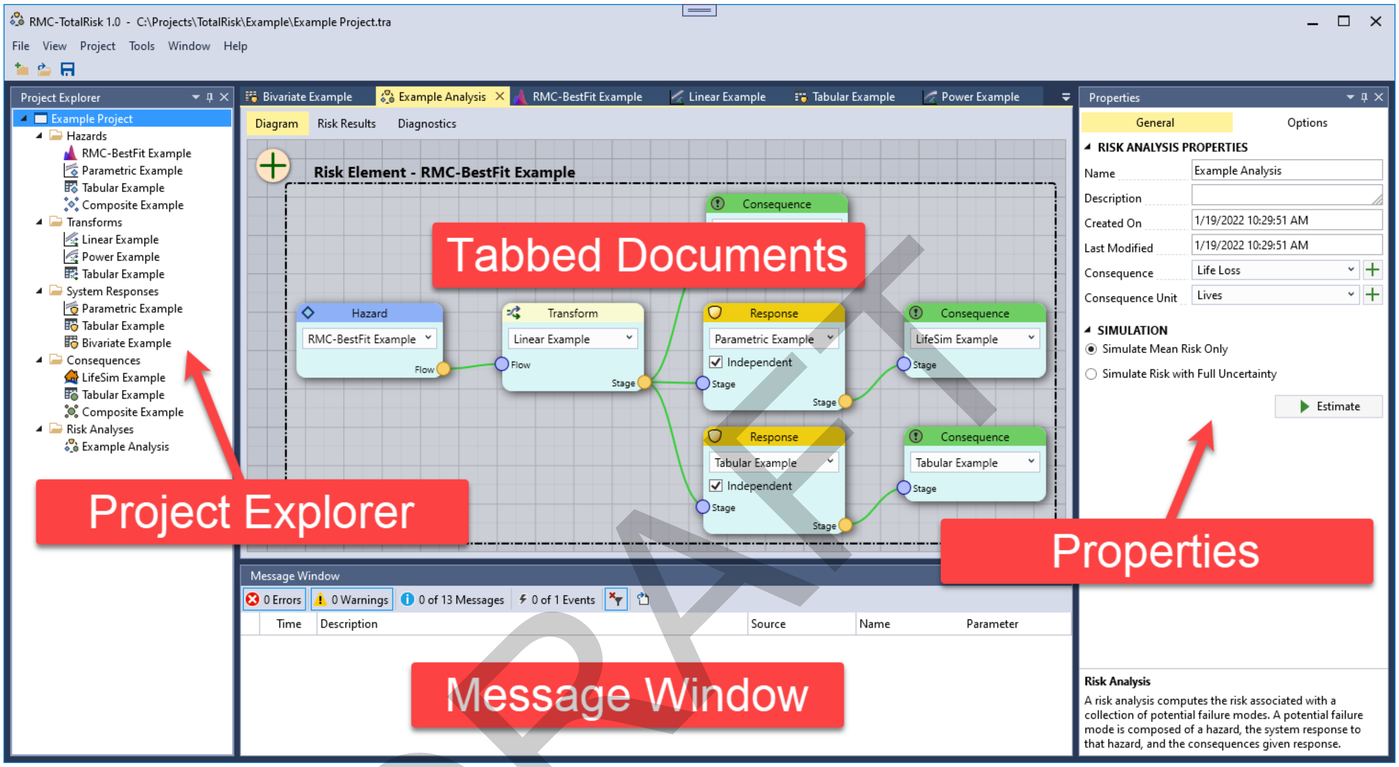


Figure 4 – RMC-TotalRisk User Interface.

Menu Bar

The menu bar located at the top of the window, as shown in Figure 5, contains important commands needed for working with RMC-TotalRisk.

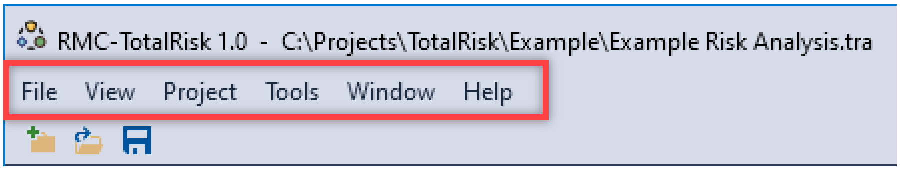


Figure 5 – RMC-TotalRisk Menu Bar.

File

The **File** menu provides essential file management functionality. From this menu, you may create a new project, open an existing project, save or save as, open recent projects, or exit the application.

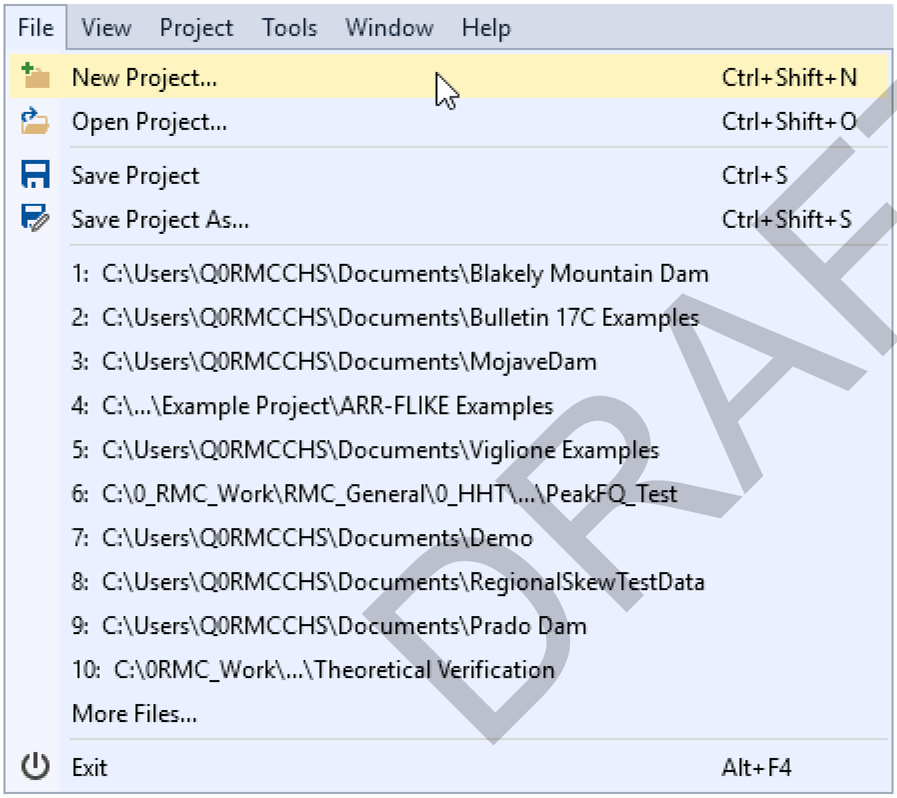


Figure 6 – File Menu.

If this is the first time you're using RMC-TotalRisk, your recent projects list will be empty. Once you have exceeded the number of projects shown in the recent project list (the default is 10), a menu item labeled as **More Files…** will be available. After clicking this item, a **Recent Files** dialog will open showing all available recent project files (Figure 7). From here, you may open any recently used project file, or clear the recent project file list.

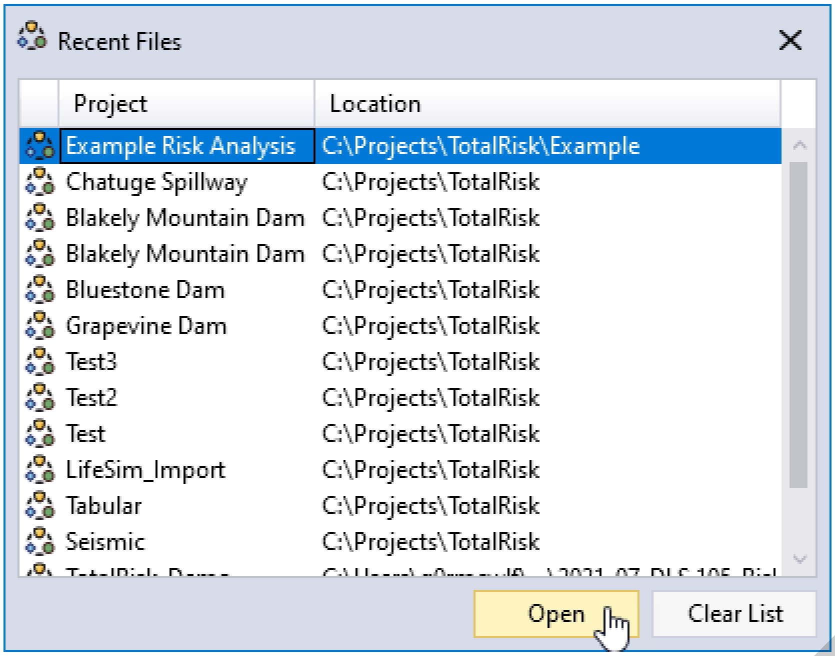


Figure 7 – Recent File Dialog.

View

You may move, dock, hide, or close the **Project Explorer**, **Properties Window**, and **Message Window** as desired. The **View** menu allows you to unhide or open these windows. In addition, you can restore the default layout of the window panes.

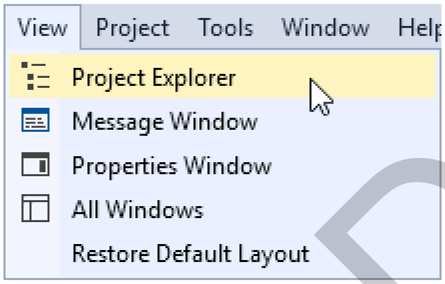


Figure 8 – View Menu.

Project

The **Project** menu contains commands related to the project you are working in. From this menu, you can create a new hazard, transform, system response, or consequence function. You can also add a new Risk Analysis. In addition, you can edit the project properties through the Properties Window.

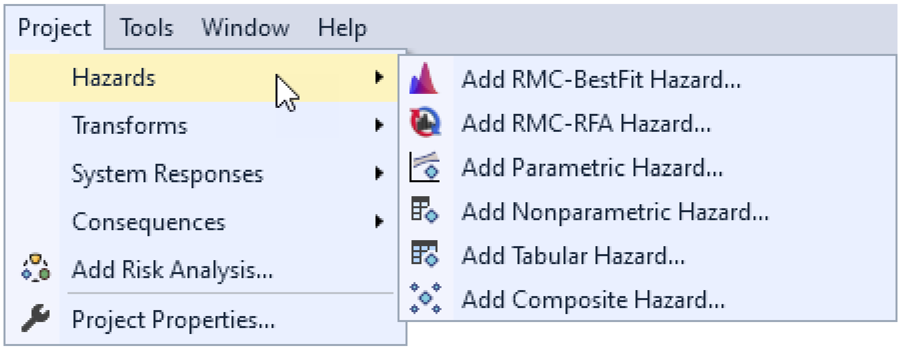


Figure 9 – Project Menu.

Tools

The **Tools** menu provides tools for managing your project and personalizing your workspace.

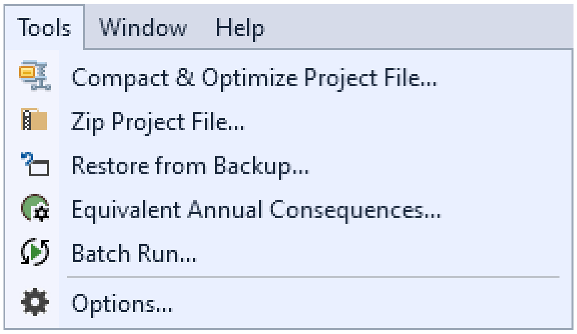


Figure 10 – Tools Menu.

- **Compact & Optimize Project File** This option will compact and optimize the project database removing unnecessary tables. Using this tool can significantly reduce the size of your file without losing any project data.
- **Zip Project File** This option will zip your project file and prompt you to save the .zip to a location on your computer. The zip file will be much smaller and can then be easily shared with others.
- **Restore From Backup** restores the project from the backup file (***.tra.bak). A backup file is created every 30 minutes by default, you can change the duration between backups in the **Options** dialog, **File Management** tab.
- **Equivalent Annual Consequences** With this tool (Figure 11) equivalent annual consequences (EqAD) between two risk analyses can be calculated. EqAD is required in USACE planning NED cost evaluation procedures [2]. To calculate, define the analysis period in years and a discount rate as percent then select current and future risk analyses and the year those results represent. The EqAD will be automatically calculated. Use the table tools to add and remove EqAD calculations. You can also manually enter Base and Future Plan results by clicking in the dropdowns and typing the value.
- **Batch Run** With this tool (Figure 12) you can simulate multiple risk analyses as a batch process. Batch processing can be very useful when inputs have been changed that are common across multiple risk analyses.
- **Options** This tool allows the user to personalize their workspace. The user can customize the Application, File Management, Message Window, and Default settings. See the *Personalize RMC-TotalRisk* section below for more details.

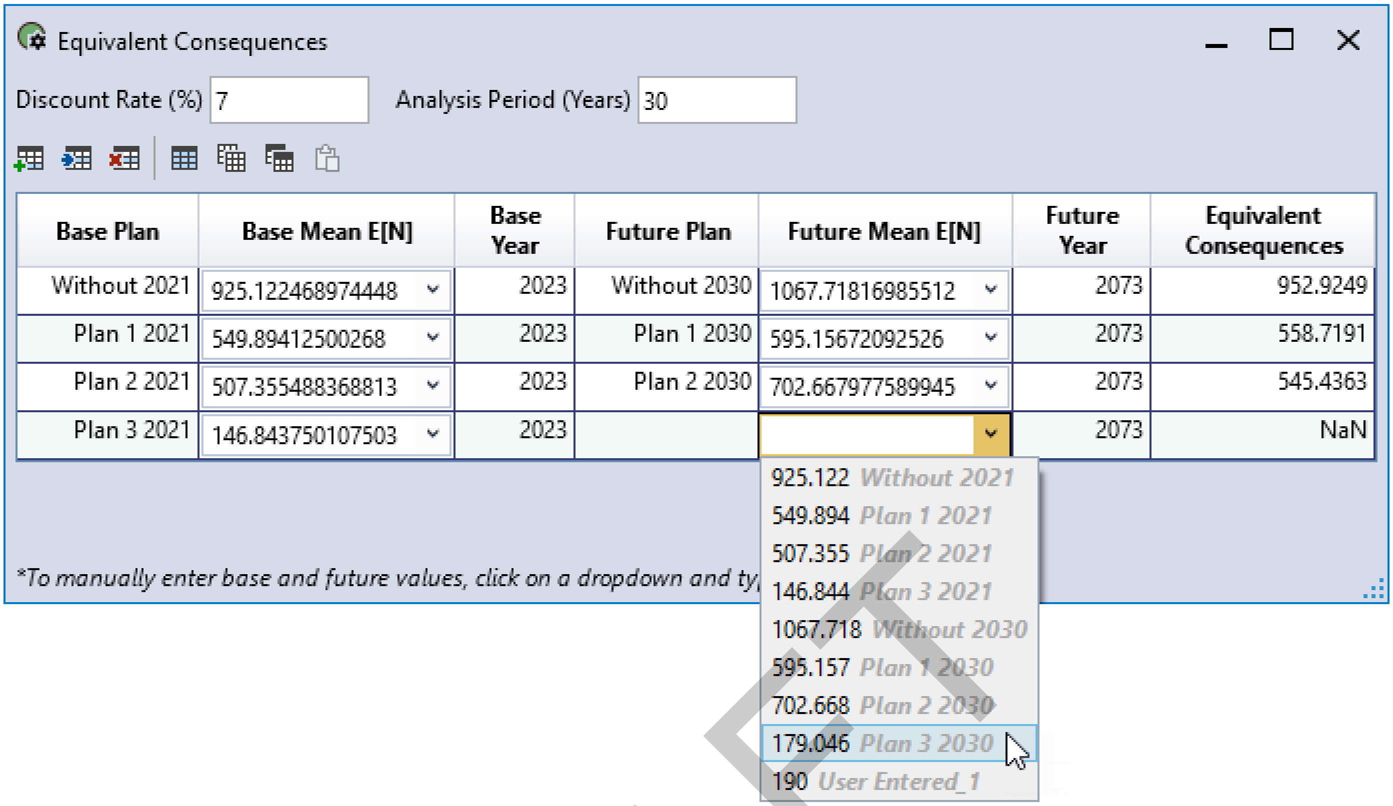


Figure 11 – Equivalent Annual Consequences Tool.

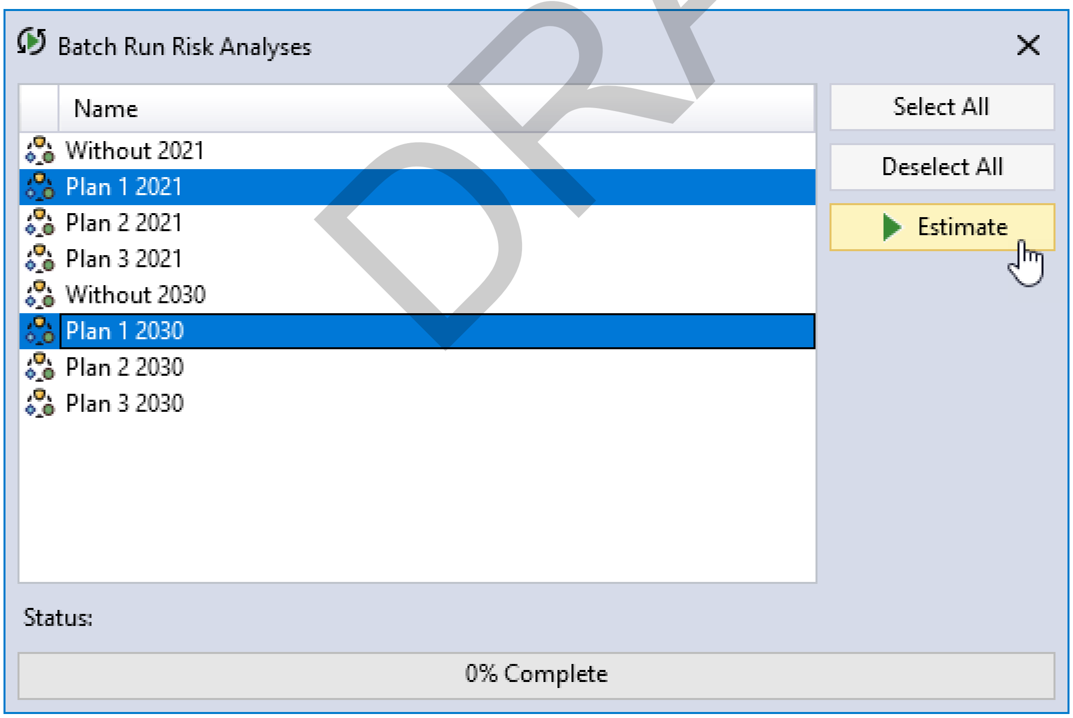


Figure 12 – Batch Run Risk Analyses Tool.

Window

The **Window** menu allows you to close or activate the document windows. The active document will have a check mark next to it as shown in Figure 13. You can see all open windows by clicking **Windows…**, which will open a **Windows** dialog. From here, you can activate or save specific documents. In addition, you can select and close multiple documents at once.

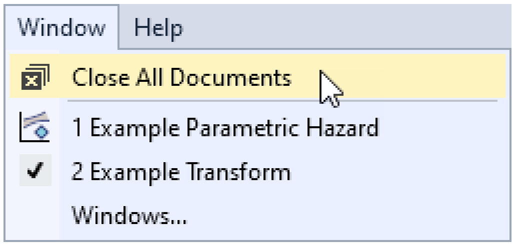


Figure 13 – Windows Menu.

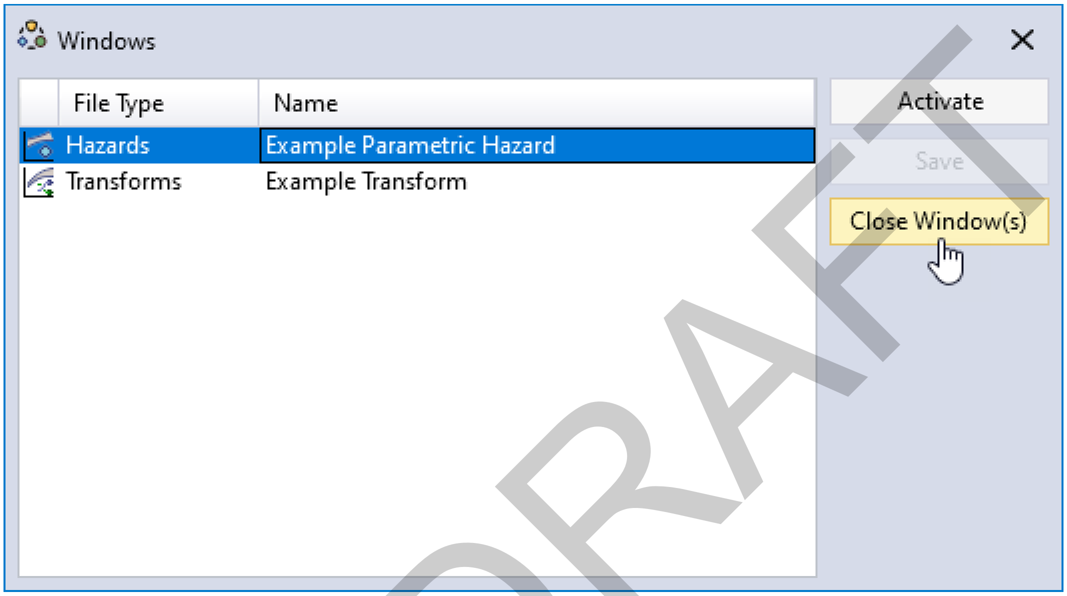


Figure 14 – Windows Dialog.

Help

From the **Help** menu, you can access this **User Guide**, view the **Terms & Conditions for Use**, or view the **About RMC-TotalRisk** splash screen.

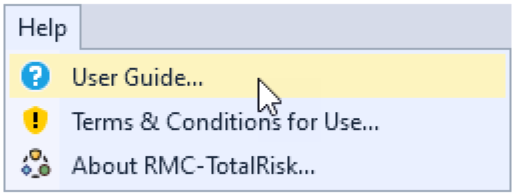


Figure 15 – Help Menu.

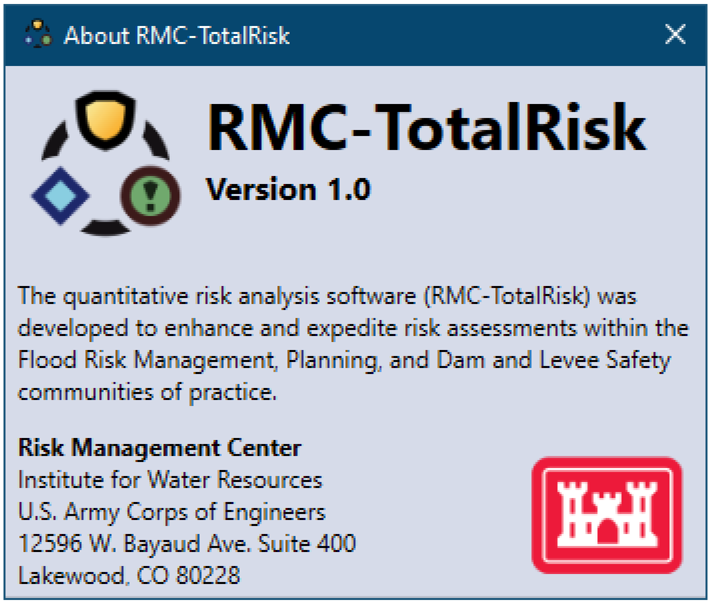


Figure 16 – About RMC-TotalRisk Splash Screen.

Tool Bar

The **Tool Bar** is located on the main window, below the **Menu Bar**. The buttons on the tool bar provide frequently used options under the **File** menu:

- New Project
- Open Project
- Save Project

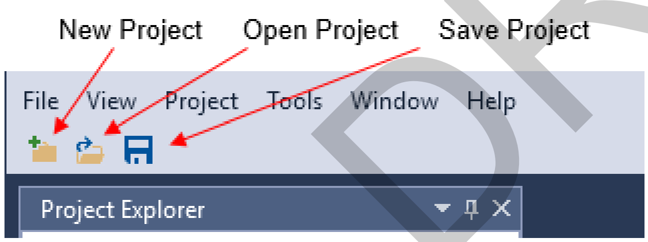


Figure 17 – RMC-TotalRisk Tool Bar.

Window Layout

In RMC-TotalRisk, you can customize the position, size, and behavior of windows to create window layouts that work best for you. When you customize the layout, RMC-TotalRisk will remember the configuration. For example, if you change the docking location of the **Project Explorer** and then close RMC-TotalRisk, the next time that you open the software, the **Project Explorer** will be docked in that same location.

Types of Windows

The RMC-TotalRisk layout is made up of four basic window types: the **Project Explorer**, **Tabbed Documents**, **Properties**, and **Message Window** (Figure 4). Document tabs provide the editing and reviewing space for the various project components including hazard, response, and consequence functions. The windows can be resized and dragged by their title bar, the document windows can be dragged by their tab. On the Project Explorer, Properties, and Message Window title bar, there is a drop-down with other window options.

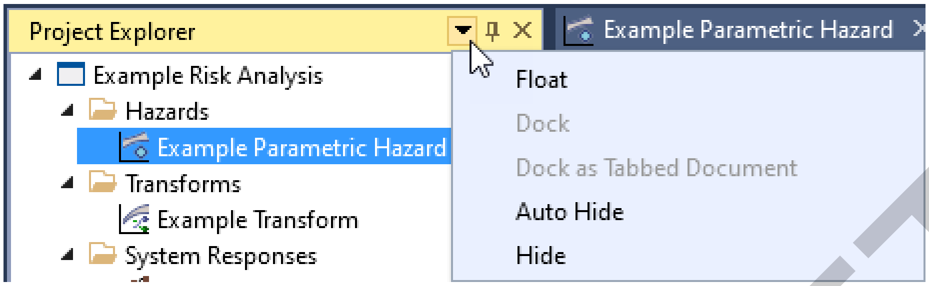


Figure 18 – Tools Window Options.

With the tabbed documents, you can right-click on the document tab to set other options on the window. These options include docking, floating, and hiding windows.

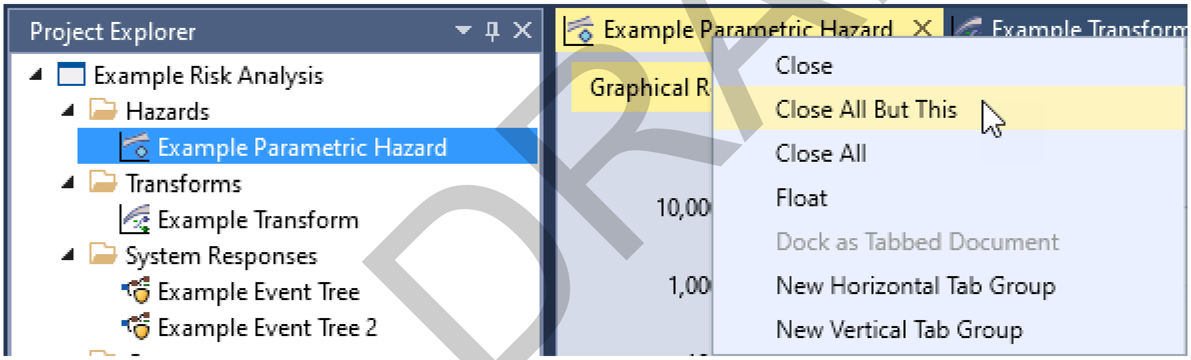


Figure 19 – Document Window Options.

Tab Groups

The tabbed documents can be grouped together to enhance your ability to manage a limited workspace while you are working with two or more open documents in RMC-TotalRisk. You can organize multiple document windows and tool windows into either vertical or horizontal tab groups or move documents from one group to another. The windows and tab groups can also be floated and moved to different monitors. When you need to view or edit two documents at once, you can split windows by creating two horizontal tab groups as shown below in Figure 20.

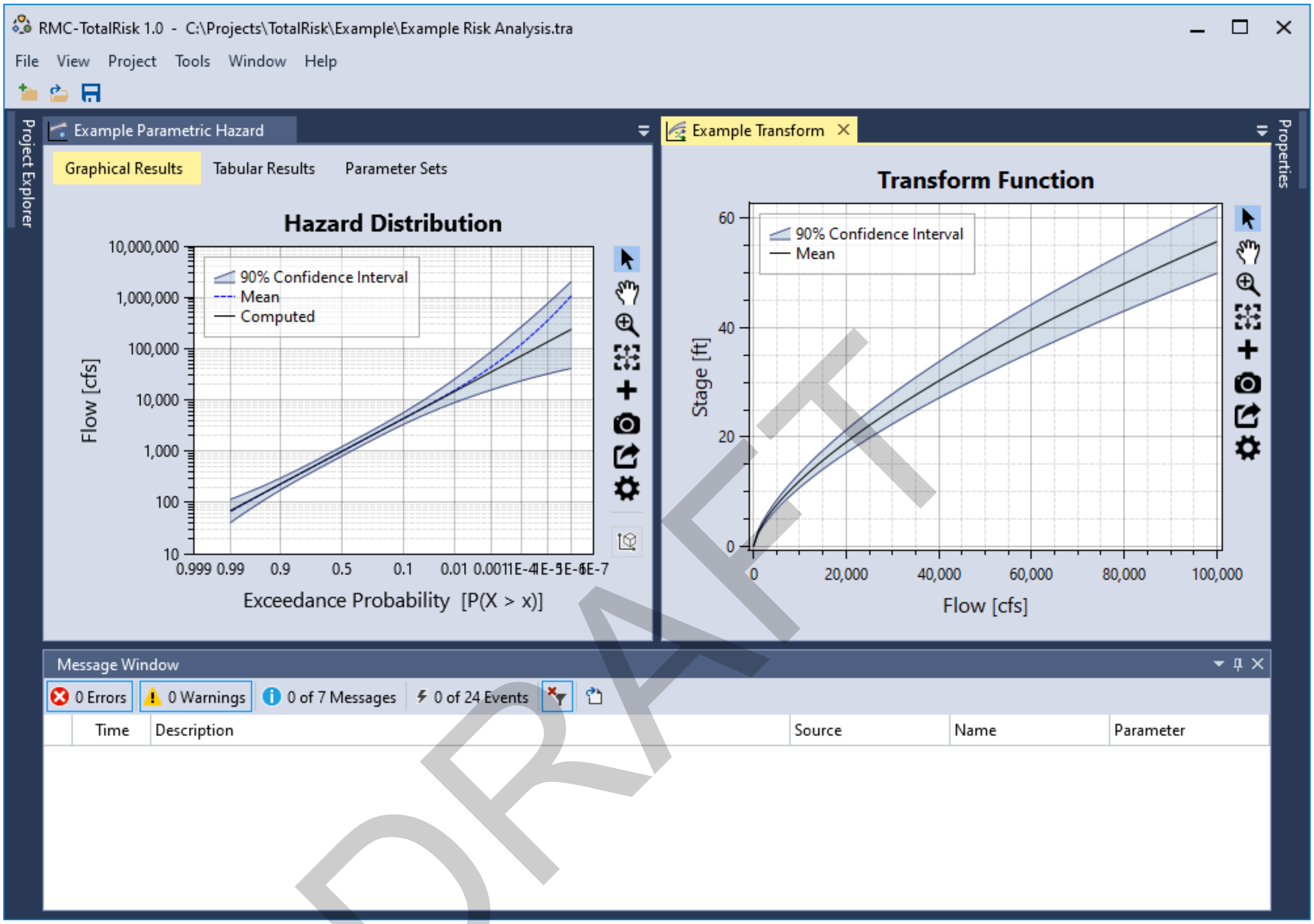


Figure 20 – Split Document Windows.

Arrange and Dock Windows

A document window can be *docked*, so that it will be in the **Tabbed Documents** area, or the document can be *floated* as a separate window independent of the main window. You can arrange windows in the following ways:

- Dock tool windows to the edge of the main window frame.
- Float tool and document windows over or outside the main window.
- Hide tool windows along the edge of the main window.
- Display windows on different monitors.
- Reset window placement to the default layout by choosing **View** > **Reset Default Layout**.

Arrange windows by dragging or right-clicking the title bar or tab of the window to be arranged.

Dock Windows

When you click and drag the title bar of a tool window, or the tab of a document window, a cross shaped window placement guide will appear. During the drag operation, when the mouse cursor is over one of the arrows in the guide, a shaded area will appear that shows you where the window will be docked if you release the mouse button. An example of the window placement guide is shown below in Figure 21 and Figure 22.

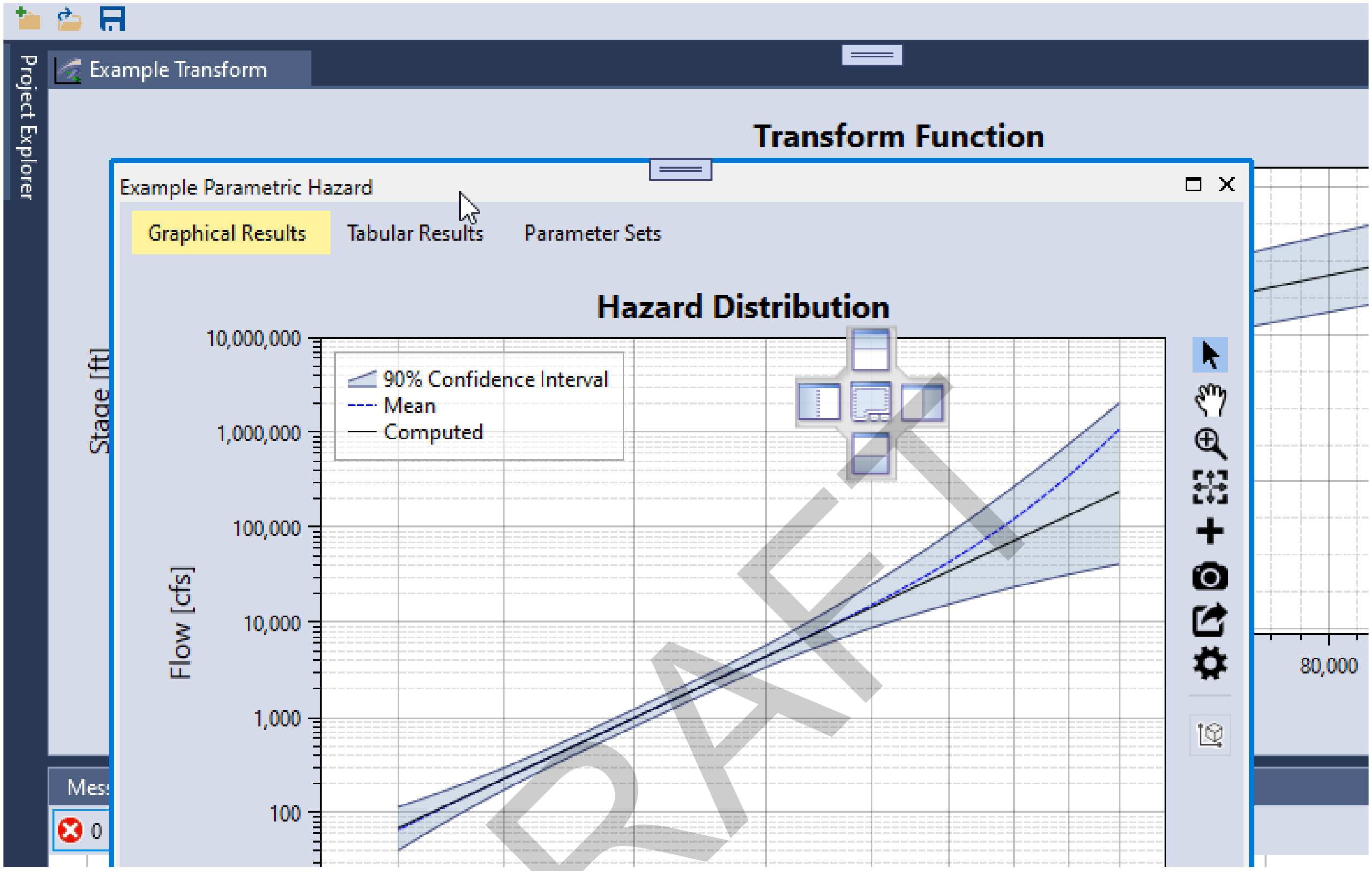


Figure 21 – Moving and Docking Document Windows.

Figure 22 shows the **Properties Windows** being docked below the **Project Explorer**. The new location is demarcated by the light blue shared area.

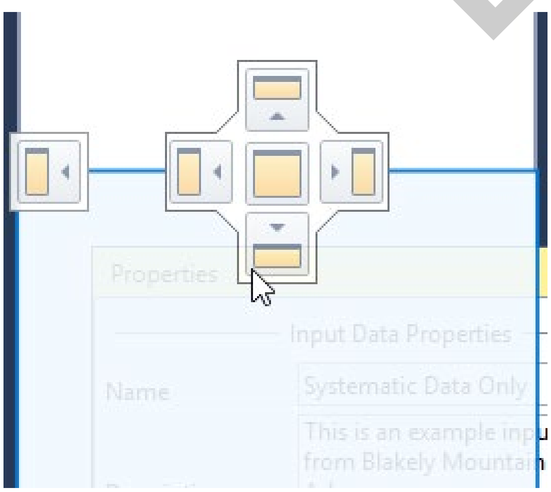


Figure 22 – Example of Docking the Properties Window Below the Project Explorer.

Close and Auto-Hide Tool Windows

You can close a tool window by clicking on the **X** in the upper right of the title bar. To reopen the tool window, navigate to the **View** menu and select the desired tool window to show. Tool windows have an *auto-hide* feature, which causes a window to slide out of the way when you use a different window. When a window is auto-hidden, the window name appears on the tab at the edge of the main window as shown in Figure 23. To show the window again, move your mouse cursor over the tab so that the window slides back into view.

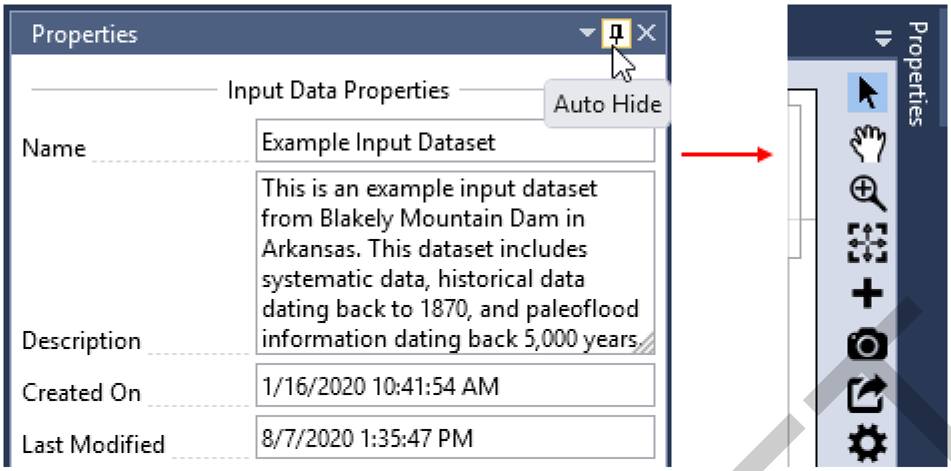


Figure 23 – Auto-Hide Tool Window.

Project Explorer

The **Project Explorer**, which is typically on the left-hand side of the main window, shows a graphical representation of the hierarchy of elements within your project. After you create a new project, you can use the **Project Explorer** to view, navigate, and manage the project elements.

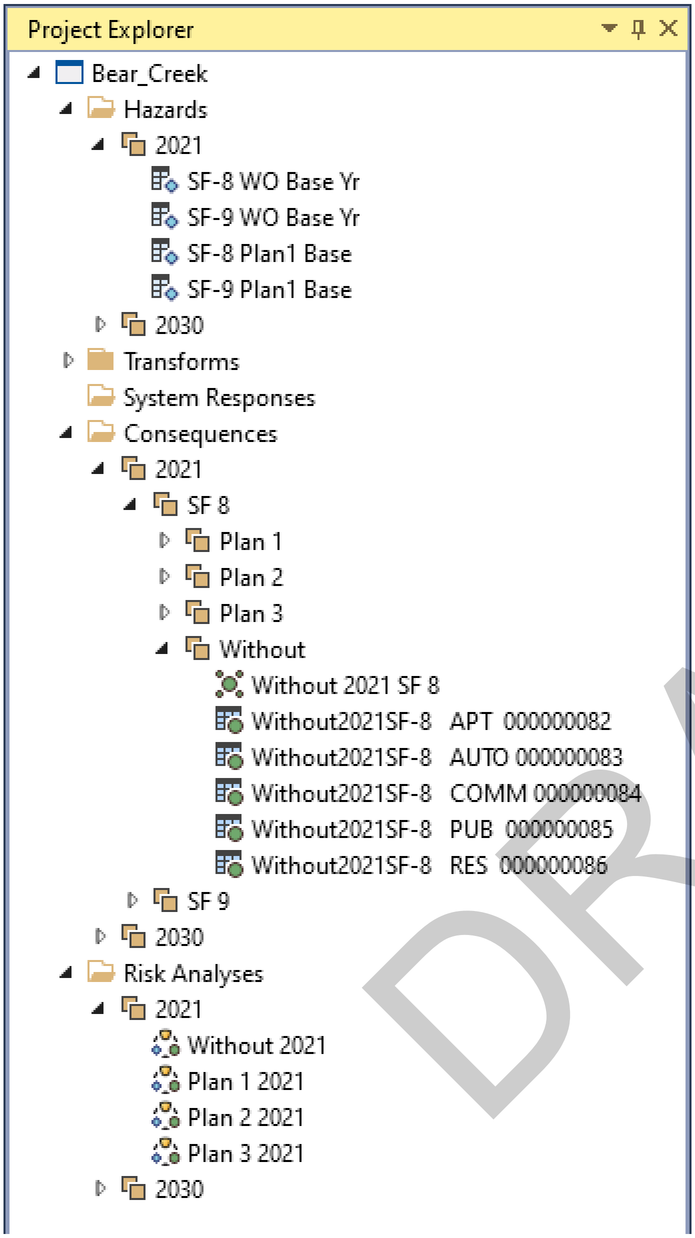


Figure 24 – Project Explorer.

Project elements are organized under the **Hazards**, **Transforms**, **System Responses**, **Consequences**, and **Risk Analyses** folder headers. Many menu commands are available from the right-click menu on various items in the Project Explorer. You can create new elements, create groups, or sort the items in each folder, by right-clicking the folder icon or name.

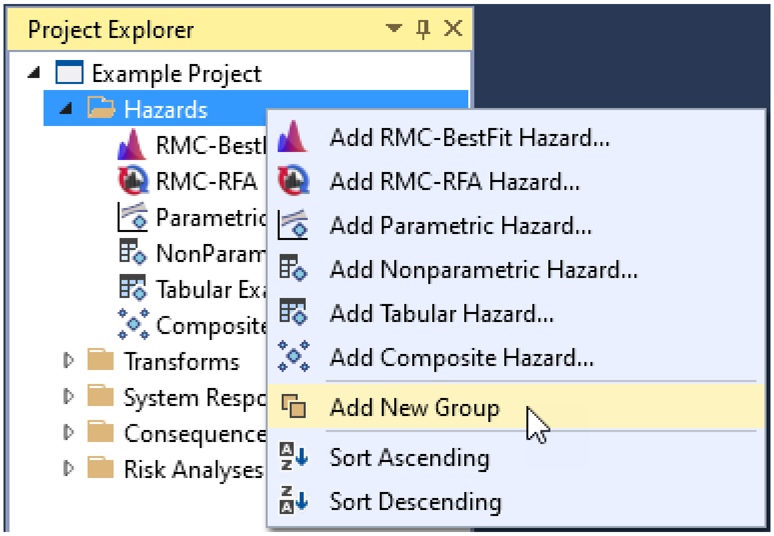


Figure 25 – Project Explorer Element Collection Header Right-Click Menu.

When right-clicking an individual project element, the following commands are made available: group, edit, copy, rename, delete, move up, and move down. When multiple project elements are selected, three right-click menu commands are available: group, edit, and delete. Double-clicking a project element will open it for editing.

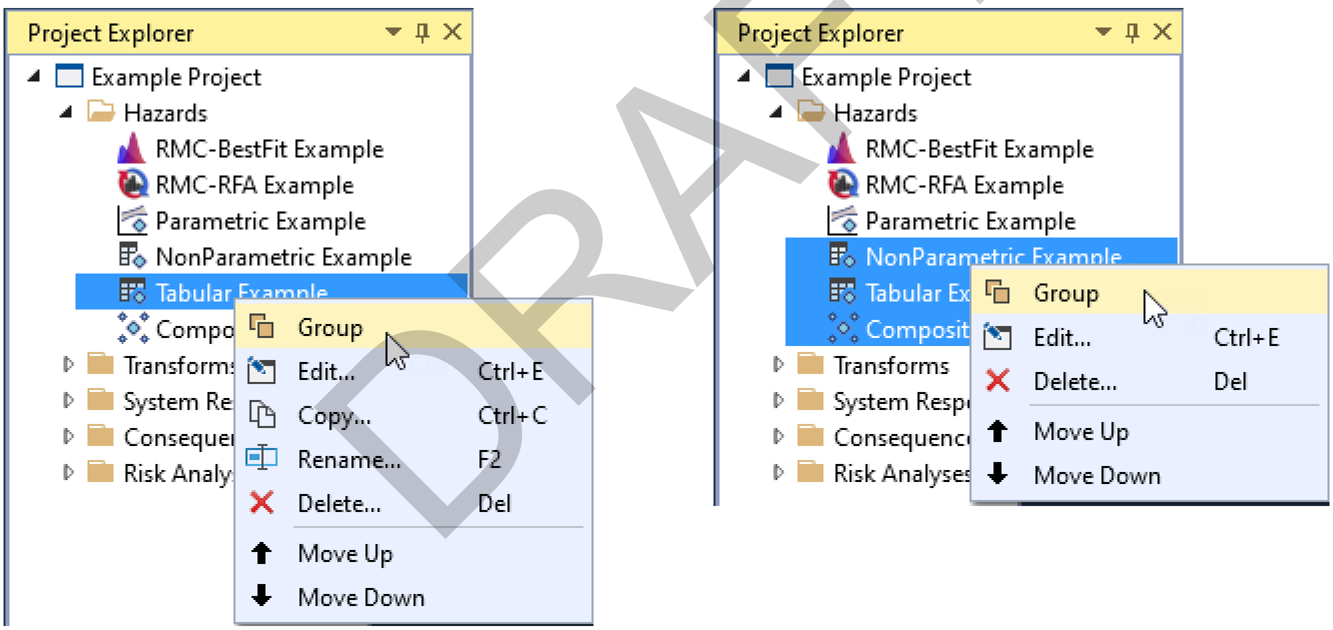


Figure 26 – Project Explorer Element Right-Click Menu. Options change when more than one item is selected.

You can move individual project elements by left-click-hold and dragging the element. A horizontal line indicates where the element will be moved, as shown in Figure 27. You can also drag and drop input data from one RMC-TotalRisk project to another.

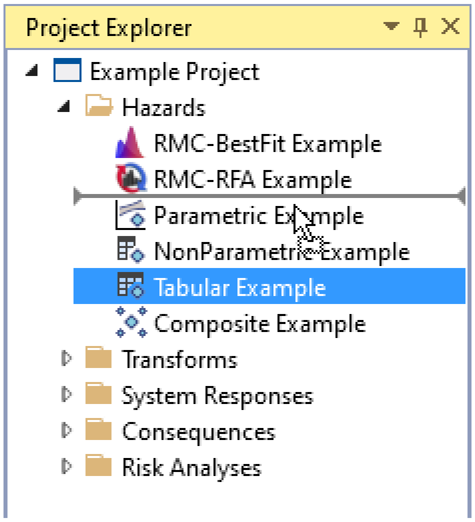


Figure 27 – Project Explorer Element Drag and Drop.

Grouping provides a way to manage the project explorer by consolidating project elements into sub-groups. When right-clicking a group element, all commands from the root folder are available plus Ungroup and Rename.

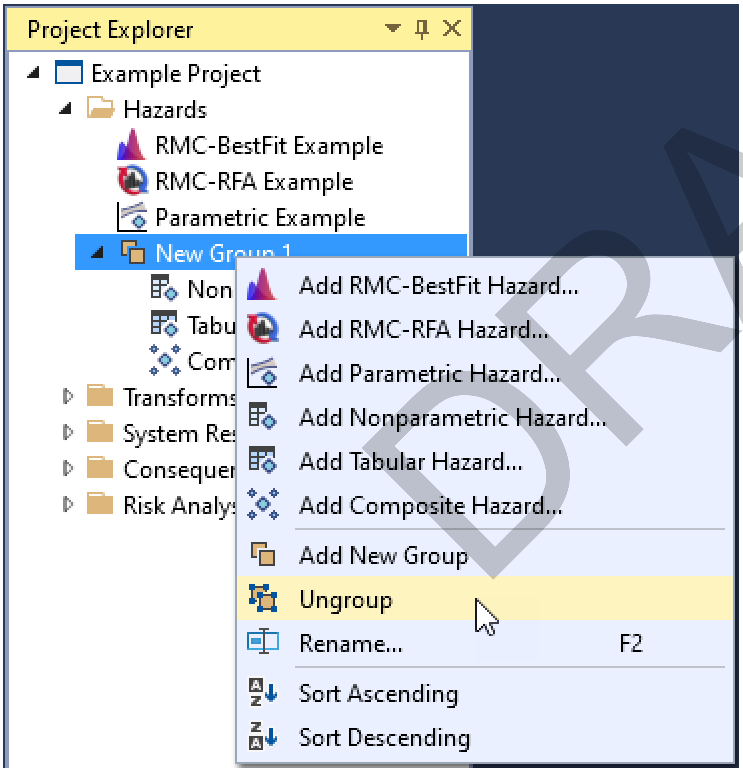


Figure 28. Project Explorer Group Element.

Tabbed Documents

In RMC-TotalRisk, *document windows* contain the project element data, such as input tabular data, event trees, and risk analyses. When you open a project element for editing, it will automatically open into the tabbed document group, which is typically located in the center of the main window (see Figure 29). You can reorder the tabbed documents, drag, or float them outside of the main window. When you click on, or activate, a document window, the associated project element properties will be shown in the **Properties Window**.

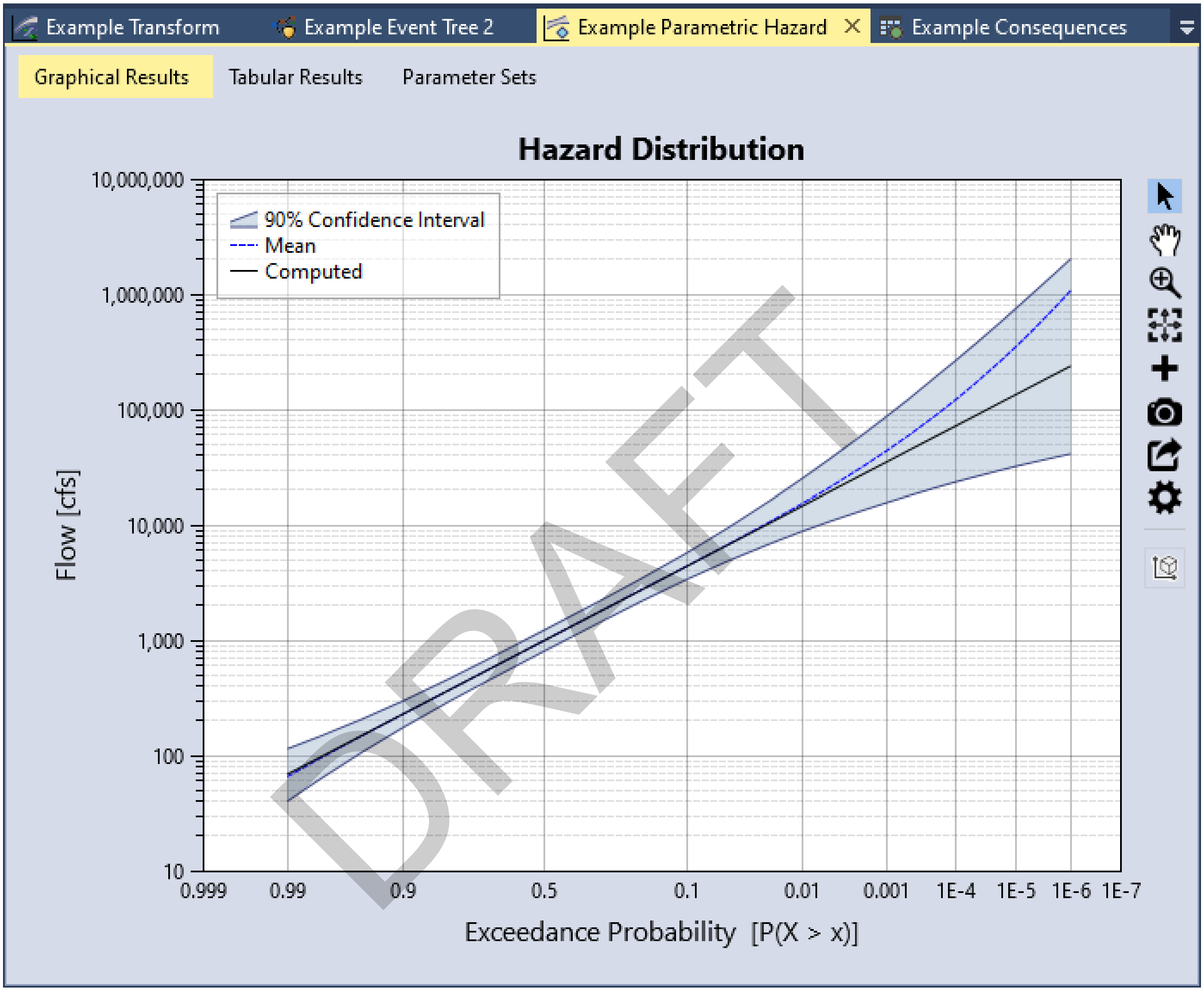


Figure 29 – Tabbed Document Group.

Properties Window

The **Properties Window**, typically on the right-hand side of the main window, displays the properties for the project and selected project elements. To access the element properties, open the element for edit (Figure 26). Some properties are common among all project elements, such as **Name** and **Description**, while others are unique to the specific elements. Properties are organized into groups for easier navigation. When you click on a property, the property description will be placed at the bottom of the properties window as shown in Figure 30. All analyses will be run from the properties window.

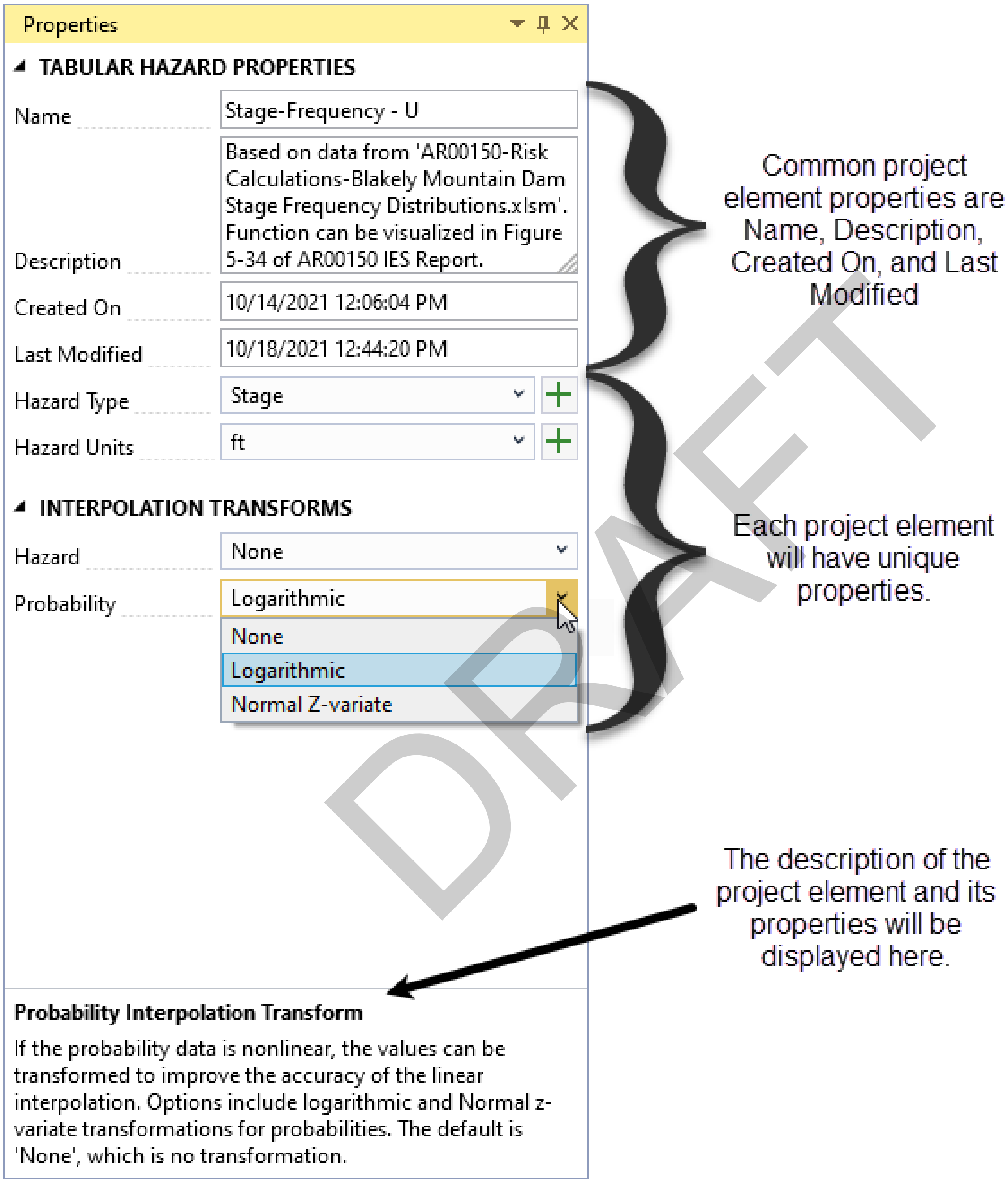


Figure 30 – Properties Window.

Message Window

The **Message Window** shows you errors, warnings, messages, and event logs regarding the current state of your project. If there are any errors in your project file, they are listed here. The **Message Window** lets you perform the following tasks:

- Display the errors, warnings, messages, and events produced while you work in RMC-TotalRisk.
- Double-click any error message entry to open the project element where the problem occurs.
- Filter the type of entries that are displayed in the Message Window. The default is to only display errors and warnings.
- Export all entries to a text file.

Once you resolve an error, warning, or message, the entry will be removed from the Message Window. You may customize the font color of the various message types by navigating to **Tools** > **Options**. See the Personalize RMC-TotalRisk section for more details.

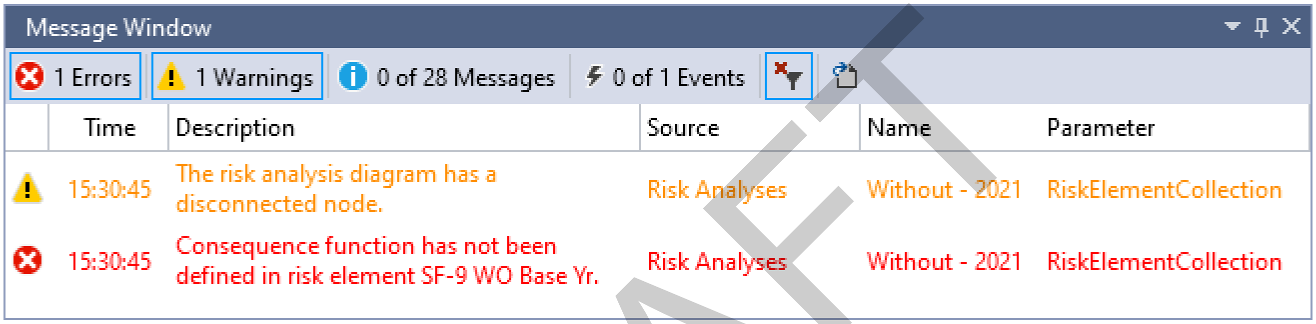


Figure 31 – Message Window.

Personalize RMC-TotalRisk

You can personalize RMC-TotalRisk in various ways to enhance the user experience by navigating to **Tools** > **Options**. The **Options** dialog allows the user to customize the Application, File Management, Message Window, and Default settings.

Application Options

You can set the application color theme to be the Light or Blue theme as shown in Figure 32 and Figure 33. The default is set to the Light theme. You can choose to **Save the window docking layout on close** so that RMC-TotalRisk will remember it when you reopen the application. You can also set the number of window items shown in the **Window** menu and the number of recent project items shown in the Recent Project list under the **File** menu.

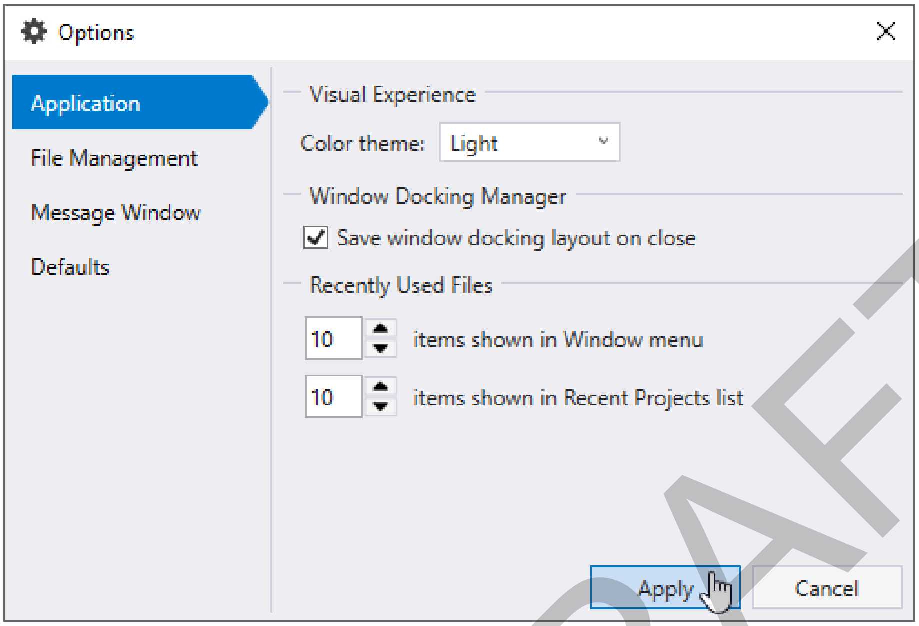


Figure 32 – Options Dialog with Light Color Theme.

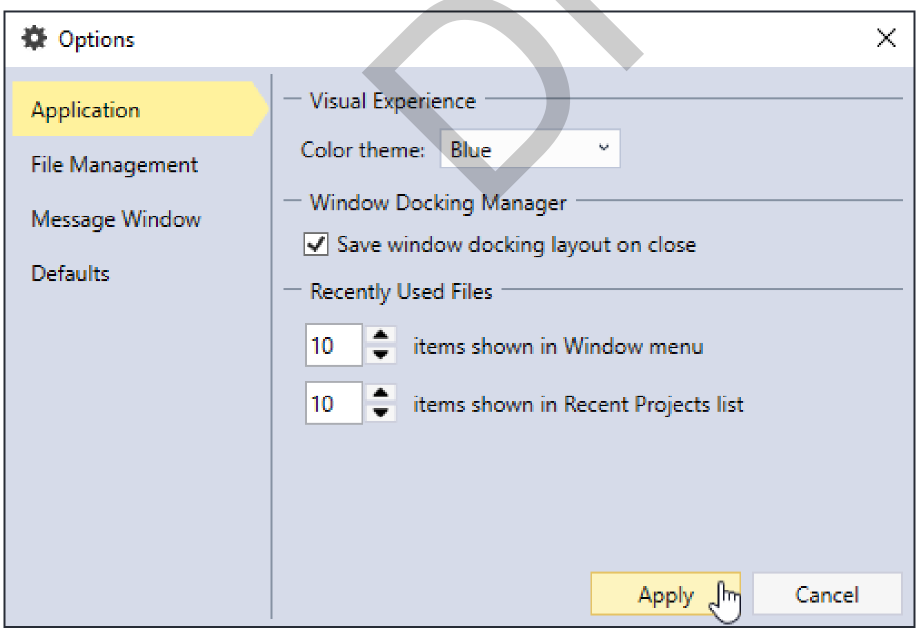


Figure 33 – Options Dialog with Blue Color Theme.

File Management Options

RMC-TotalRisk project files are saved as SQLite databases. SQLite is a self-contained, high-reliability, SQL database engine, which is also one of the most used database engine in the world (https://www.sqlite.org/). Database files can grow quickly as you use them, sometimes hindering performance. They can also occasionally become corrupt or damaged. You can use the **Tools** > **Compact & Optimize Project File** command to prevent or fix these problems. You can also set RMC-TotalRisk to **Compact & optimize project file on close**.

You can set the time interval in which a project backup file is created. A file with the extension .bak is automatically created when a project is opened. If the project closes successfully, then the .bak file is deleted. The database file can be damaged or corrupted, or the system could close unexpectedly causing you to lose important data, so on occasion, you might need to restore the project from a backup file by selecting **Tools** > **Restore from Backup**.

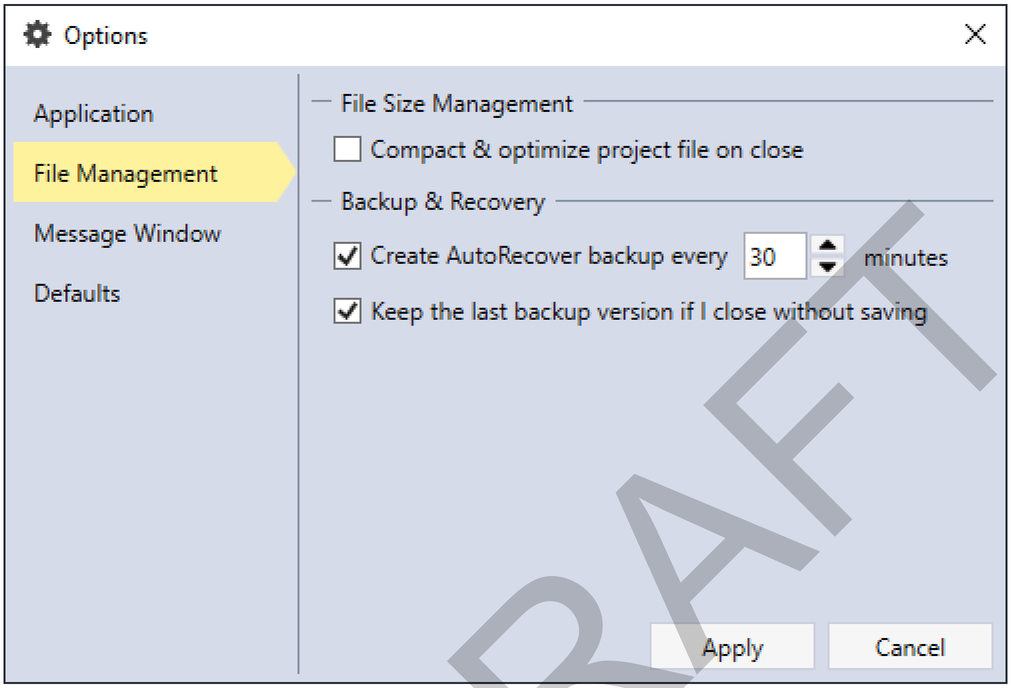


Figure 34 – File Management Options.

Message Window Options

You can adjust the auditory and visual setting for the **Message Window**. You can choose to turn on or off the beep sound effect and select the font color for the different message types, as shown below in Figure 35.

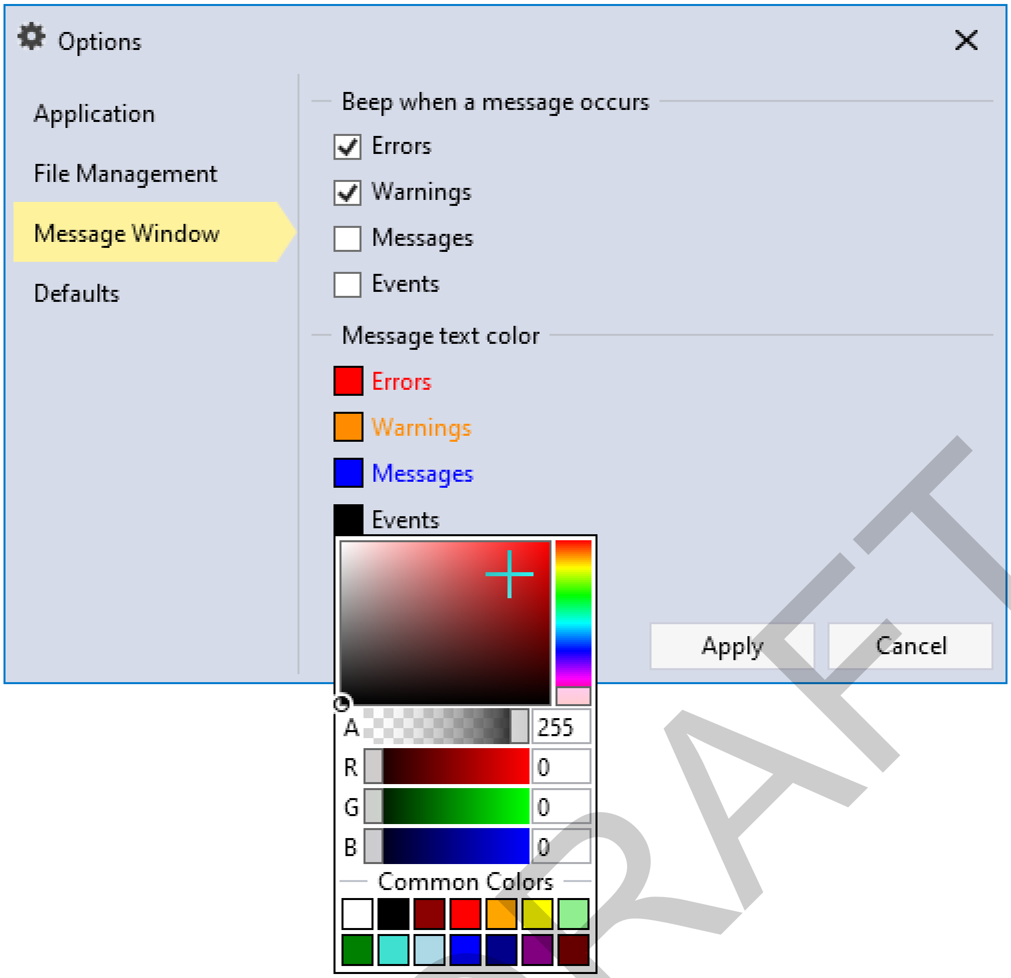


Figure 35 – Message Window Options.

Default Options

You can set the default project location directory, and the default decimal digits for the project inputs and outputs (Figure 36 below). In addition, the default hazard type and units can be set for each input function category in TotalRisk. For example, by default, when you create a new hazard function, the hazard type and unit will automatically be set to **Stage** and **ft**, respectively.

If the desired hazard type or unit is missing, click the + button to add a new option, if you want to delete an option, click the ✖ button that appears inside the dropdown.

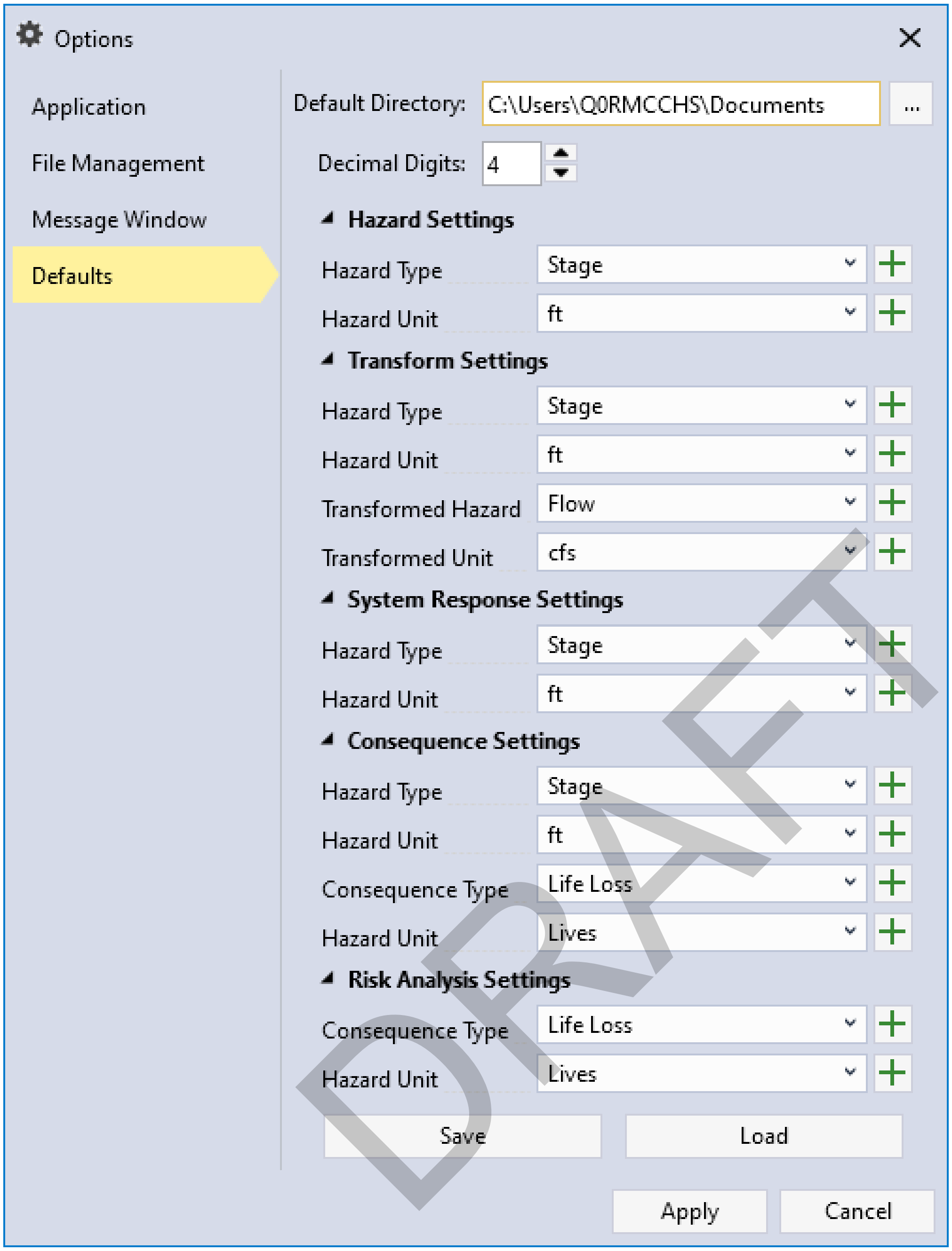


Figure 36 – Default Options.

Plot Features

RMC-TotalRisk has plot features which allow you to examine and customize the plots. There is a tool bar located to the right of each plot, which allows you to interact with the plot in the following ways:

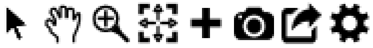


Figure 37 – RMC-TotalRisk Plot Features.

Track Data

Track Data to get the X-Y point values (Figure 38). Click on any plotted point or line in the graph to show a tooltip displaying the plot series name and X and Y data points.

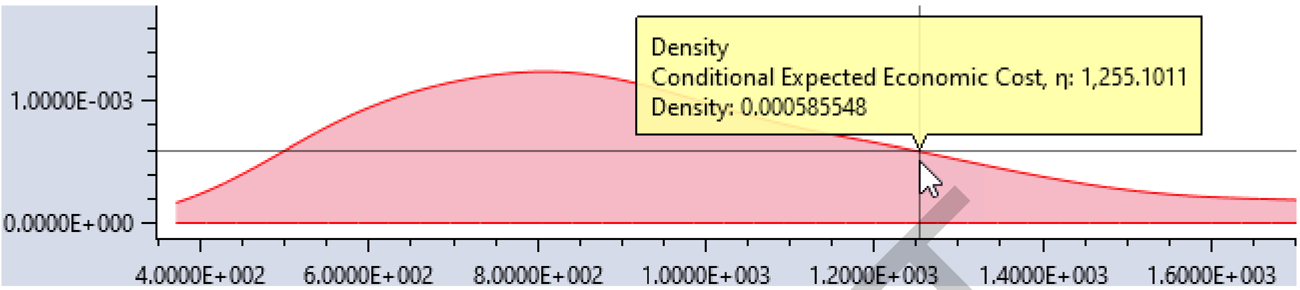


Figure 38 – Track Data on Plot.

Pan

Pan/move the plot area by click-hold-dragging on the graph. The plot can be panned in any direction, up, down, and side to side. You can also Pan by click-hold-dragging the middle mouse button.

Zoom In

Zoom in on the plot. Zooming works by click-hold-drag highlighting the area of interest with the magnifying glass cursor (Figure 39), or by click-hold-dragging on an axis to restrict zooming to only that axis. You can also zoom in and out using the mouse wheel.

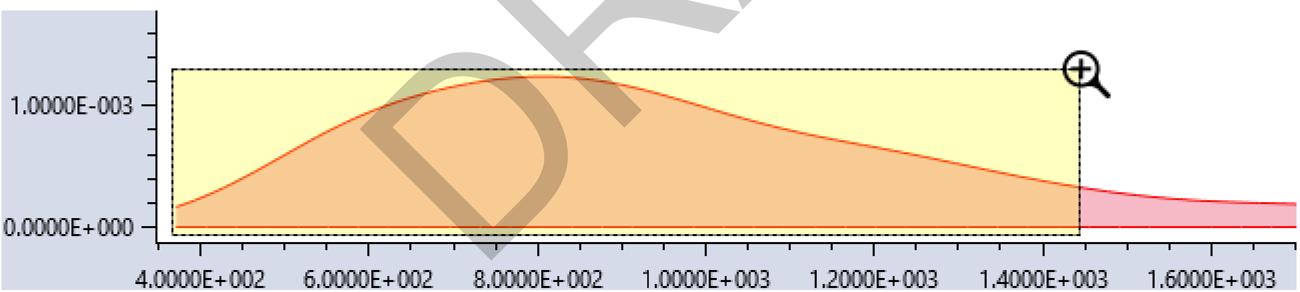


Figure 39 – Zoom In on Plot.

Zoom Out

Zoom out to the plot extents. You can also hit the escape key to zoom out to plot extents.

Add Annotations

Add annotations to the plot (Figure 40). Annotations are elements of the plot that show information that is not part of a plot series. Annotations are not included in the legend and not used by the tracker. You may add the following annotation types to the plot: Arrow, Text, Vertical Line, Horizontal Line, Rectangle, Ellipse, Point, Polygon, and Polyline.

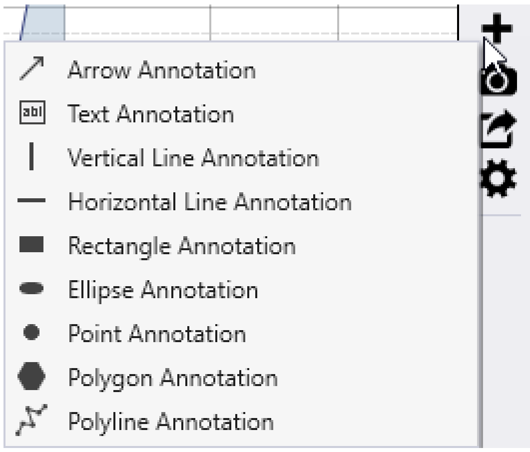


Figure 40 – Plot Annotations.

The annotations can be moved by clicking and dragging them to a new spot. An example of an arrow and horizontal line annotation is shown in Figure 41.

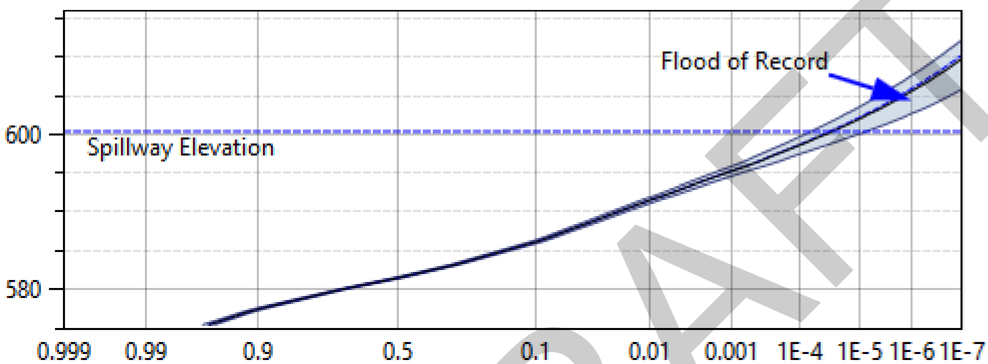


Figure 41 – Example of Arrow Annotation.

Save

Save the plot image as a PNG, PDF, or SVG file. Select from common image sizes or define your own.

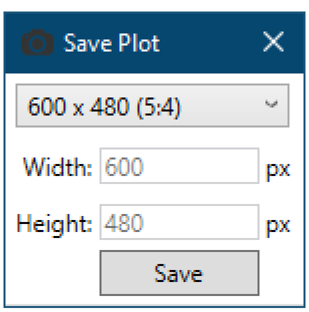


Figure 42 – Set the Width and Height of the Plot Image.

Export

Export plot series data to a Comma Separate (.csv), Excel (.xlsx), or SQLite (.sqlite) file. After clicking the Export Series Data button, a Save As dialog will open. Select the desired file type and give the file a name, then click save. If saving to an existing excel file, the plot series data will be saved as tabs in the existing file.

Plot Properties

Plot Properties to customize appearance. In properties, you can edit the general plot settings, legend, axes, series, and annotations. Click the chevron ▾ in the upper right to open a drop down showing the other plot elements to edit. Changes to plots in RMC-TotalRisk are saved and persist when you open and close a project.

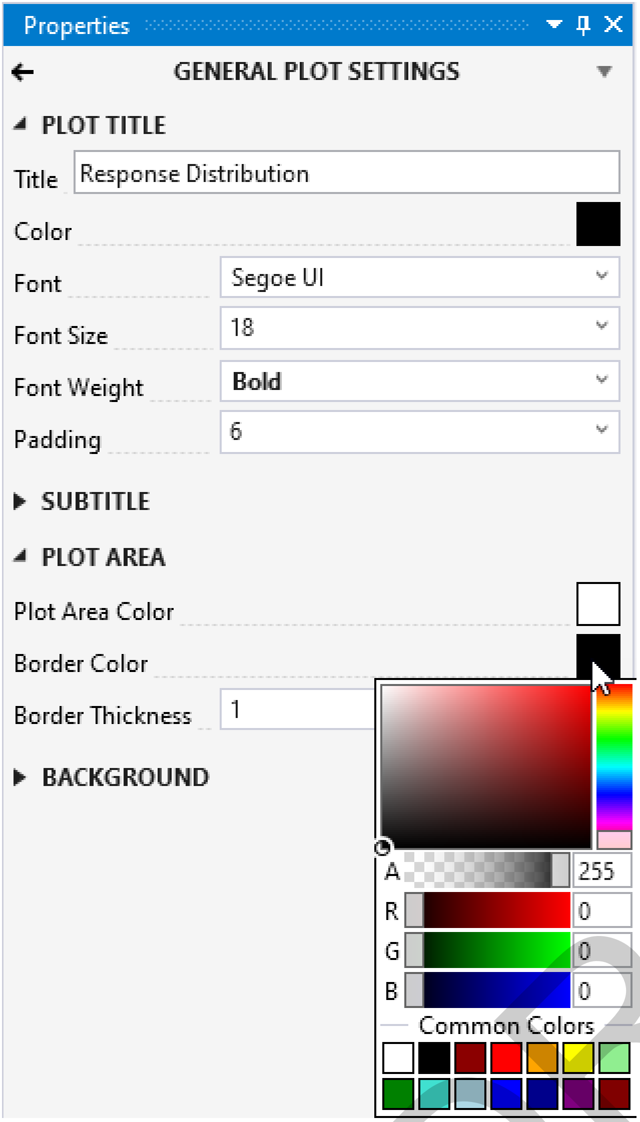


Figure 43 – Plot Properties.

Table Features

Several tables in RMC-TotalRisk contain the **Add and Remove Row Tools**, the **Export and Copy Tools**, and the **Row Selection Tools** toolbars.

Table Add/Insert/Remove Row Tools

Add Row

This tool adds a row to the bottom of the table.

Insert Row

This tool inserts a row above the selected cell(s).

Delete Row

This tool deletes the row(s) of the selected cell(s).

Table Export and Copy Tools

Select All Cells

This tool selects all cells in the table.

Copy Selected Cells

This tool copies cells selected in the table. The information is copied to the clipboard and needs to be pasted to another application (e.g., Microsoft Excel®) for saving.

Copy Selected Cells with Table Headers

This tool copies cells selected in the table and the table headers. The information is copied to the clipboard and needs to be pasted to another application (e.g., Microsoft Excel®) for saving.

Paste from Clipboard into Table

This tool pastes data copied from another table into the current table.

Export Table

The Export Table tool opens a Save As browser window, which allows the user to export the data in the table to other formats including Microsoft Excel® (*.xlsx) file. Note, if an existing excel file is selected, it will add the table to the existing file as a new tab.

Table Row Selection Tools

Select Rows By Attribute

This tool opens the Select By Attribute dialog box (Figure 44), which allows the user to perform queries, make selections, and locate features in the table.

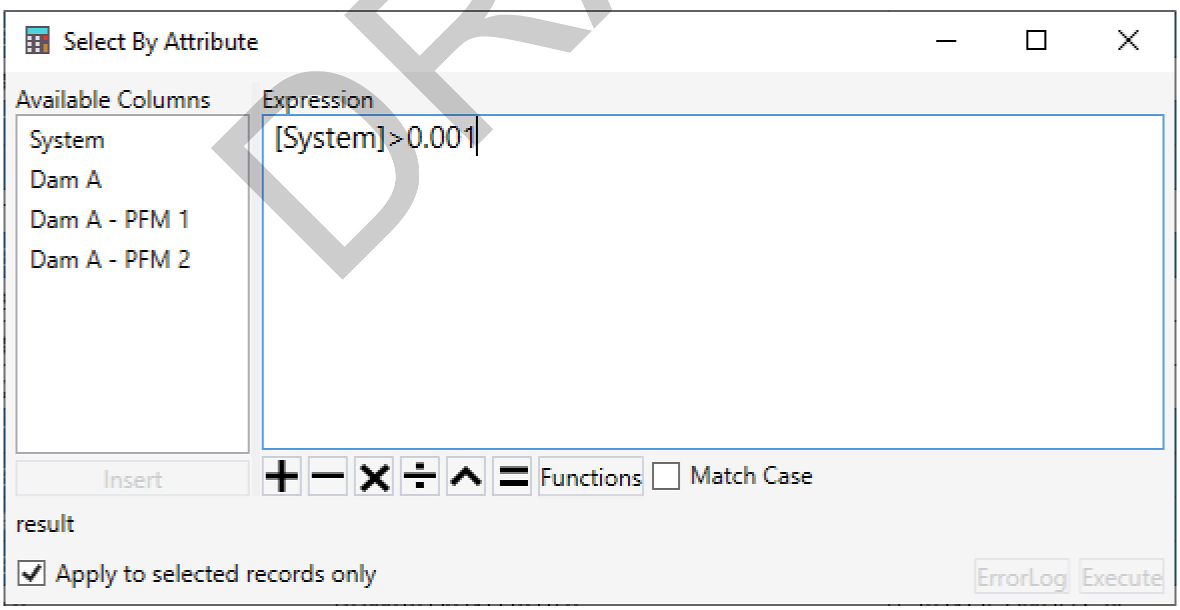


Figure 44 – Select By Attribute Dialog.

Show All Rows

This tool allows the user to display all rows (selected or unselected) in the table.

Show Selected Rows Only

This tool allows the user to only display rows selected in the table.

Deselect All Rows

This tool unselects all rows in the table.

Table Column Features

RMC-TotalRisk table columns can be sorted, searched, and when numeric they can have summary statistics generated (Figure 45). Sorting can be done by right-clicking on a column header and selecting the desired sort option or double clicking on the column header to sort. Note, double clicking a column header that is already sorted will sort in the opposite order.

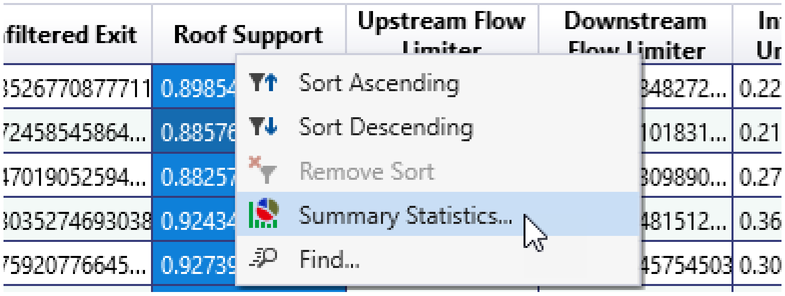


Figure 45 – Table column header right-click options.

Viewing summary statistics can be a very useful tool to view the data in a column. Note that you can check the Selected Rows Only checkbox to get summary statistics for only selected rows (e.g. rows where "SRP" is greater than the 25th percentile).

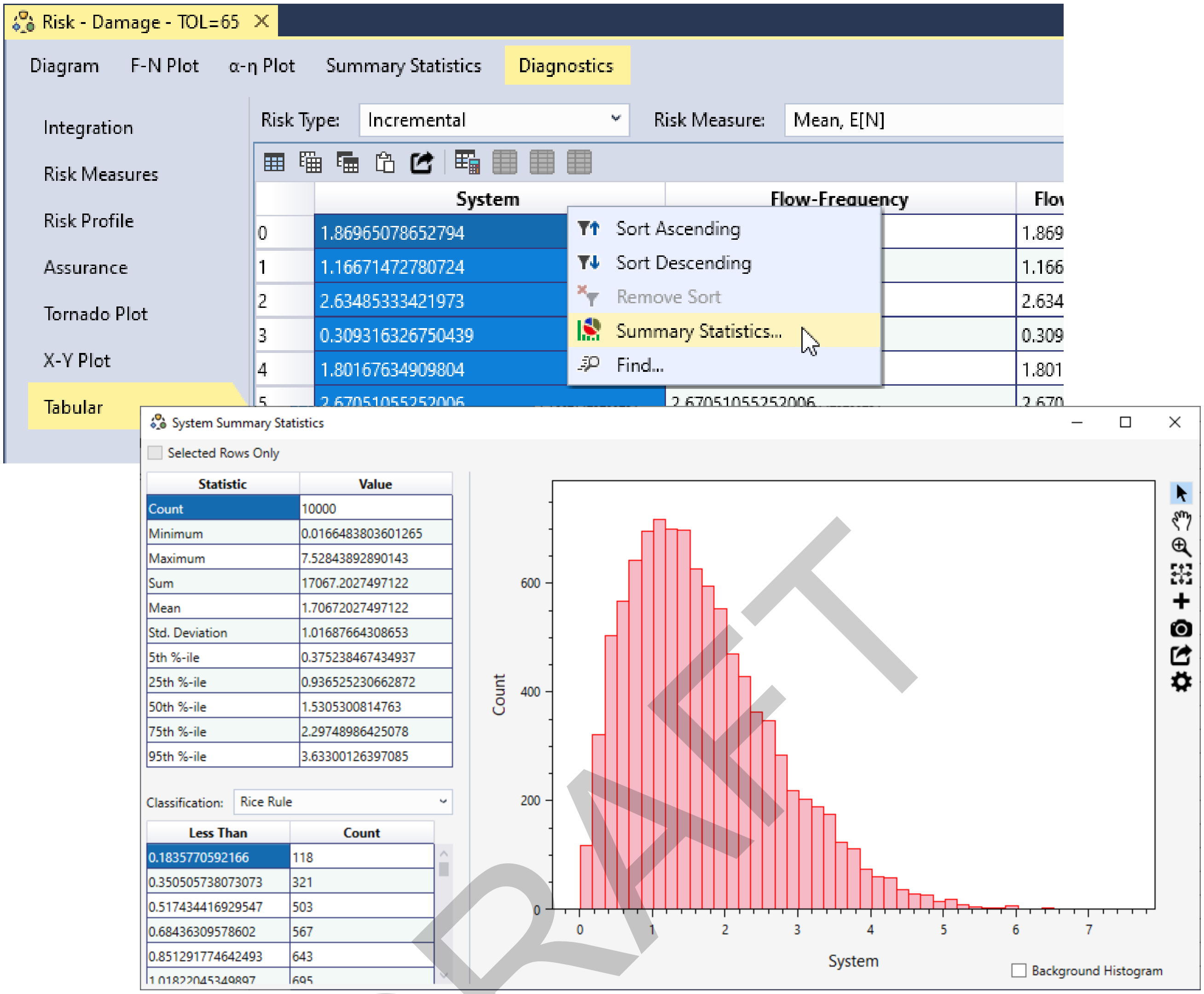


Figure 46 – Table Column Summary Statistics Dialog.

Working with RMC-TotalRisk

In this guide, we will demonstrate how to create a project, enter hazard, transform, response, and consequence functions, set up a risk diagram, perform a risk analysis, and review results.

Create a Project

When you open RMC-TotalRisk, a **Blank Project** file is automatically created, as shown in Figure 47. The blank project is stored in your local temp directory. You may begin working with the blank project file immediately.

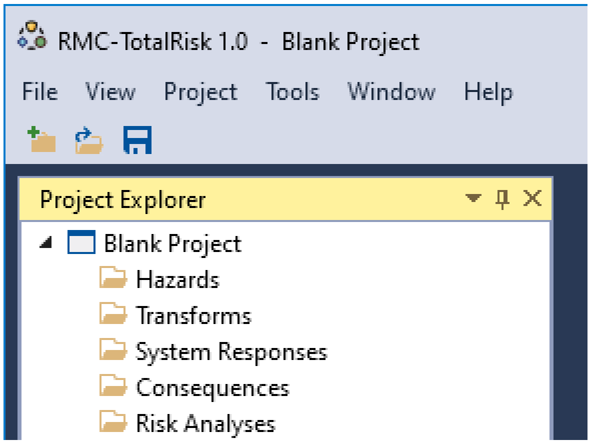


Figure 47 – RMC-TotalRisk Blank Project.

To save changes to the blank project, click the **Save** button on the tool bar or under the File menu. This will open the **Save Project As…** prompt. Enter the desired file name and click the save button in the bottom right. Now you are ready to continue working with RMC-TotalRisk.

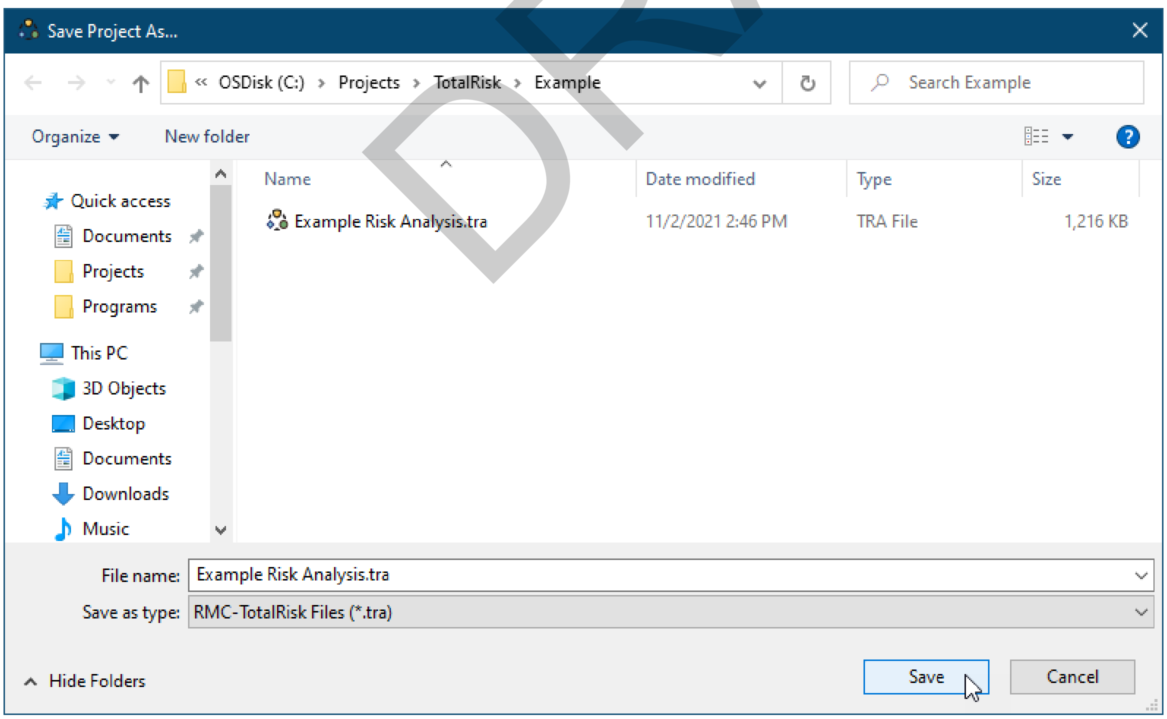


Figure 48 – Save Project As….

A new project can also be created by clicking **New Project…** under the File menu, or by clicking the New Project button located on the tool bar as shown in Figure 49 and Figure 50. If this is the first time you're using RMC-TotalRisk, your recent projects list will be empty.

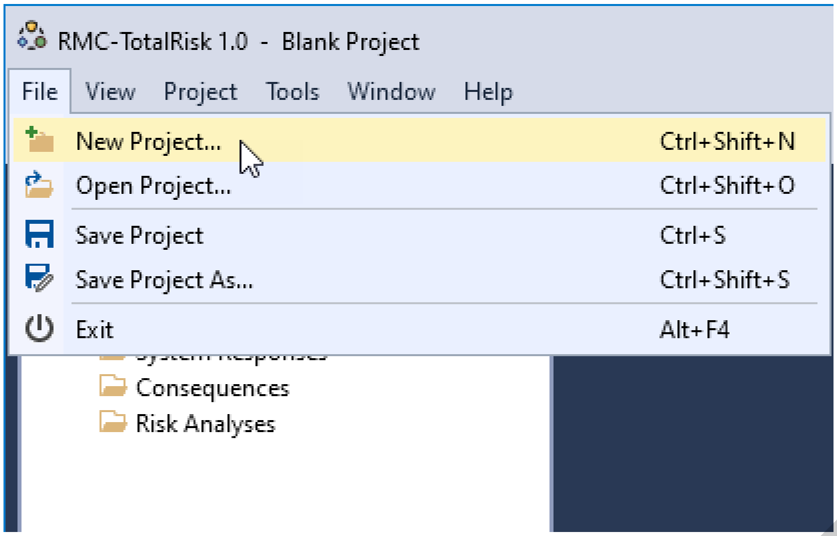


Figure 49 – Create New Project from the File Menu.

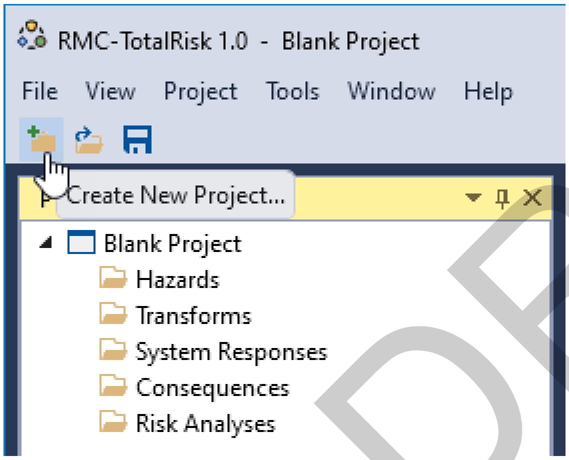


Figure 50 – Create New Project from the Tool Bar.

The project properties will be shown in the **Properties Window**, which is typically located on the right-hand side of the main window. You may edit the project name and description.

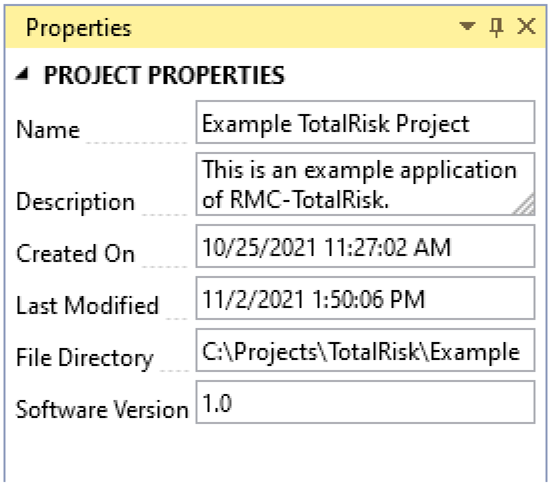


Figure 51 – Project Properties.

Overview of the Risk Analysis Framework

In RMC-TotalRisk, a risk analysis computes the risk associated with a collection of potential failure modes for each component in the system. A failure mode is composed of a hazard, the system response to the hazard, and the consequences given the response to the hazard. A non-failure mode is composed of a hazard and the non-failure consequences given the hazard.

The conceptual risk analysis process for a levee with a single failure mode and a single system component is shown in Figure 52 below. Beginning in the top left of the figure, the flood hazard is defined by an annual maximum 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 system response function is defined by a probability of failure given WSE, 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 numerically integrating over these functions following Figure 52. Greater details on the mathematics of risk analysis are provided in the technical reference [1]. Additional details on risk analysis for flood risk management can be found in [3] and [4].

Figure 52 illustrates the key inputs for a single failure mode for a single system component. Starting from the top left of Figure 52 and moving clockwise, the key inputs are as follows:

- **<u>Hazard Function</u>**: A hazard function describes the exceedance probabilities of various hazard levels. Hazard functions are also commonly referred to as *frequency curves*. Examples include annual maximum peak flow-frequency, peak reservoir pool stage-frequency, and peak ground acceleration.

- **<u>Transform Function</u>**: 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 optional inputs in TotalRisk.

- **<u>System Response Function</u>**: A system response function describes the conditional probability of failure for various hazard levels, such as water surface elevations. System response functions are sometimes referred to as *fragility curves*. The system response function defines the failure mode in RMC-TotalRisk.

- **<u>Consequence Function</u>**: A consequence function describes the consequences of failure or non-failure for various hazard levels, such as annual maximum peak water surface elevations. Consequence functions are also sometimes referred to as *damage functions*.

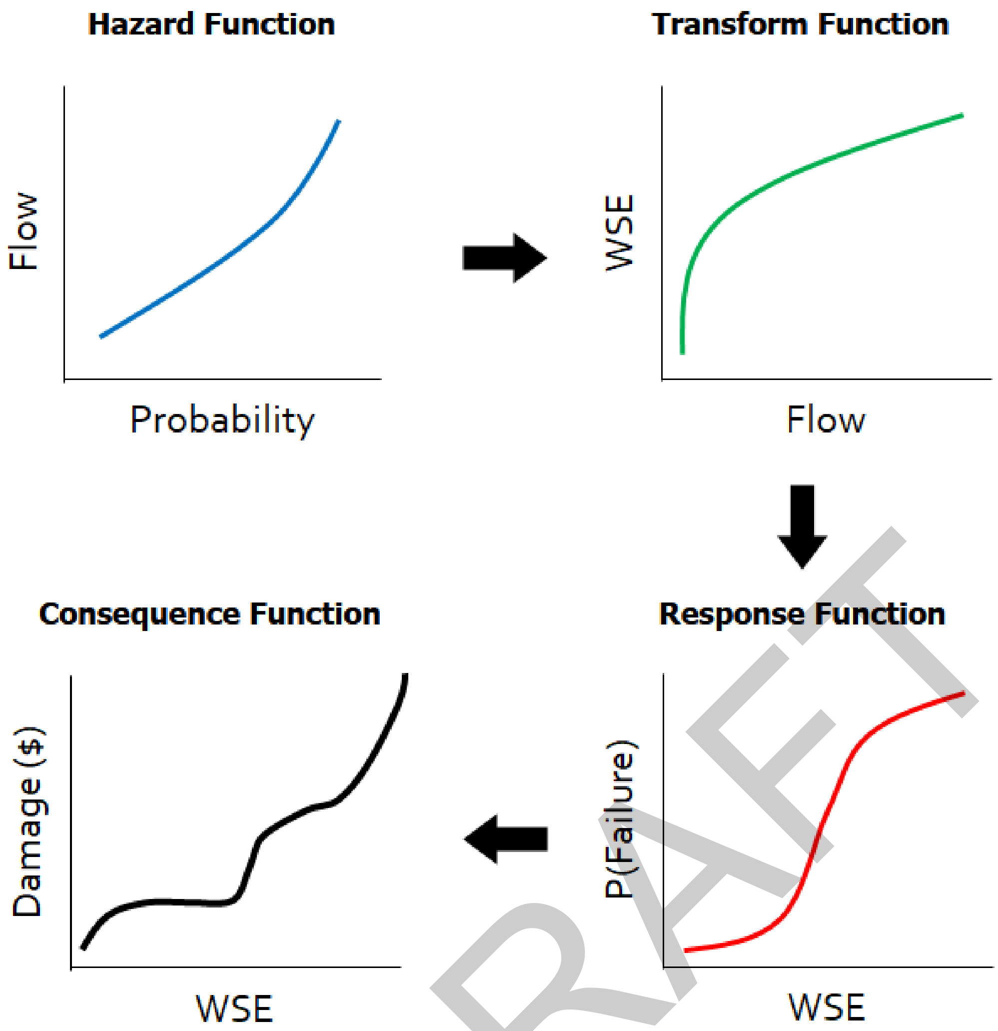


Figure 52 - Levee risk analysis process for a single failure mode and a single system component.

The following chapters describe the hazard, transform, response, and consequence function options available in RMC-TotalRisk.

Hazard Functions

In RMC-TotalRisk, a hazard function is defined by the exceedance probabilities of various hazard levels, such as annual maximum peak flow or water surface elevation. Hazard functions are also commonly referred to as *frequency curves*. In the risk assessment of dams and levees, the annual maximum peak water surface elevation (or stage) or the annual maximum peak ground acceleration are typically the primary hazard parameters for evaluating a potential failure mode [3] [5]. As such, the hazard functions will commonly describe the annual exceedance probability (AEP) of these hazard levels.

There are 6 options for adding a hazard function to RMC-TotalRisk: Import from RMC-BestFit, import from RMC-RFA, Parametric, Nonparametric, Tabular, and Composite. The following sections detail each option for adding hazard functions to RMC-TotalRisk.

RMC-BestFit

The USACE 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 Flood Risk Management, Planning, and Dam and Levee Safety communities of practice [6]. RMC-BestFit can be downloaded from https://www.rmc.usace.army.mil/Software/RMC-BestFit/. Results from an RMC-BestFit analysis can be imported directly into RMC-TotalRisk.

To import results of an RMC-BestFit analysis, right-click on the **Hazards** folder in **Project Explorer** (Figure 53) or from the **Project Menu→Hazards** and select **Add RMC-BestFit Hazard….** A dialog will appear where you enter the name of the hazard function, select the RMC-BestFit project file, and select the Bayesian analysis from the project that you would like to import.

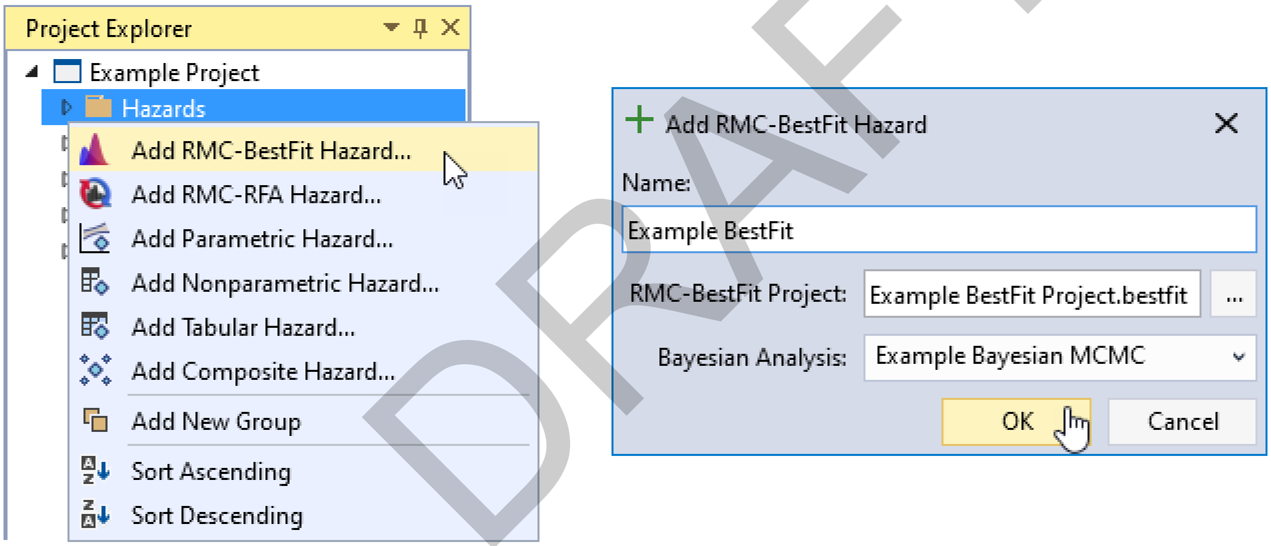


Figure 53 – Add RMC-BestFit hazard function option and RMC-BestFit import dialog.

Once satisfied with the import settings, click **OK** (Figure 53) and the RMC-BestFit hazard function will be added to the **Hazards** folder in **Project Explorer**, the function will be automatically opened into the **Tabbed Documents** area, and the input data properties will be displayed in the **Properties Window**. From here, you can set the **Name**, **Description**, **Hazard Type** and **Hazard Units.**

When you create the new RMC-BestFit hazard function, the H**azard Type** and **Units** will automatically be set to **Stage** and **ft**, respectively. The default hazard type and units can be changed by navigating to **Tools** > **Options** > **Defaults**. See the **Default Options** section for more details.

The **Hazard Type** and **Units** can also be defined using the dropdown menus in the **Properties Window** (Figure 54). If the desired hazard type or unit is missing, click the + button to add a new option, if you want to delete an option, click the ✖ button. Once the **Hazard Type** and **Hazard Units** have been defined, the hazard function is ready to be used.

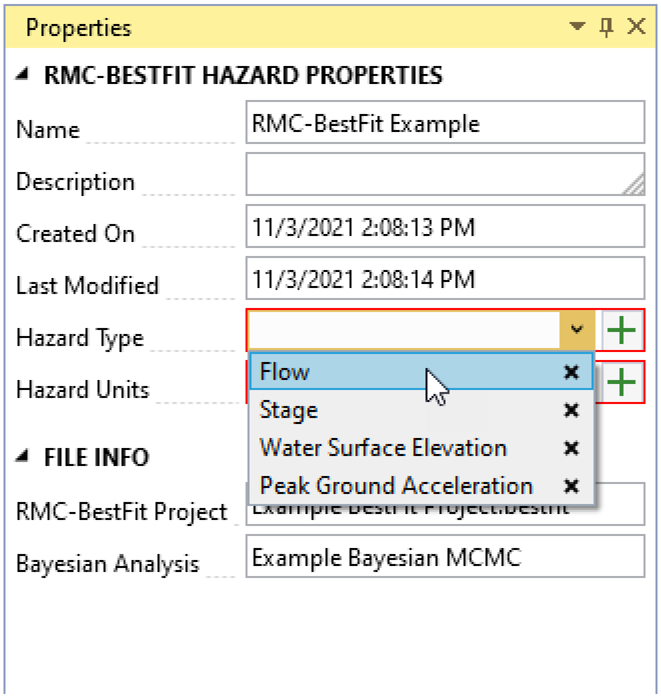


Figure 54 – RMC-BestFit hazard function properties window.

The **Tabbed Document** contains three tabs: **Graphical Results**, **Tabular Results**, and **Parameter Sets**. RMC-TotalRisk provides several tools for exploring the results of the Bayesian analysis. The results will open to the **Graphical Results** tab by default as shown in Figure 55.

Frequency Results

The posterior predictive (mean), posterior mode, and Bayesian credible intervals (90% confidence) will be plotted on the **Graphical Results** tab. For consistency with other hazard function options, these are labeled as mean, computed, and confidence intervals, respectively. By default, the hazard function is plotted as a frequency curve, with exceedance probabilities plotted on the X-axis using a Normal scale, and magnitude on the Y-axis using a logarithmic scale. You may edit the plot properties, flip the axes, or change the axes scales as desired. RMC-TotalRisk will save and persist all changes you have made to the plot.

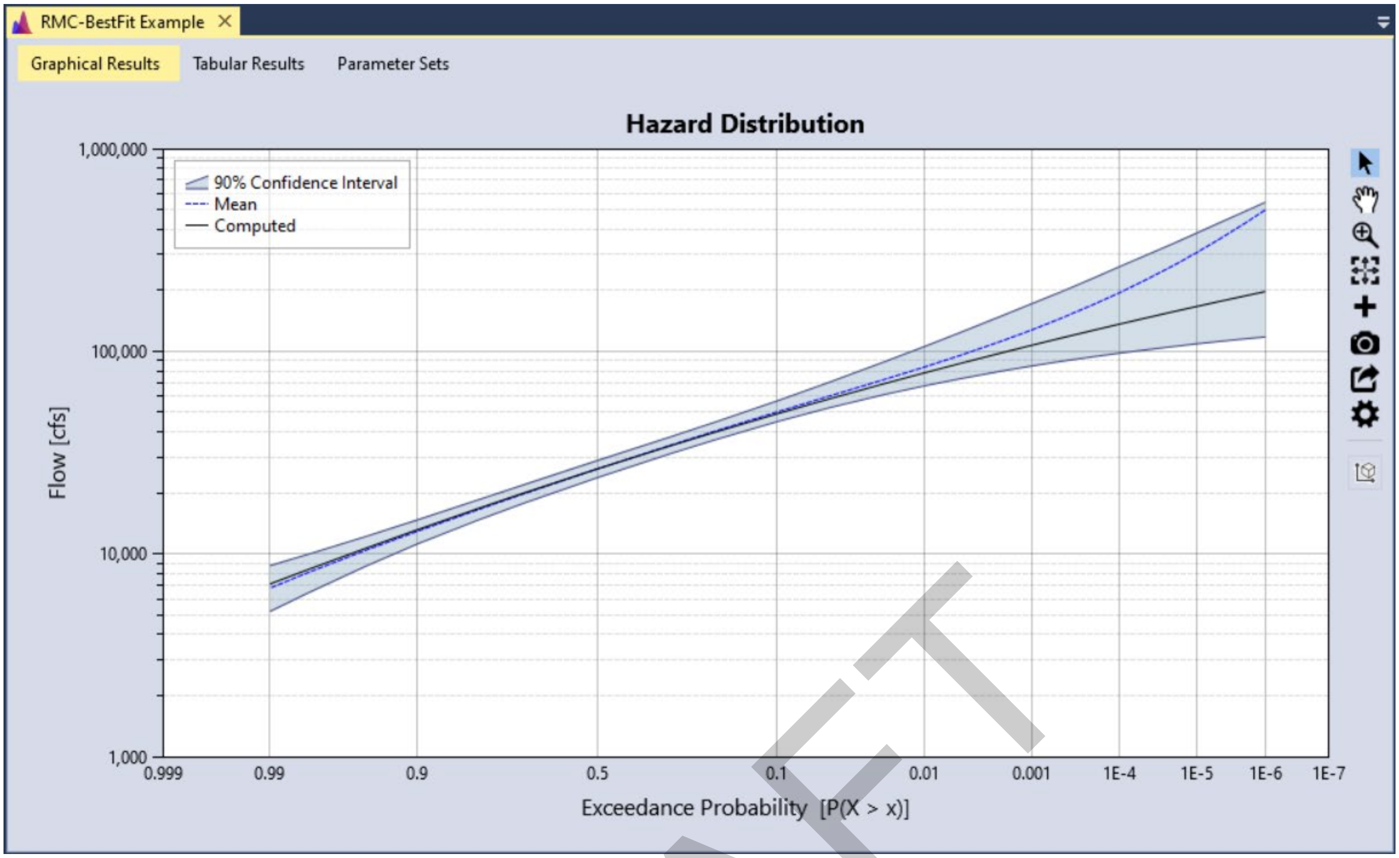
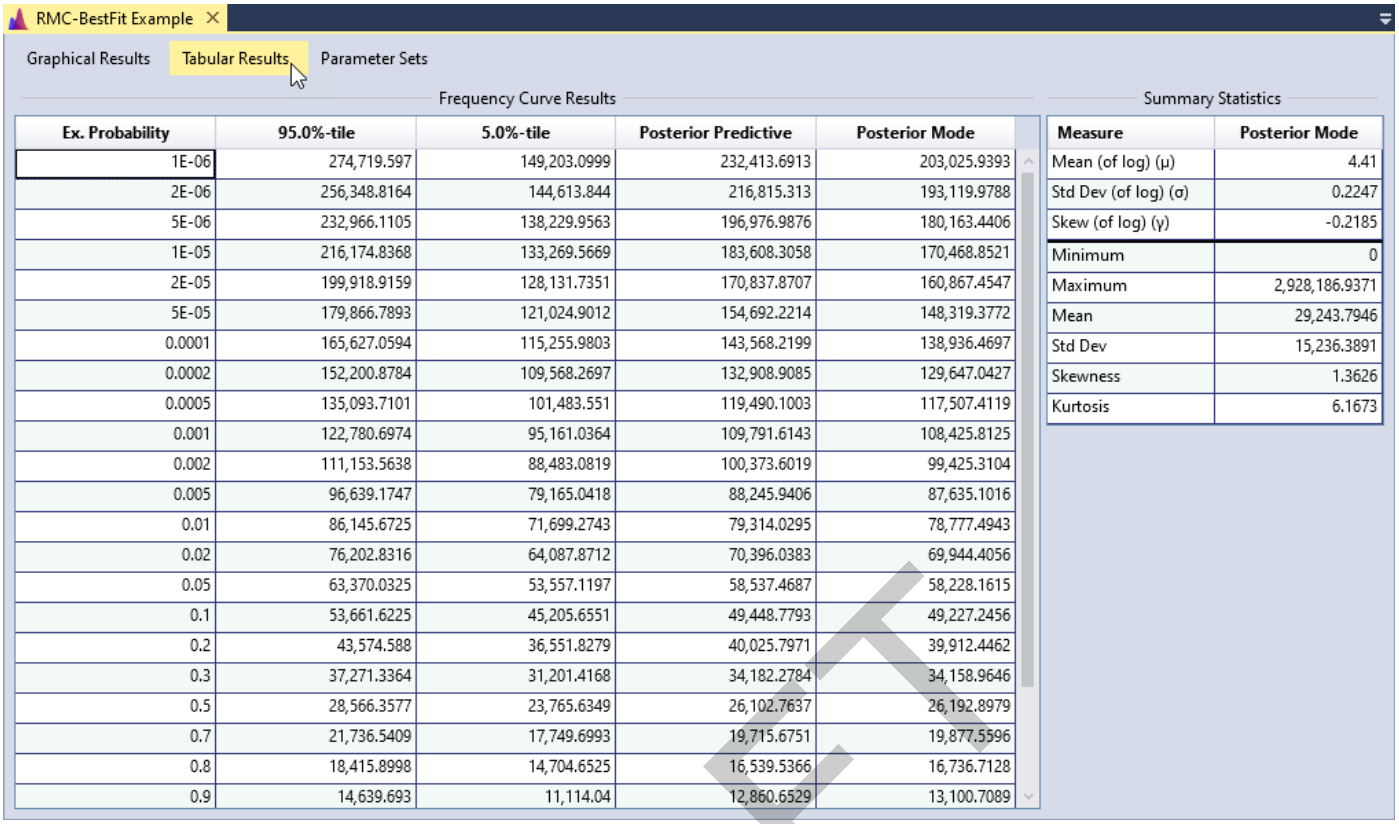


Figure 55 – Graphical Frequency Results.

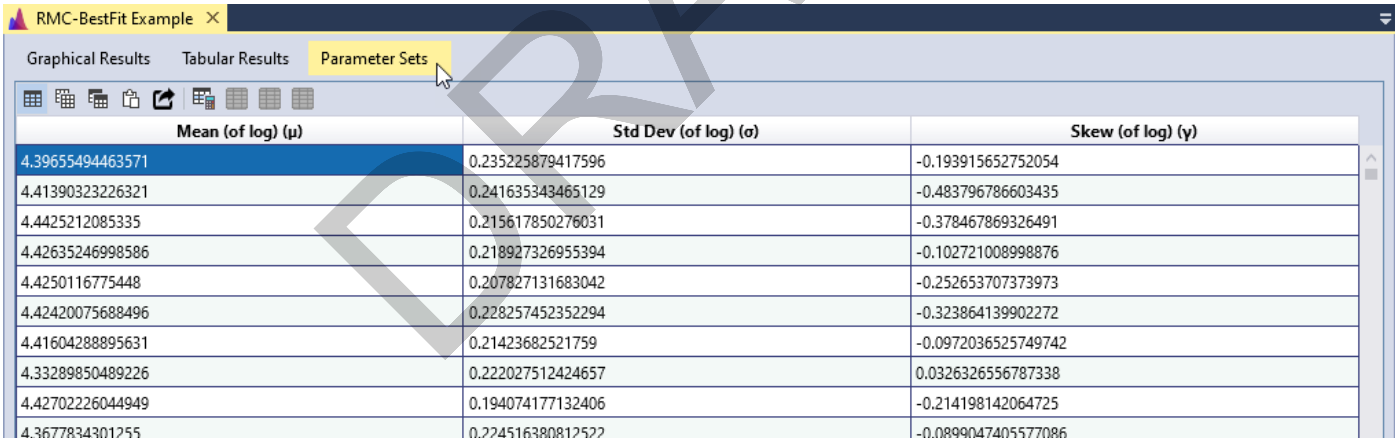
Click the **Tabular Results** tab to view the frequency curve results and the posterior mode summary statistics as shown in Figure 56. All output posterior parameter sets are available on the **Parameter Sets** tab as shown in Figure 57. You may sort these tables, copy, or export all values for external use. It can also be useful to generate summary statistics on the parameter sets column, such as the **Mean (of log) (μ)** column shown in Figure 58.



Ex. Probability	95.0%-tile	5.0%-tile	Posterior Predictive	Posterior Mode
1E-06	274,719.597	149,203.0999	232,413.6913	203,025.9393
2E-06	256,348.8164	144,613.844	216,815.313	193,119.9788
5E-06	232,966.1105	138,229.9563	196,976.9876	180,163.4406
1E-05	216,174.8368	133,269.5669	183,608.3058	170,468.8521
2E-05	199,918.9159	128,131.7351	170,837.8707	160,867.4547
5E-05	179,866.7893	121,024.9012	154,692.2214	148,319.3772
0.0001	165,627.0594	115,255.9803	143,568.2199	138,936.4697
0.0002	152,200.8784	109,568.2697	132,908.9085	129,647.0427
0.0005	135,093.7101	101,483.551	119,490.1003	117,507.4119
0.001	122,780.6974	95,161.0364	109,791.6143	108,425.8125
0.002	111,153.5638	88,483.0819	100,373.6019	99,425.3104
0.005	96,639.1747	79,165.0418	88,245.9406	87,635.1016
0.01	86,145.6725	71,699.2743	79,314.0295	78,777.4943
0.02	76,202.8316	64,087.8712	70,396.0383	69,944.4056
0.05	63,370.0325	53,557.1197	58,537.4687	58,228.1615
0.1	53,661.6225	45,205.6551	49,448.7793	49,227.2456
0.2	43,574.588	36,551.8279	40,025.7971	39,912.4462
0.3	37,271.3364	31,201.4168	34,182.2784	34,158.9646
0.5	28,566.3577	23,765.6349	26,102.7637	26,192.8979
0.7	21,736.5409	17,749.6993	19,715.6751	19,877.5596
0.8	18,415.8998	14,704.6525	16,539.5366	16,736.7128
0.9	14,639.693	11,114.04	12,860.6529	13,100.7089

Measure	Posterior Mode
Mean (of log) (μ)	4.41
Std Dev (of log) (σ)	0.2247
Skew (of log) (γ)	-0.2185
Minimum	0
Maximum	2,928,186.9371
Mean	29,243.7946
Std Dev	15,236.3891
Skewness	1.3626
Kurtosis	6.1673

Figure 56 – Tabular Frequency Results.



Mean (of log) (μ)	Std Dev (of log) (σ)	Skew (of log) (γ)
4.39655494463571	0.235225879417596	-0.193915652752054
4.41390323226321	0.241635343465129	-0.483796786603435
4.4425212085335	0.215617850276031	-0.378467869326491
4.42635246998586	0.218927326955394	-0.102721008998876
4.4250116775448	0.207827131683042	-0.252653707373973
4.42420075688496	0.228257452352294	-0.323864139902272
4.41604288895631	0.21423682521759	-0.0972036525749742
4.33289850489226	0.222027512424657	0.0326326556787338
4.42702226044949	0.194074177132406	-0.214198142064725
4.3677834301255	0.224516380812522	-0.0899047405577086

Figure 57 – Parameter Set Results.

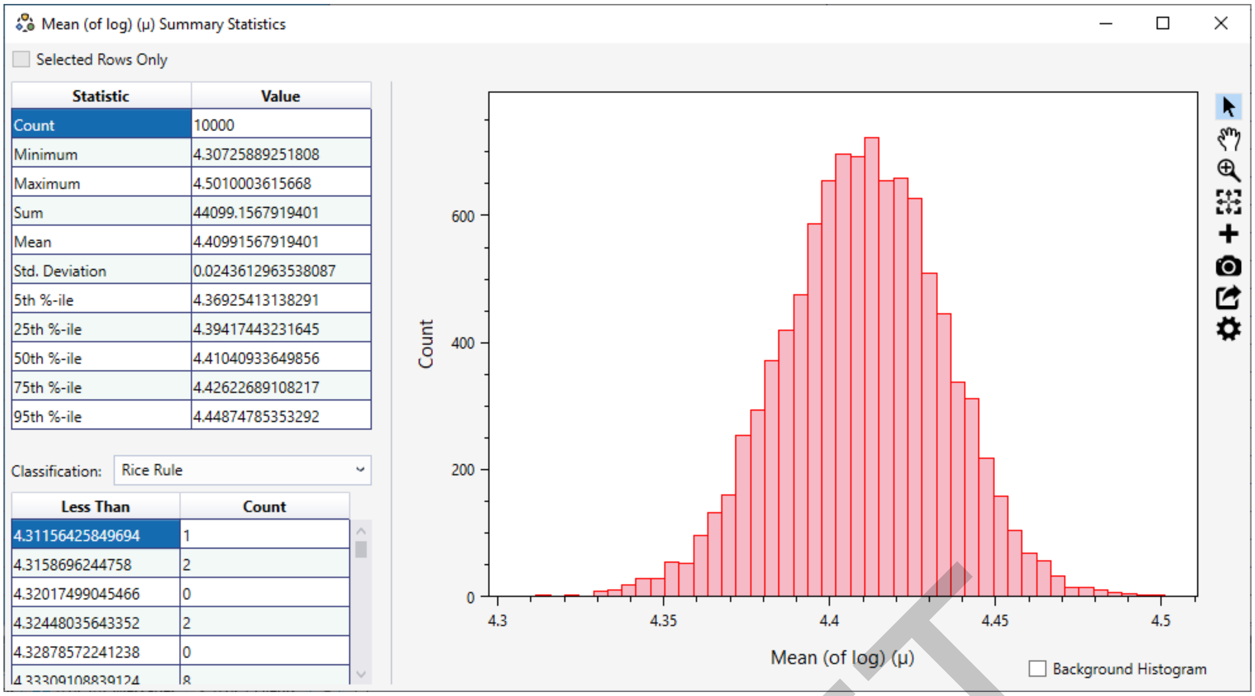


Figure 58 – Summary statistics on parameter sets for Mean (of log) (μ).

RMC-RFA

The USACE RMC developed the Reservoir Frequency Analysis (RMC-RFA) software to facilitate hydrologic hazard assessments within the USACE Dam Safety Program [7]. RMC-RFA produces a reservoir stage-frequency curve with uncertainty bounds by utilizing a deterministic flood routing model while treating the inflow volume, the inflow flood hydrograph shape, the seasonal occurrence of the flood event, and the antecedent reservoir stage as uncertain variables rather than fixed values [5]. RMC-RFA can be downloaded from the following link, https://www.rmc.usace.army.mil/Software/RMC-RFA/. Results from an RMC-RFA analysis can be imported directly into RMC-TotalRisk.

To import results of an RMC-RFA analysis, right-click on the **Hazards** folder in **Project Explorer** (Figure 59) or from the **Project Menu→Hazards** and select **Add RMC-RFA Hazard…**. A dialog will appear where you enter the name of the hazard function, select the RMC-RFA project file, select the output type, and select the simulation from the project that you would like to import.

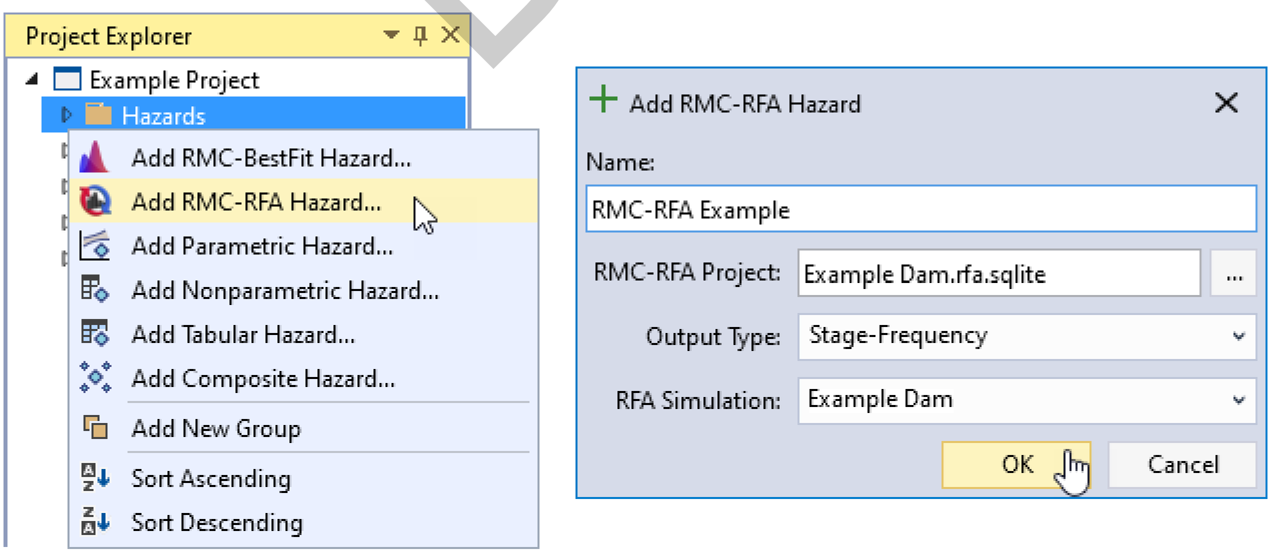


Figure 59 – Add new RMC-RFA hazard function and import dialog.

Once satisfied with the import settings, click **OK** (Figure 59) and the RMC-RFA hazard function will be added to the **Hazards** folder in **Project Explorer**, the function will be automatically opened into the **Tabbed Documents** area, and the input data properties will be displayed in the **Properties Window** (Figure 60). From here, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, and **Hazard** and **Probability** interpolation transforms as shown in Figure 60 below**.**

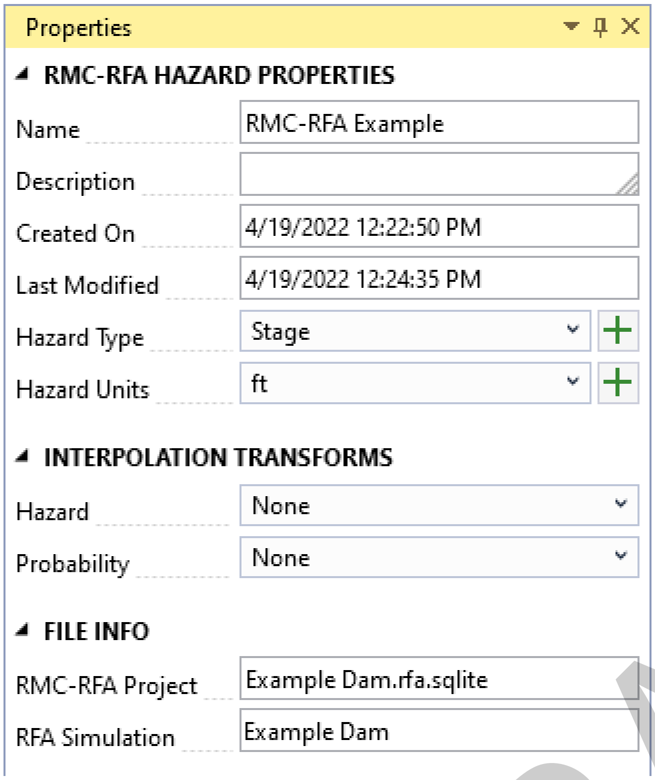


Figure 60 - RMC-RFA hazard function properties.

As before with the RMC-BestFit hazard function, the RMC-RFA results can be viewed in either graphical or tabular form. For more information on these viewing options, see the *Frequency Results* section under RMC-BestFit.

Parametric Function

The parametric hazard option allows the user to define a hazard function using a parametric distribution. To create a parametric hazard function, right-click on the **Hazards** folder in **Project Explorer** (Figure 61) or from the **Project Menu→Hazards** and select **Add Parametric Hazard…**. Next, give the **Parametric Hazard** function a name and click **OK**.

When the new Parametric Hazard function is created, it will be automatically opened into the **Tabbed Documents** area, and the parametric function properties will be displayed in the **Properties Window**. From the properties, you can set the **Name**, **Description**, **Hazard Type** and **Hazard Units**. Define the parametric distribution with uncertainty by setting the **Effective Record Length**, type of **Distribution**, and parameters for the distribution. Uncheck the **Is Uncertain** checkbox to use the parametric function without uncertainty. Once the parameters have been set, click the **Compute** button as shown in Figure 62 to generate and view the parametric hazard function. Further options for computing the parametric function are available in the **Options** tab which include bootstrap sampling **Confidence Interval**, number of **Realizations**, **PRNG Seed** for random number generation, and sample **Probability Ordinates**.

The parametric frequency results can be viewed in either graphical or tabular form. For more information on these viewing options, see the *Frequency Results* section under RMC-BestFit.

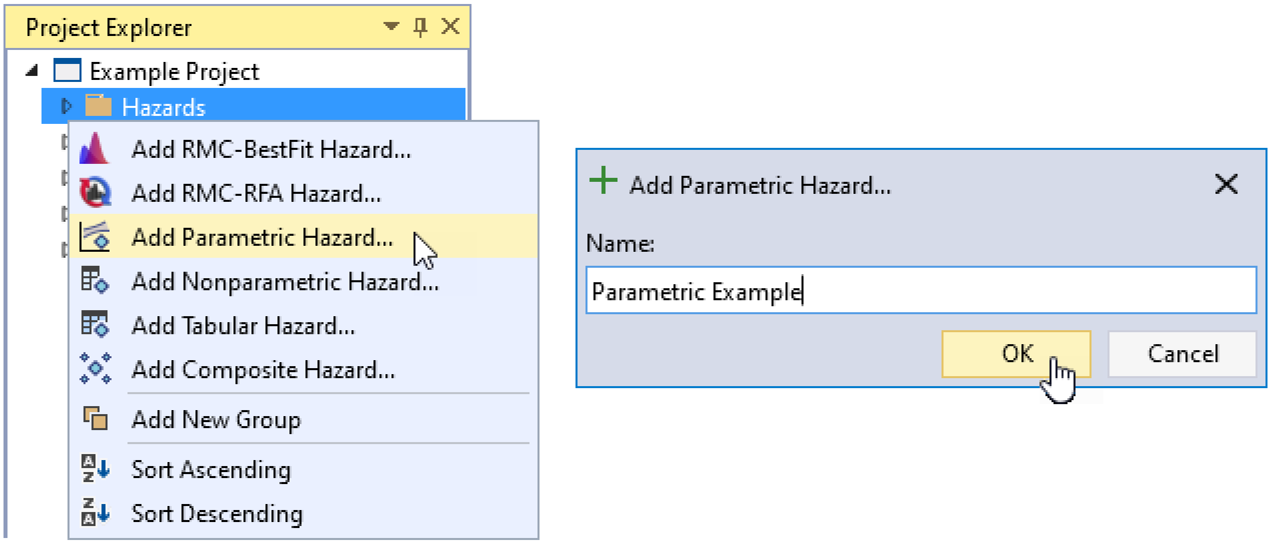


Figure 61 – Create new Parametric hazard function.

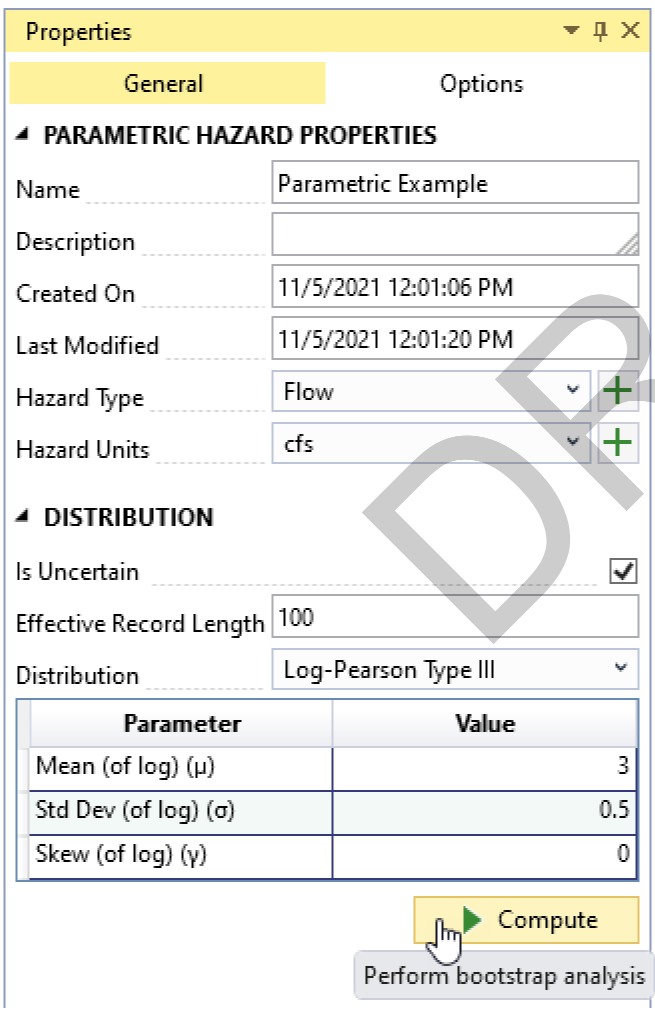


Figure 62 – Parametric Hazard Function properties.

Nonparametric Function

The nonparametric hazard function option provides an easy way to define a parametric distribution using tabular data where uncertainty is defined by a single parameter, effective record length (ERL). The longer the ERL, the less uncertainty and narrower the confidence intervals [1]. The most common use case is copying and pasting a nonparametric frequency function from another application such as Microsoft Excel®, HEC-FDA, or HEC-SSP, then enter the ERL to define uncertainty. To create a nonparametric hazard function, right-click on the **Hazards** folder in **Project Explorer** (Figure 63) or from the **Project Menu→Hazards** and select **Add Nonparametric Hazard….** Next, give the **Nonparametric Hazard** function a name and click **OK**.

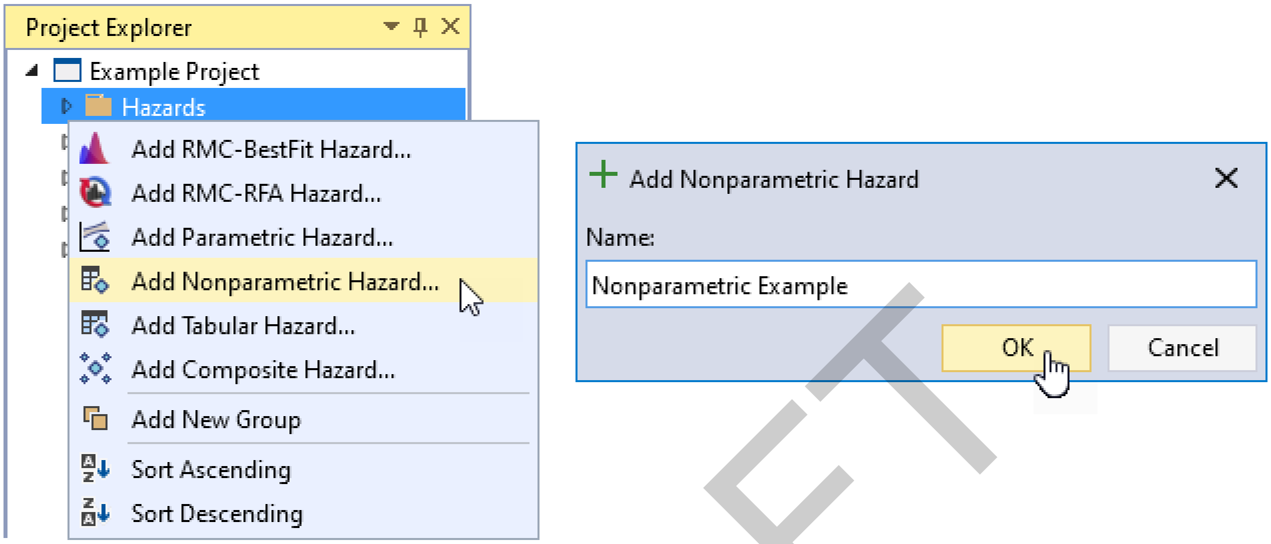


Figure 63 – Create New Nonparametric Hazard Function.

When the new Nonparametric Hazard function is created, it will be automatically opened into the **Tabbed Documents** area, and the tabular function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, **Hazard** and **Probability** interpolation transforms, **Effective Record Length**, and **Extrapolation Probability** as shown in Figure 64. The hazard and probability interpolation transforms define how the data is interpolated when sampling values between the specified tabular ordinates. Effective Record Length is used for estimating uncertainty in the nonparametric function. The **Extrapolation Probability** input is used to extrapolate to a less frequent exceedance probability. If the user defined data already extends beyond the entered value, no extrapolation will be performed.

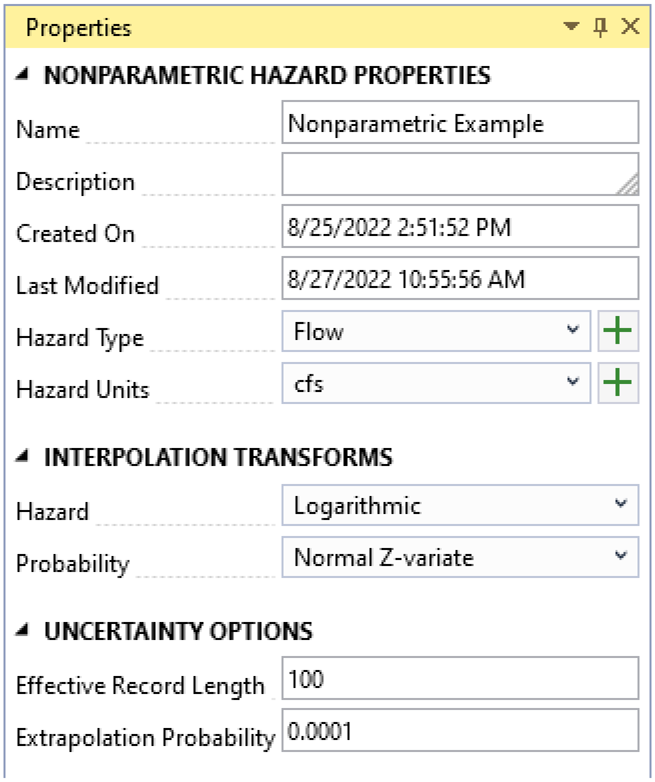


Figure 64 – Nonparametric Hazard Function properties.

The **Tabbed Document** for a nonparametric function contains the table where tabular data is entered and a graphical representation of that data (Figure 65). Data can be entered manually into the table or pasted from another source such as Microsoft Excel®.

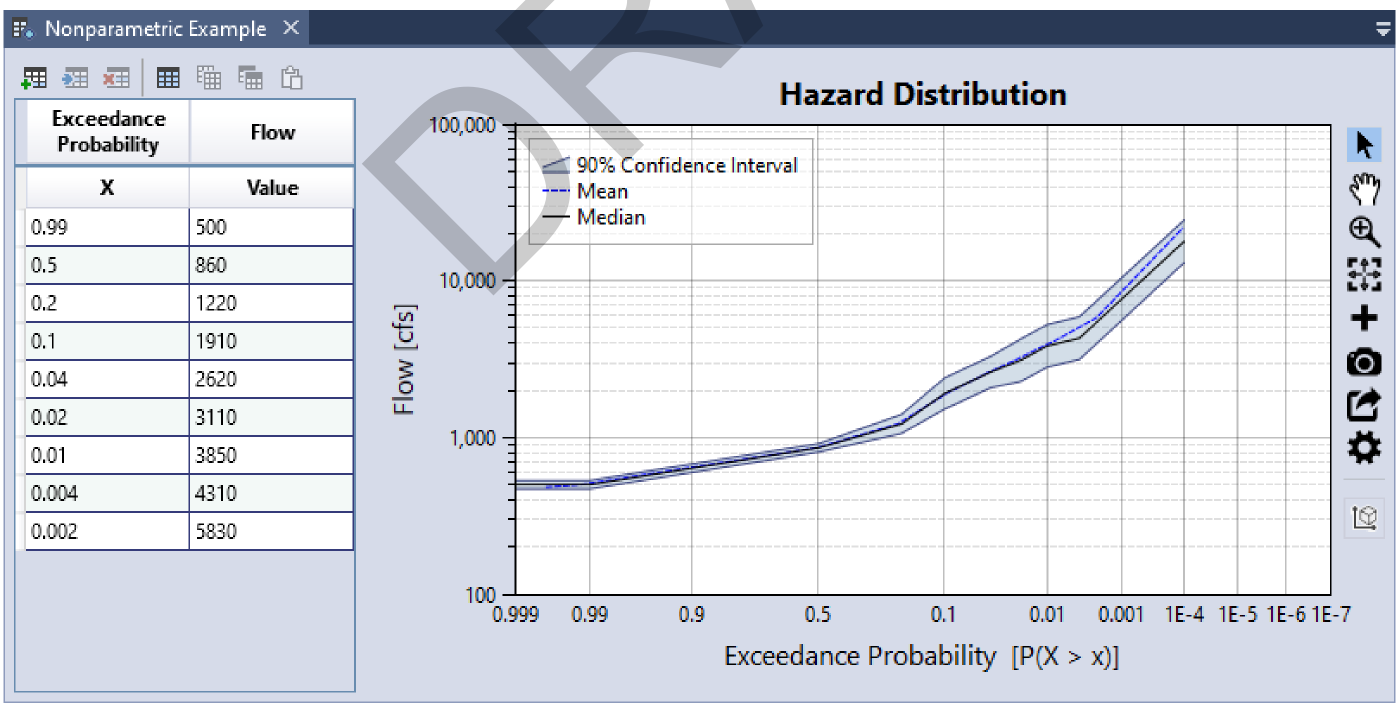


Figure 65 – Nonparametric Hazard Function completed flow-frequency function.

Tabular Function

The tabular hazard function option provides an easy way to define a hazard function using tabular data. The most common use case is copying and pasting a frequency function from another application such as Microsoft Excel® or HEC-SSP. To create a tabular hazard function, right-click on the **Hazards** folder in **Project Explorer** (Figure 66) or from the **Project Menu→Hazards** and select **Add Tabular Hazard…**. Next, give the **Tabular Hazard** function a name and click **OK**.

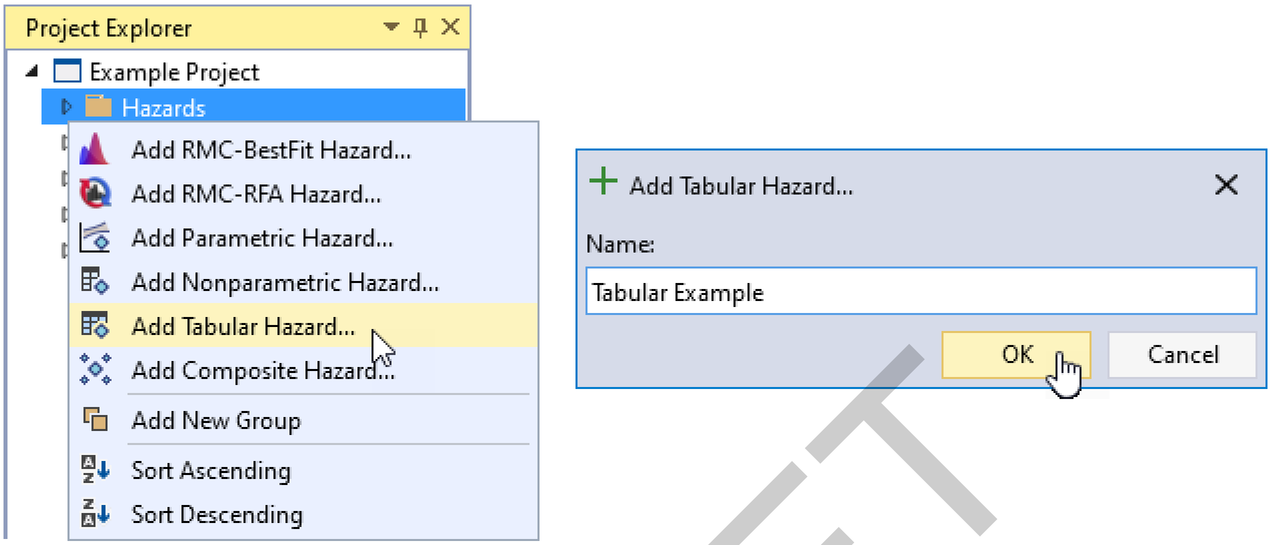


Figure 66 – Create New Tabular Hazard Function.

When the new Tabular Hazard function is created, it will be automatically opened into the **Tabbed Documents** area, and the tabular function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, and **Hazard** and **Probability** interpolation transforms as shown in Figure 67. The hazard and probability interpolation transforms define how the data is interpolated when sampling values between the specified tabular ordinates.

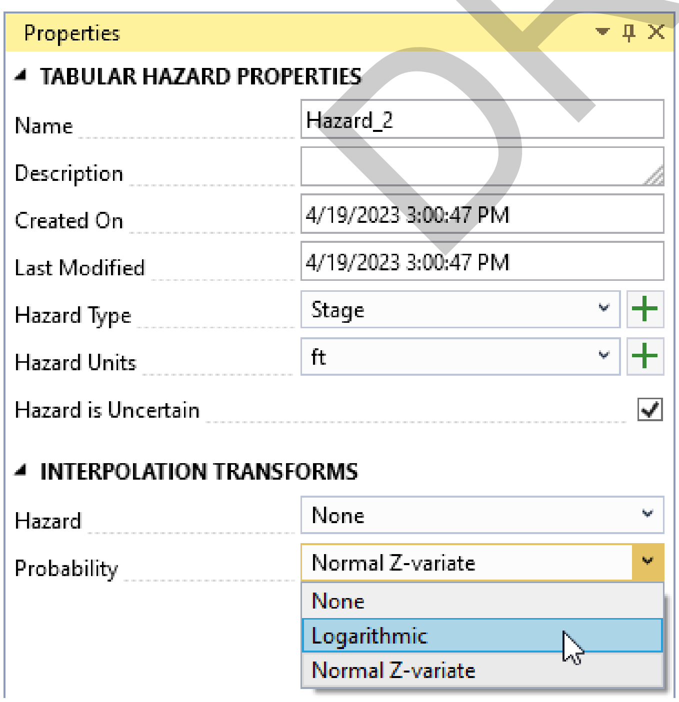


Figure 67 – Tabular Hazard Function properties.

The **Tabbed Document** for a tabular function contains the table where data is entered, and a graphical representation of that data is provided (Figure 68). Uncertainty can be defined around either the hazard or the probability by checking the **Hazard Is Uncertain** checkbox in the top left of the document. A distribution must be selected to define uncertainty, parameters for the selected distribution must be entered for every ordinate in the tabular data. Data can be entered manually into the table or pasted from another source such as Microsoft Excel®.

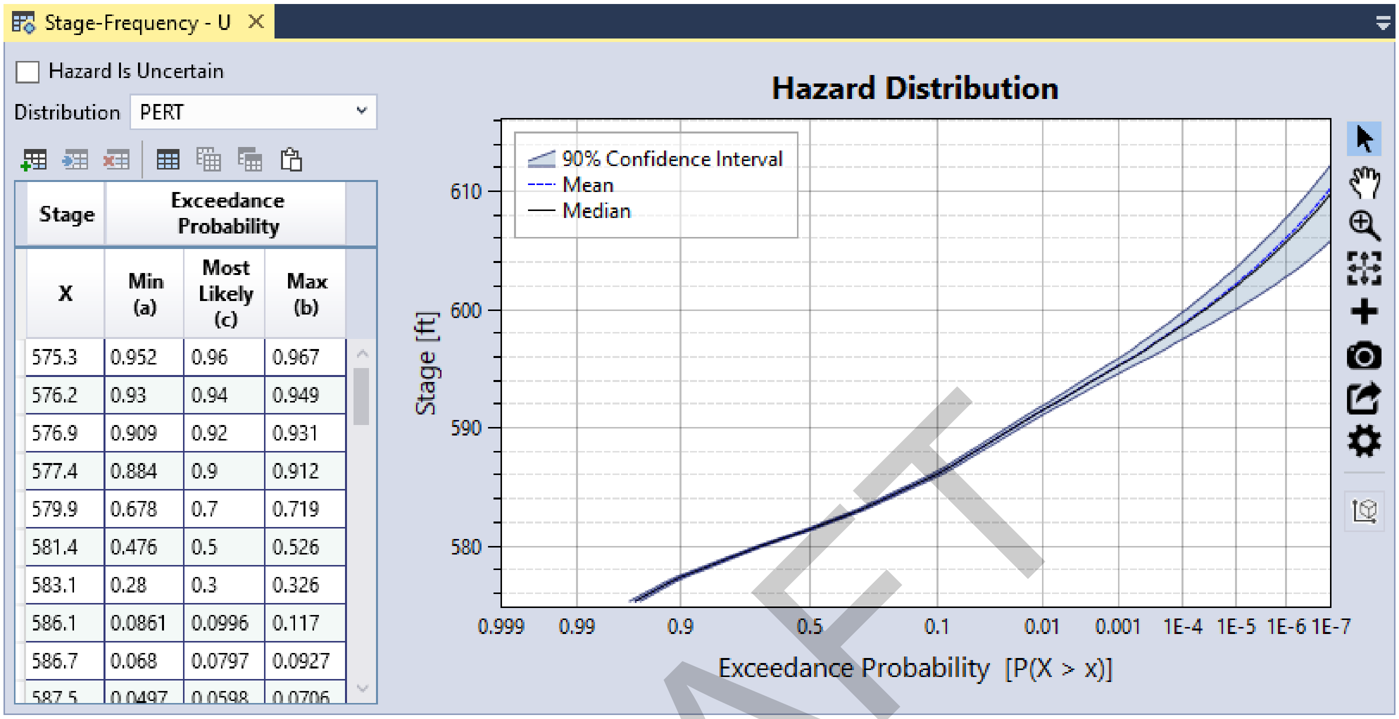


Figure 68 – Tabular Hazard Function completed tabular reservoir stage frequency function.

Data Validation

The input data table has built-in validation. The **Tabular Data** has the following requirements:

- Hazard values must be in ascending order.
- Probability values must be in descending order since they are exceedance probabilities.
- If uncertainty is defined, uncertain ordinates must contain valid distribution parameters. The uncertainty bounds must also be ordered.
- Probability values must be between 0 and 1.

When invalid data is entered, the table cell will turn red, and provide a tooltip indicating the source of the error as shown in Figure 69. In addition, an error message will appear in the **Message Window** indicating that you must resolve all errors in the data table.

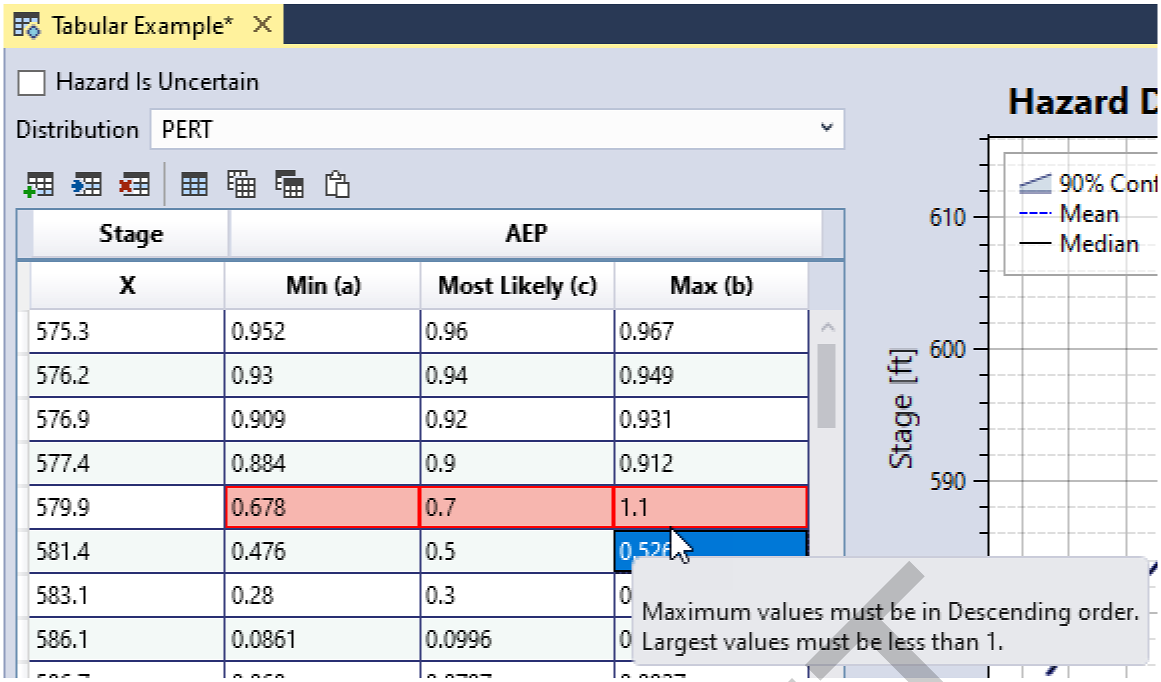


Figure 69 – Input Data Validation.

Composite Function

The composite hazard function option allows the user to combine multiple hazard functions into a single function by weighting the individual input functions. To create a composite hazard function, right-click on the **Hazards** folder in **Project Explorer** (Figure 70) or from the **Project Menu→Hazards** and select **Add Composite Hazard…**. Next, give the **Composite Hazard** function a name and click **OK**.

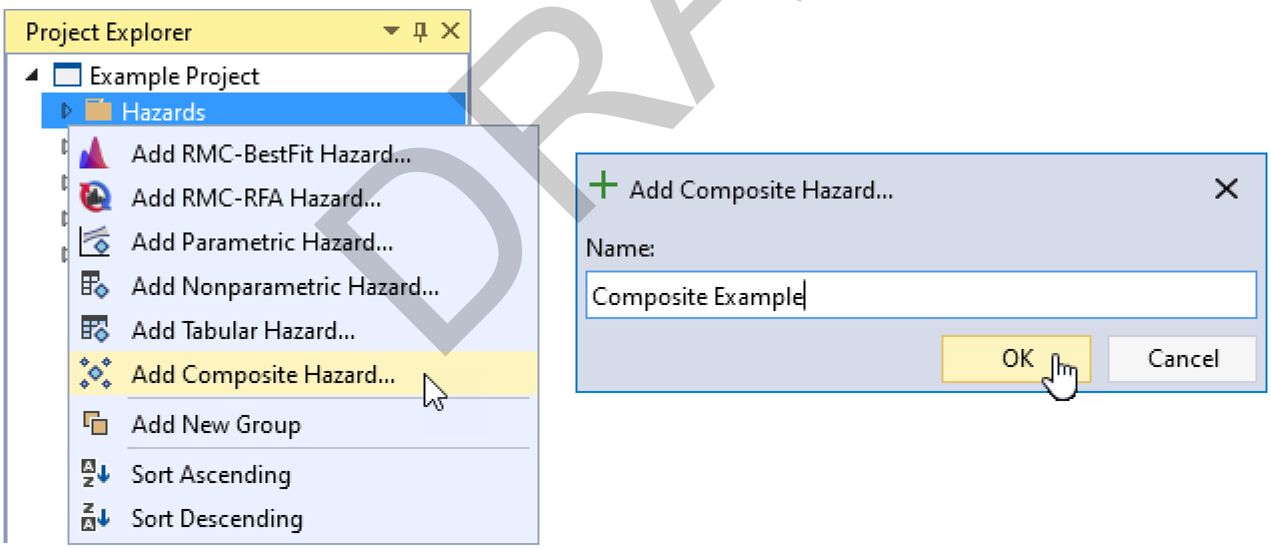


Figure 70 – Create new Composite Hazard Function.

When the new Composite Hazard function is created, it will be automatically opened into the **Tabbed Documents** area, and the composite function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, and input **Hazard Functions** as shown in Figure 71. The Hazard functions table is where the input functions are to be defined. Click the Add Row(s) button in the Hazard Functions table toolbar to add new rows for input to the composite. The hazard function weights must sum to 1. The user has the option to combine the functions using the probability of union assuming each hazard function is independent by unchecking the **Is Mixture** checkbox.

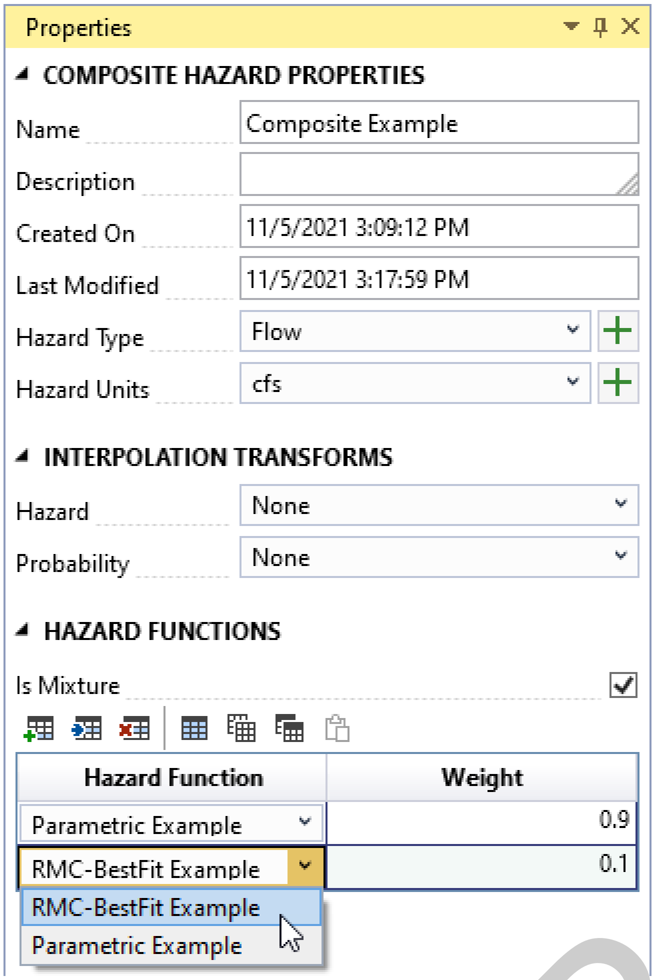


Figure 71 – Composite Hazard Function properties.

The **Tabbed Document** for a composite function contains a graphical representation of the composite function (Figure 72).

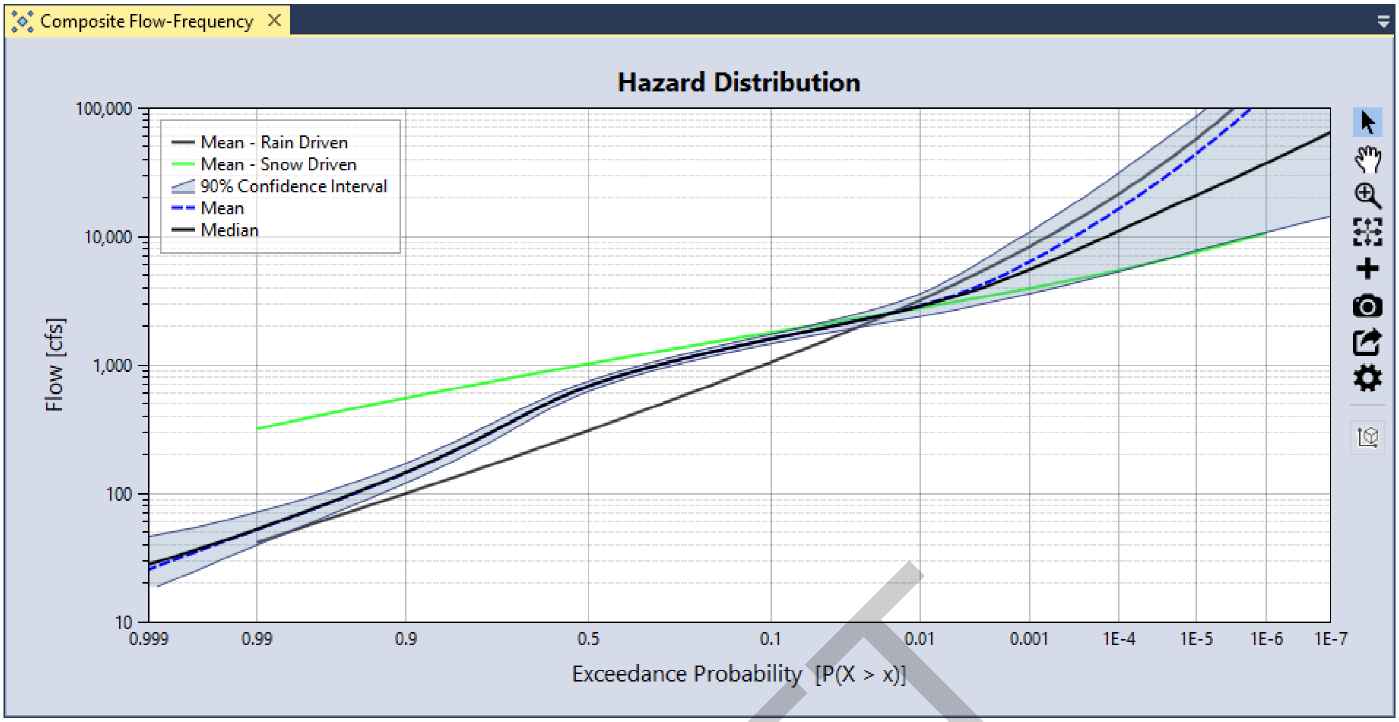


Figure 72 – Composite Hazard Function graphical display.

Transform Functions

In RMC-TotalRisk, transform functions will transform from one hazard type into another hazard type. For example, a peak flow-frequency function can be transformed to a stage-frequency function using a flow-stage rating curve derived from a hydraulic model.

Linear Function

The linear transform option allows the user to transform a hazard from one type to another using a simple linear function. To create a linear transform function, right-click on the **Transforms** folder in **Project Explorer** (Figure 73) or from the **Project Menu→Transforms** and select **Add Linear Transform…**. Next, give the **Linear Transform** function a name and click **OK**.

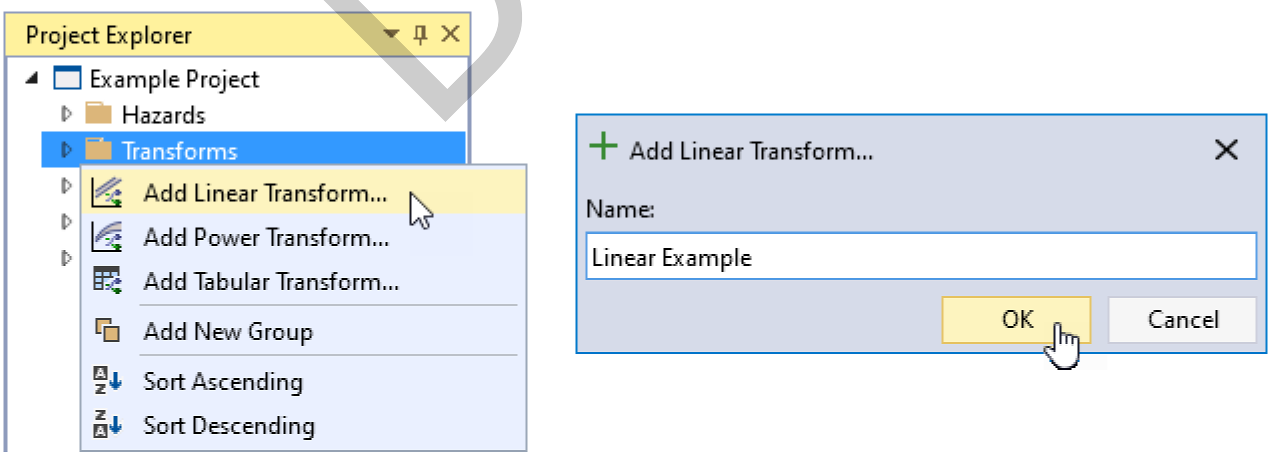


Figure 73 – Create new Linear Transform Function.

When the new Linear Transform function is created, it will be automatically opened into the **Tabbed Documents** area, and the transform function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, **Transformed Hazard**, **Transformed Units**, and linear transform **Parameters** as shown in Figure 74. The function is defined as $Y = \alpha + \beta X + \epsilon$, where $\epsilon \sim N(0, \sigma)$. If the **Is Uncertain** checkbox is un-checked then the Standard Error (σ) parameter is removed and only the slope (β) and intercept (α) are required.

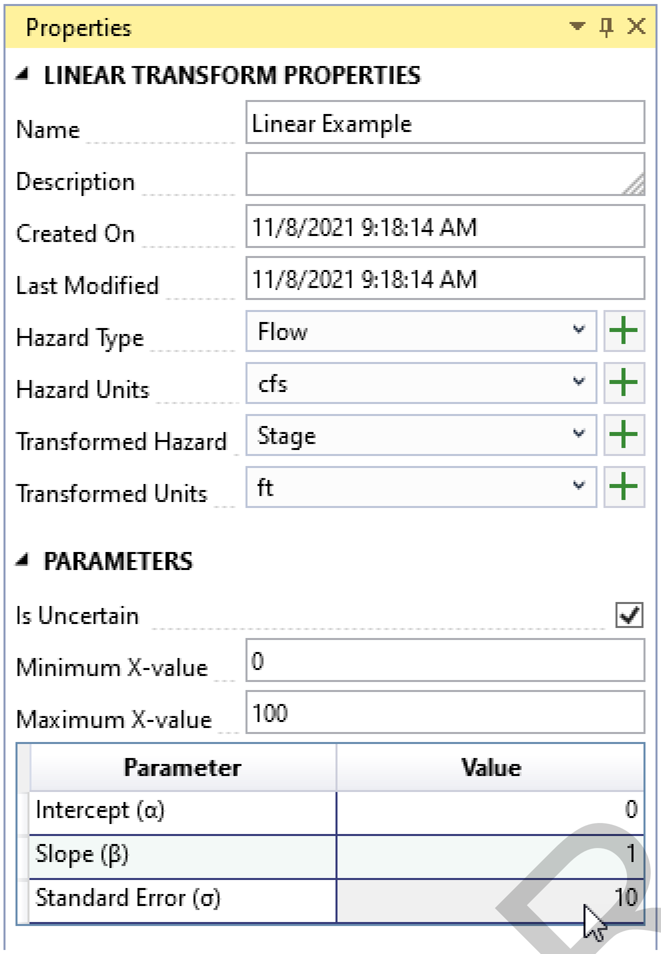


Figure 74 – Linear Transform Function properties.

The **Tabbed Document** for a linear transform function contains a graphical representation of the function (Figure 75).

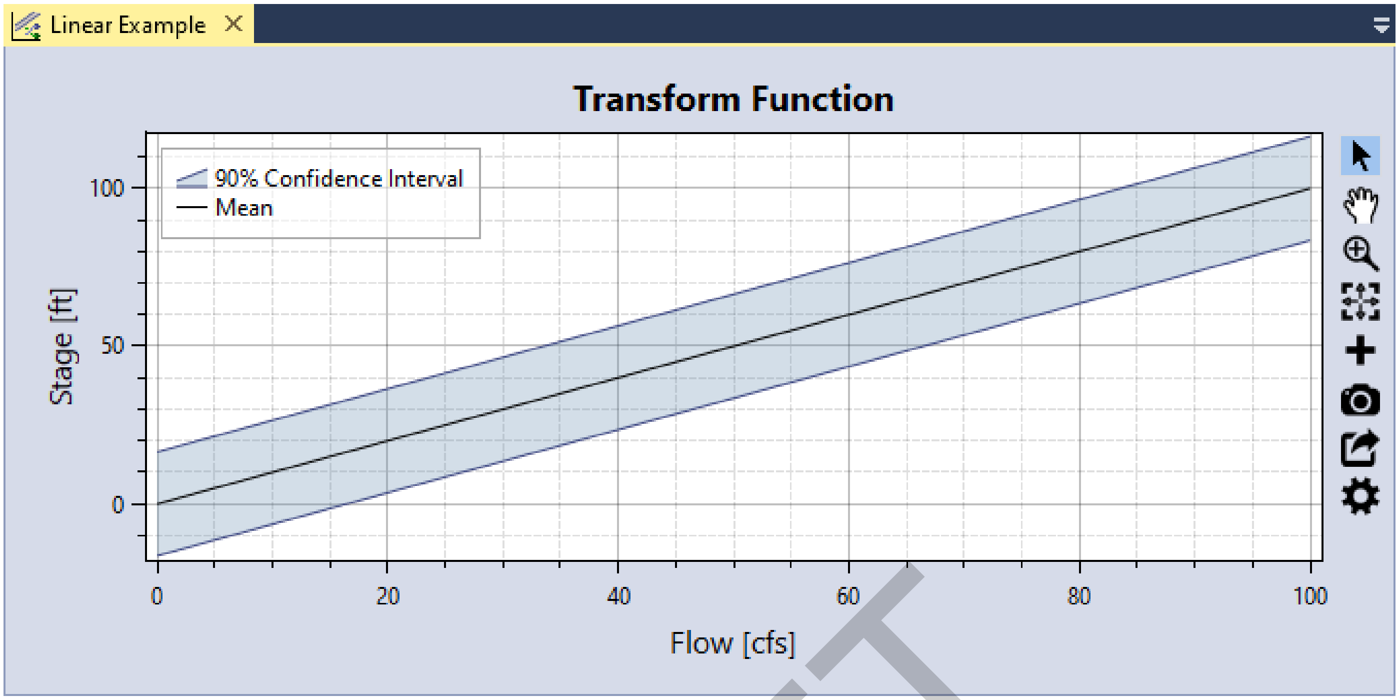


Figure 75 – Linear Transform Function graphical display.

Power Function

The power transform option allows the user to transform a hazard from one type to another using a power function. To create a power transform function, right-click on the **Transforms** folder in **Project Explorer** (Figure 76) or from the **Project Menu→Transforms** and select **Add Power Transform…**. Next, give the **Power Transform** function a name and click **OK**.

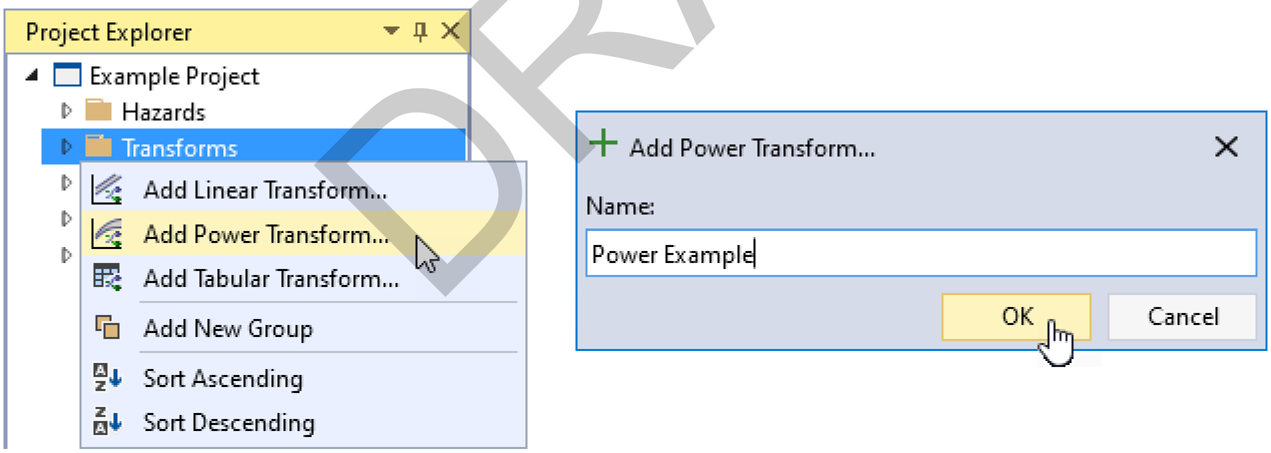


Figure 76 – Create new Power Transform Function.

When the new Power Transform function is created, it will be automatically opened into the **Tabbed Documents** area, and the transform function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, **Transformed Hazard**, **Transformed Units**, and power transform **Parameters** as shown in Figure 77. The function is defined as $Y = \left[\alpha\,(X - \xi)^{\beta}\right] \cdot \epsilon$, where $\epsilon \sim N(0, \sigma)$. The standard error σ should be in log-space. If the **Is Uncertain** checkbox is unchecked then the Standard Error (σ) parameter is removed and only the coefficient (α), exponent (β), and location (ξ) are required.

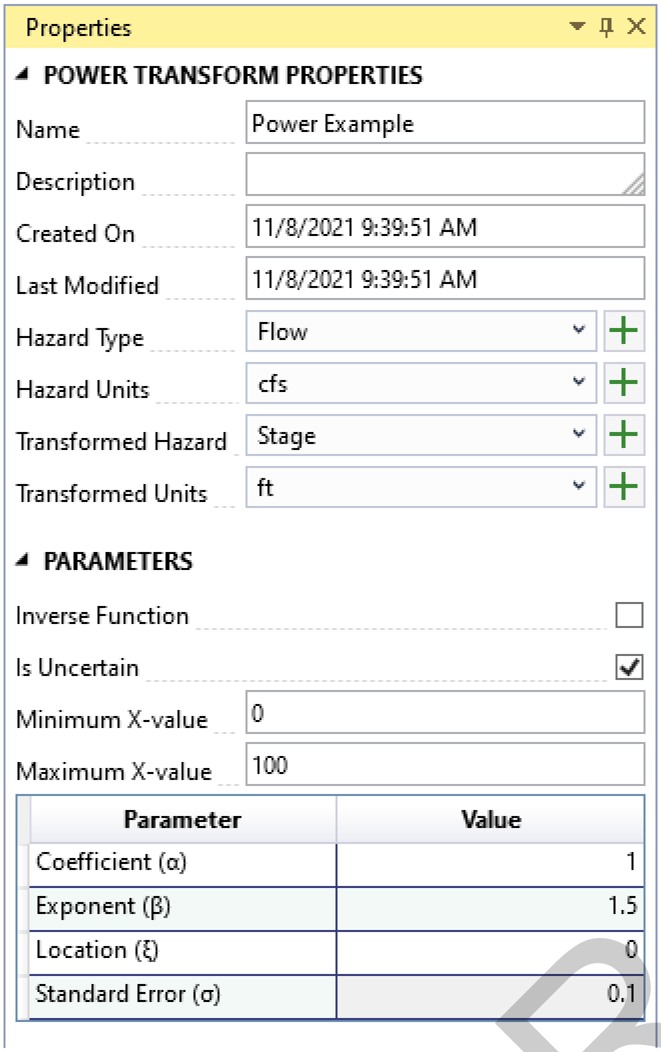


Figure 77 – Power Transform Function properties.

The **Tabbed Document** for a power transform function contains a graphical representation of the function (Figure 78).

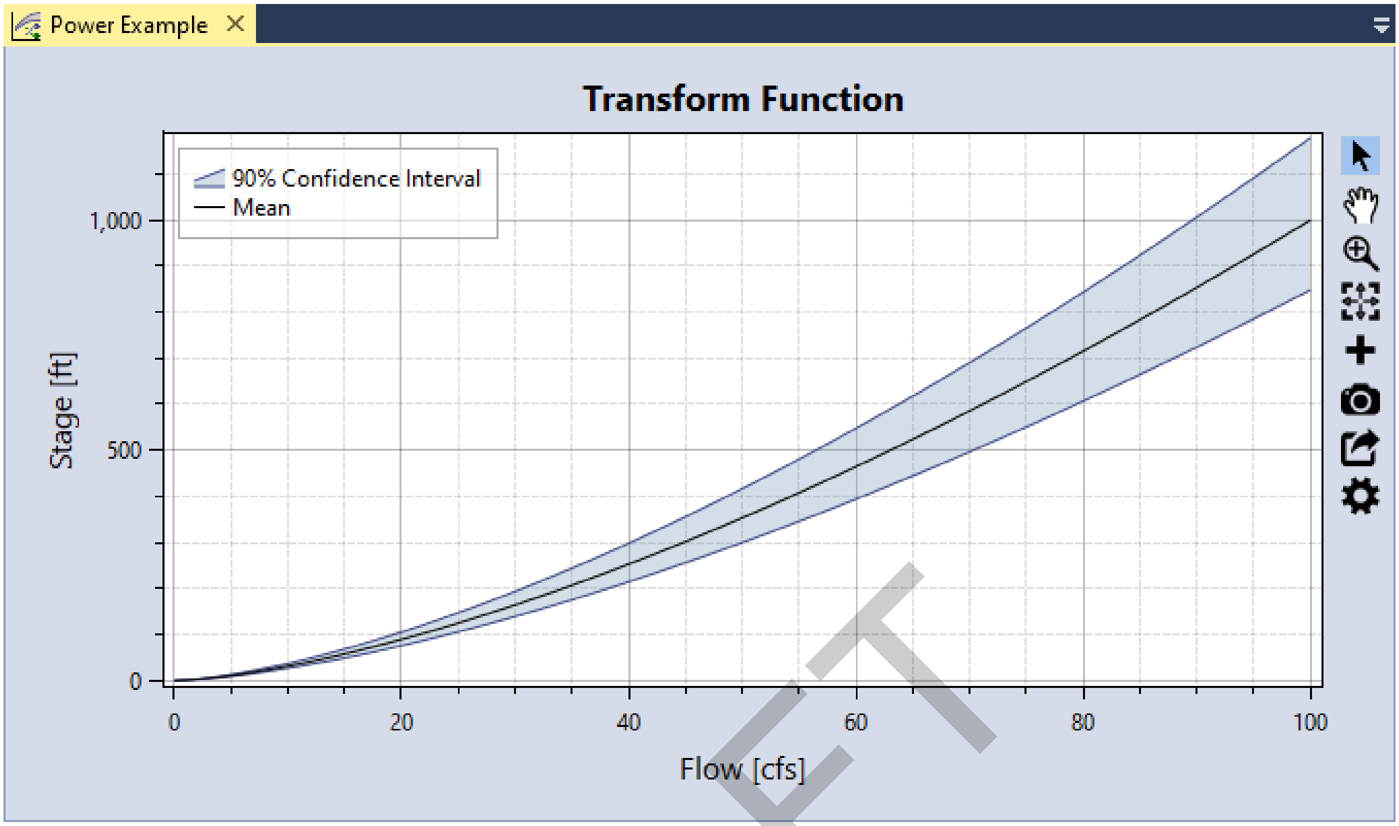


Figure 78 – Power Transform Function graphical display.

Tabular Function

The tabular transform function option provides an easy way to define a hazard transform function using tabular data. The most common use case is copying and pasting a transform function (e.g., flow-stage rating curve) from another application such as Microsoft Excel® or HEC-RAS. To create a tabular transform function, right-click on the **Transforms** folder in **Project Explorer** (Figure 79) or from the **Project Menu→Transforms** and select **Add Tabular Transform…**. Next, give the **Tabular Transform** function a name and click **OK**.

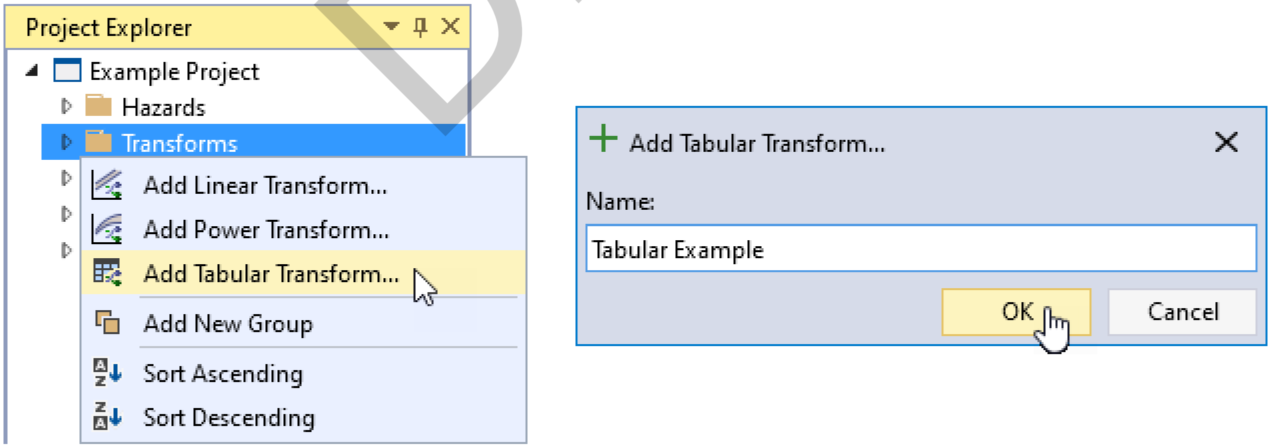


Figure 79 – Create new Tabular Transform Function.

When the new Tabular Transform function is created, it will be automatically opened into the **Tabbed Documents** area, and the tabular function properties will be displayed in the **Properties Window.** From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, **Transformed Hazard**, **Transformed Units**, and

Hazard and **Transformed Hazard** interpolation transforms as shown in Figure 80. The hazard and transformed hazard interpolation transforms define how the data is interpolated when sampling values between the specified tabular ordinates.

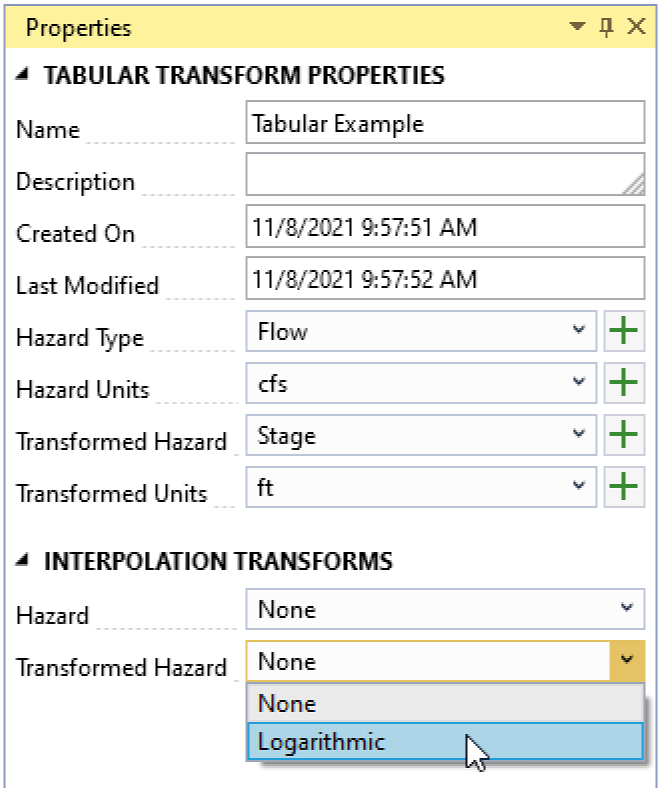


Figure 80 – Tabular Transform Function properties.

The **Tabbed Document** for a tabular function contains the table where tabular data will be entered and a graphical representation of that data (Figure 81). Uncertainty can be defined around the transformed hazard for each tabular ordinate. A distribution must be selected to define uncertainty, parameters for the selected distribution can be entered for every ordinate in the tabular data.

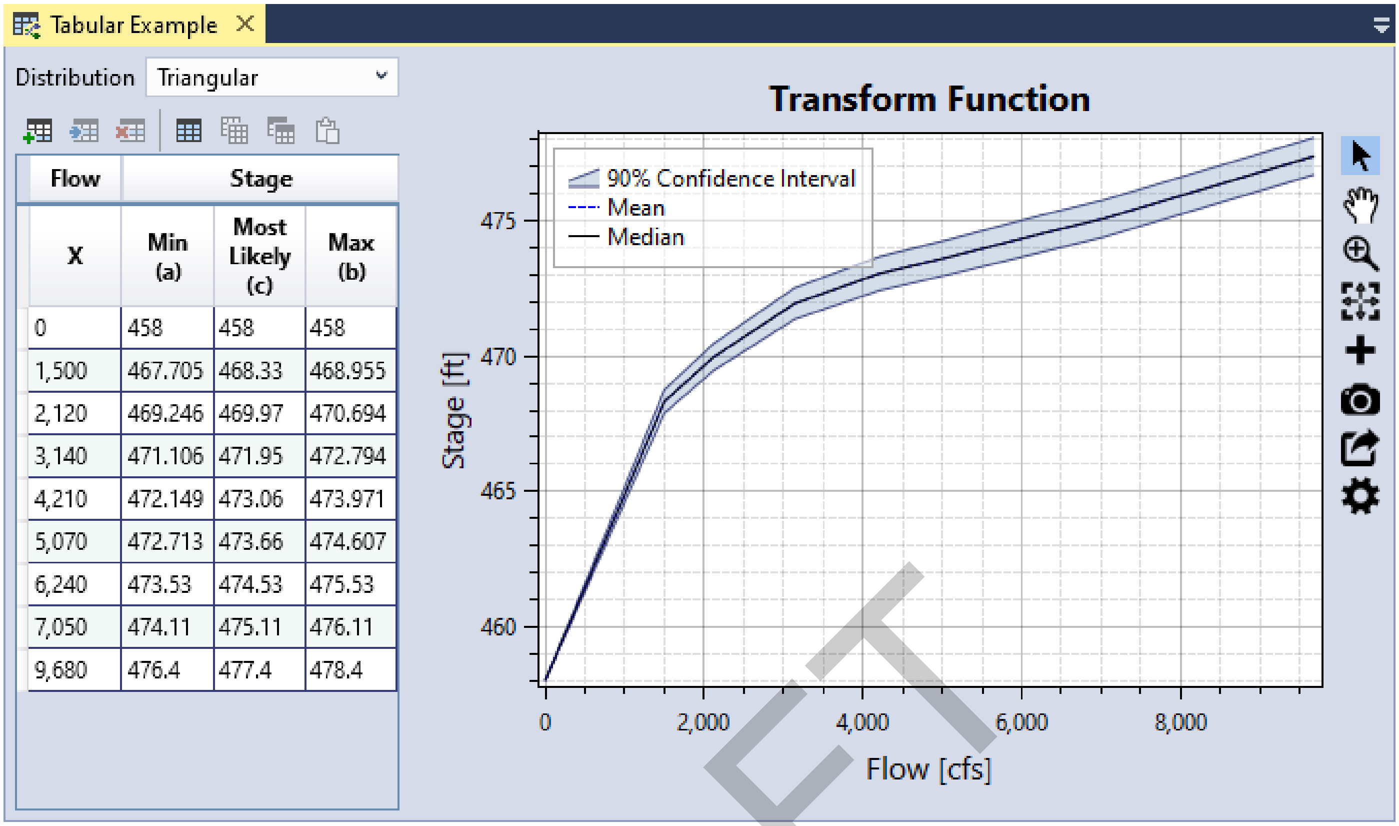


Figure 81 – Tabular Transform Function transforming flow to stage.

Data Validation

The input data table has built-in validation. The **Tabular Data** has the following requirements:

- Hazard and transformed hazard values must be in ascending order.
- If uncertainty is defined, uncertain ordinates must contain valid distribution parameters.

When you enter invalid data, the table cell will turn red, and provide a tooltip indicating the source of the error as shown in Figure 82. In addition, an error message will appear in the **Message Window** indicating that you must resolve all errors in the data table.

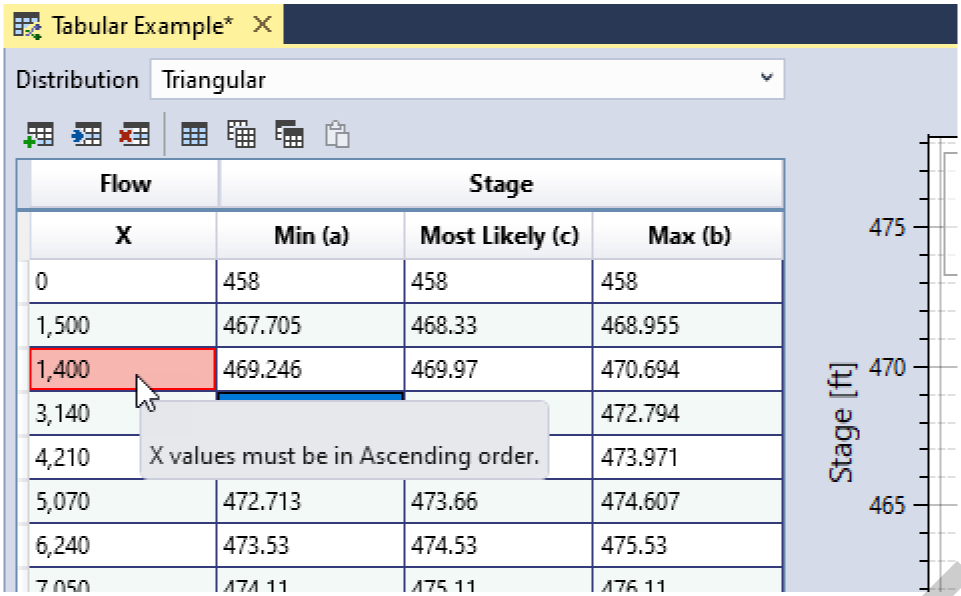


Figure 82 – Input Data Validation.

System Response Functions

System response functions define how a system will respond given a hazard. In RMC-TotalRisk, a system response function describes the conditional probability of failure for various hazard levels, such as water surface elevations [8] [1]. Typically, the response function describes the probability of failure for a given hazard level. In dam and levee safety risk analyses, system response functions are developed for multiple potential failure modes (PFM). Common failure modes include seepage and piping, erosion and bank caving, and overtopping. It is important to keep the PFMs distinct in a risk analysis since each PFM can have different consequence outcomes. In RMC-TotalRisk, system response functions can be defined using an event tree, parametric function, tabular function, bivariate tabular function, or a composite of multiple functions. The following will go over each input option in detail.

Event Tree Function

RMC-TotalRisk provides the ability to define system response probabilities using an event tree. Event tree analyses (ETAs) represent the logic of how an initiating event, like a flood or earthquake, can lead to various types of damage and failure [3]. The event tree consists of a sequence of interconnected nodes and branches [9]. Each node is associated with an uncertain event (a crack forms in the embankment) or a state of nature (existence of adversely oriented joint planes). Branches originating from a node represent each of the possible events or states of nature that can occur. Probabilities are estimated for each node to represent the likelihood for each event or condition. These probabilities are conditional on the occurrence of the preceding events to the left in the tree. See [1] for more details on the event tree calculations in RMC-TotalRisk.

To create an event tree response function, right-click on the **System Responses** folder in **Project Explorer** (Figure 83) or from the **Project Menu→System Responses** and select **Add Event Tree Response…**. A dialog will appear where you enter the name of the dataset and select an event tree template that you would like to import. This example will use the **Basic** template to show the development of an event tree from scratch. However, you can select from a list of default templates as well as user-defined templates.

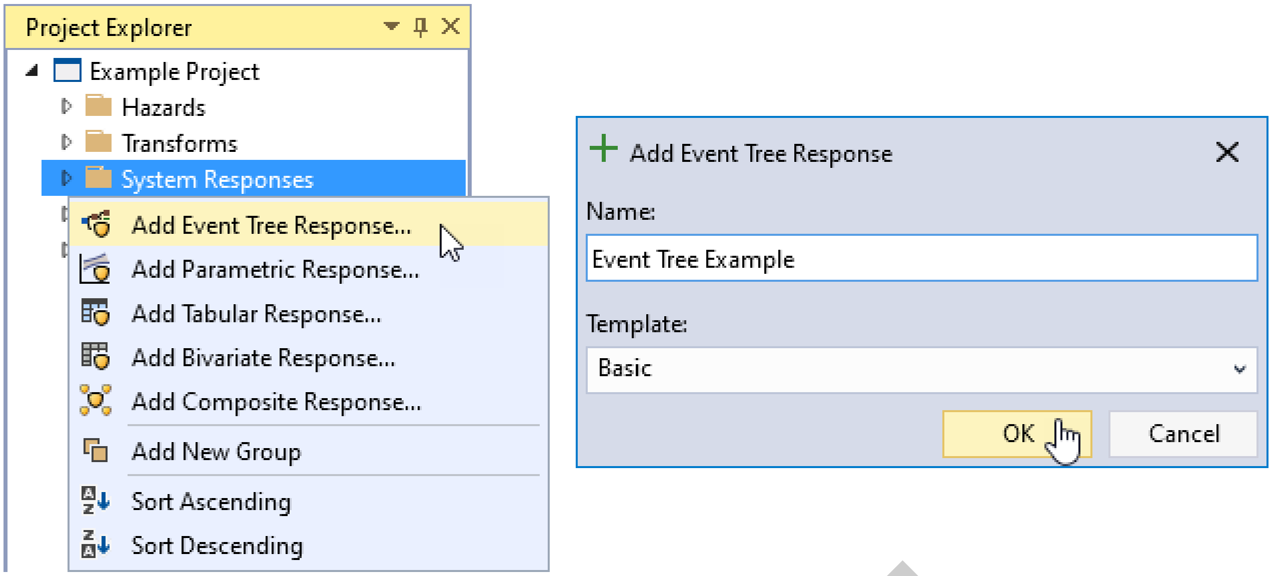


Figure 83 – Create new Event Tree Response Function.

When the new Event Tree Response function is created, it will be automatically opened into the **Tabbed Documents** area, and the event tree properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, **Hazard Interpolation**, **Probability Interpolation**, and selected **Event Tree Node** properties as shown in Figure 84. The hazard and probability interpolation transforms define how the data is interpolated when sampling values between hazard and probability intervals.

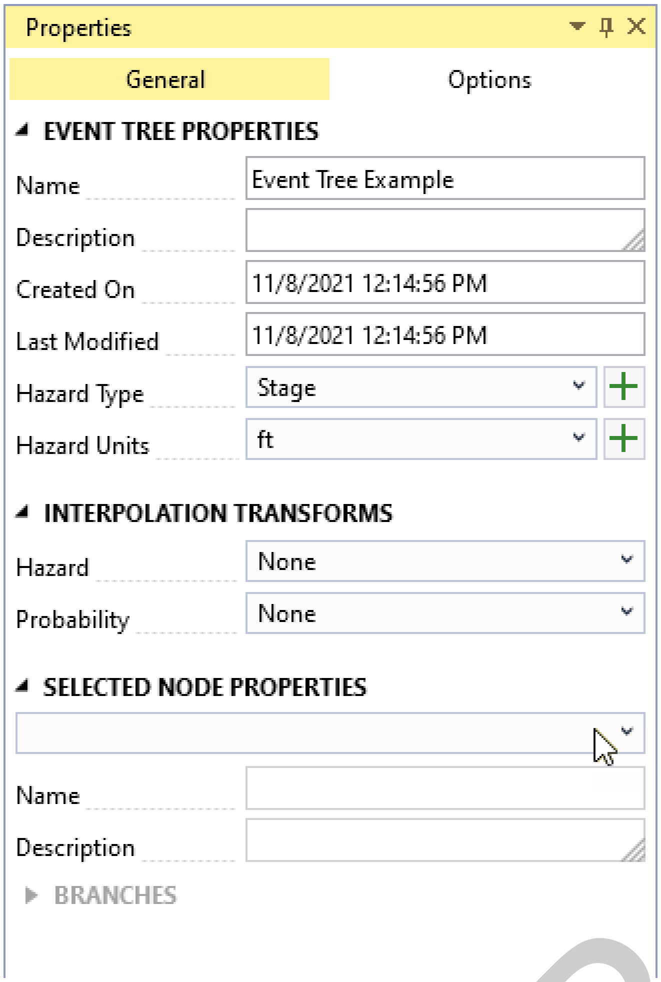


Figure 84 – Event Tree Response Function properties.

Terminology

This section provides definitions for the event tree terminology used in RMC-TotalRisk [1].

- <u>**Node**</u>: A branching point in the event tree that signifies a random event in the event tree. This is also commonly referred to as an event or state. There are four basic node types that define the event tree:

  Initiating Hazard Node: Always the first node in an event tree. This node defines the hazard levels. It is crucial to relating system response probabilities to the hazard function. For a more accurate assessment of risk, probabilities should be defined for enough hazard levels to cover nearly the entirety of probability space. Only hazard levels are entered for this node, not hazard exceedance probabilities.

  Chance Node: Represents the probability that the given event will occur for each hazard level defined in the initiating hazard node. Probabilities can be defined as a single value for all hazard levels (Single Value), unique for each hazard level (Multi Value), or from another source (see reference node below). This is the most fundamental component of an event tree.

  Reference Node: The reference node performs the same task as a chance probability node except that instead of probability being defined at the node itself, it is defined using a previously added response function or node in the event tree. The selected function or node can be sampled independently or the same for all references to the source.

Remainder Node: This node represents the probability that remains when all other chance node and reference node probabilities for the current branching point are considered. For example, from a given event with two potential outcomes the remainder node represents the probability that neither of the potential outcomes occurs. The remainder probability is computed automatically and is not set by the user.

- **Branch**: The line that connects two nodes together.
- **End Node**: A node that has no downstream branches. The end node defines the end state for a sequence of events. This is also commonly referred to as a *leaf node* or *terminal node*.
- **Pathway**: A unique sequence of events representing a possible failure progression. The probability of this pathway occurring is computed as the joint probability of each node in the series that connects the initiating hazard node to the end node. This is also commonly referred to as *path*, *sequence*, *connections*, or *root-to-node*.
- **Upstream Nodes**: All nodes to the left of a selected node in the tree. The upstream nodes of the selected node must occur prior to the selected node event. This is also commonly referred to as *parent node*, *conditional events*, or *preceding nodes*.
- **Downstream Nodes**: All nodes to the right of a selected node in the tree. The downstream nodes occur after the selected node event. This is also commonly referred to as *child node*, *conditional events*, *proceeding nodes*, or *subsequent nodes.*
- **Node Probability**: The probability that the selected node event occurs conditioned on the occurrence of the upstream nodes in the tree.
- **Event Likelihood**: The likelihood, or probability, of a node occurring in the event tree for a given hazard level. This is the joint probability of the selected node event and all the upstream nodes occurring.

Navigating an Event Tree

The event tree can be moved around the workspace by click-and-holding any mouse button on the background canvas and dragging the mouse. You can zoom in and out using the mouse wheel. A node or branch will become highlighted when the cursor is over it. Nodes and branches can be selected by left-clicking on them. Right-clicking on a node or branch will display the context menu options.

When the mouse cursor is hovering over any node a toolbar will appear just above the node as shown below. The toolbar options are also available by right-clicking on a node.

Figure 85 – Event Tree Node Toolbar.

Delete Branches Click to delete all child branches from the target node.

Copy Branches Click to copy the child nodes into memory to be pasted elsewhere.

Paste Branches Click to paste previously copied branches to this node.

Add New Branch Click to add a new branch to the node.

When the mouse cursor is hovering over any branch a toolbar will appear just above the branch name as shown below. The branch toolbar options are also available by right-clicking on the branch. A branch can be renamed by double-clicking on the branch or through the branch properties.

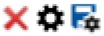


Figure 86 – Event Tree Branch Toolbar.

Delete Branch Click to delete the target branch and all child branches from the event tree.

Branch Properties Click to edit branch properties (e.g., name, description, probabilities) directly in the workspace.

Save Template Save the event tree as a template for future use. This option is only available on initiating hazard nodes.

Customizing an Event Tree

Tools to customize the look of your event tree can be found in the **Options** tab within the event tree **Properties Window** (Figure 87).

- **Height** Defines the height, in pixels, of each node. Changing the height to greater than 70 will allow the node names to be on more than 1 line.
- **Width** Defines the width, in pixels, horizontally between each node.
- **Smooth** Defines the smoothness of the connector lines between nodes.
- **Extend** If checked, this option will extend the terminal leaf nodes to the right-most column in the event tree.
- **Background Color** Defines the background color in the event tree workspace.
- **Gridline Color** Defines the background grid line color in the event tree workspace.
- **Node Fill** Defines the fill color for the specified node.
- **Node Stroke** Defines the outline color for the specified node.
- **Reset** If this button is pressed, the options will be reset back to their default settings.
- **Zoom Scale** Defines the current zoom scale factor for the event tree workspace. A value of 1 means that the event tree is at the base zoom level.

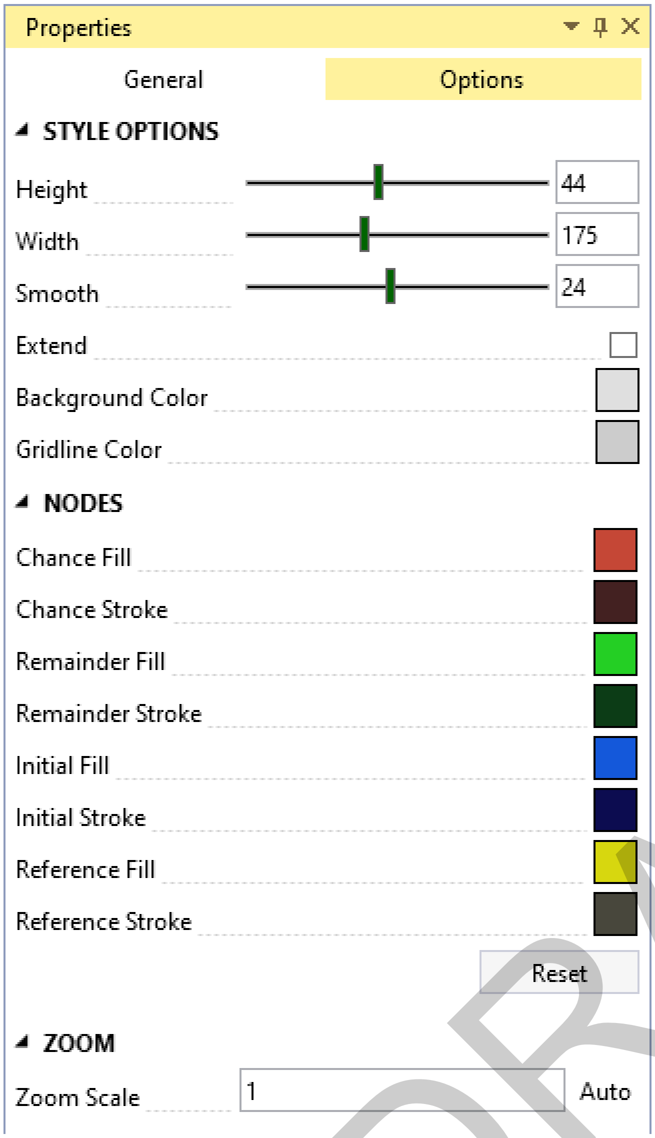


Figure 87 – Event tree style options.

Building an Event Tree

The following example represents an event tree developed for spillway erosion. The sequence of events are as follows: Pool elevation rises producing spillway flow, grass in spillway is removed, headcut initiates, headcut advances to control section, failure of control structure, unsuccessful intervention, breach.

1) Define the hazard. Click on the Initiating Hazard Node branch, *Hazard*, to select it. Once selected, edit in the **Properties Window** under the **Selected Branch Properties** sub-section (Figure 88). Alternatively, the branch can be edited by clicking the branch properties button, ⚙, in the event tree node toolbar. Change the name to *Pool Elevation* and,
2) Use the table editing tools to enter the desired **Hazard Levels**.

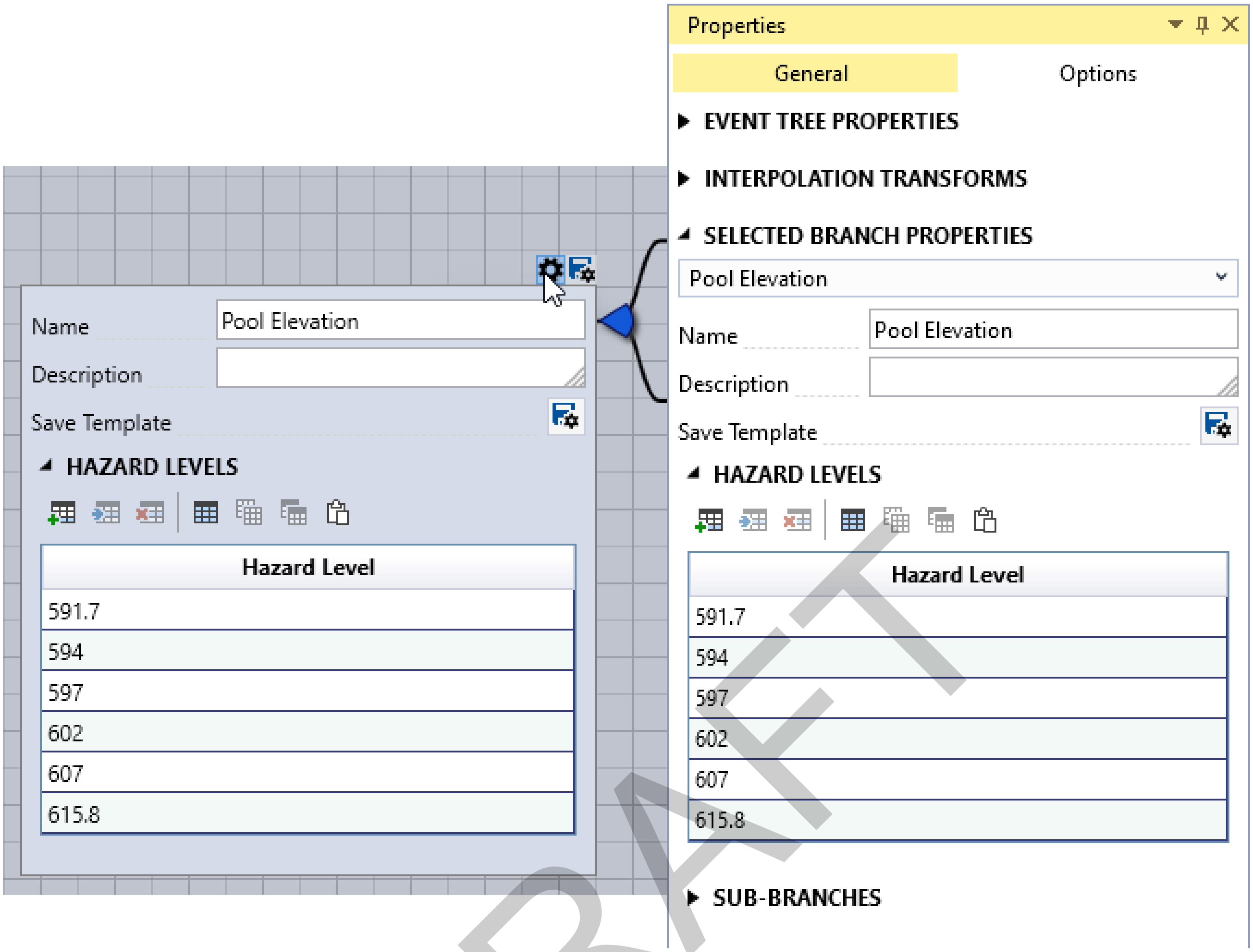


Figure 88 – Event tree selected node properties editor in the properties window and from the node toolbar options, completed Initiating Hazard Node.

3) Next, delete the *Fail* node that was added by default by either clicking the delete button ❌ in the toolbar or in the **SUB-BRANCHES** properties of the Initiating Hazard Node. A message will appear requiring confirmation of the deletion. Click **Yes** to confirm deleting the unwanted node.
4) Add the next node in the event tree by clicking the Add Branch button ➕ in the node toolbar, right-click node context menu, or in the **SUB-BRANCHES** properties section. Using the node properties editor, change the

name of the new node, add a description, and define the probability of the event for each hazard level defined in step 1 as shown in Figure 89 below.

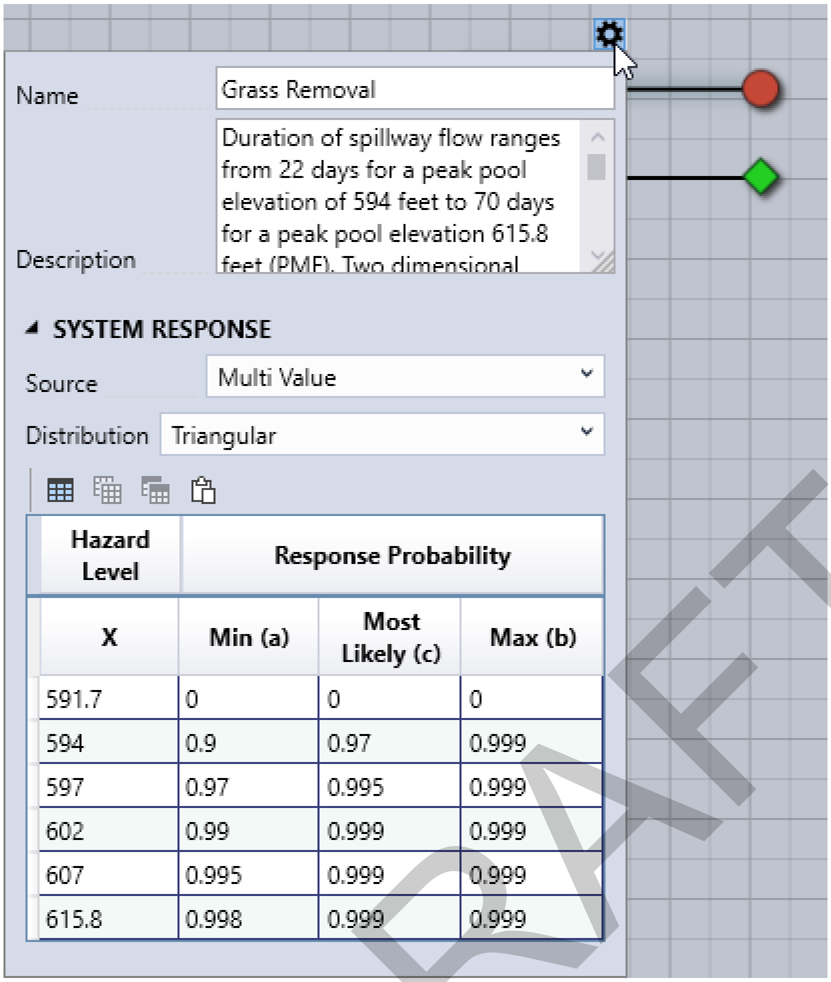


Figure 89 –Properties for the Grass Removal probability event tree node.

5) Continue this process of adding nodes and defining the properties until the event tree is complete as shown in Figure 90 below.

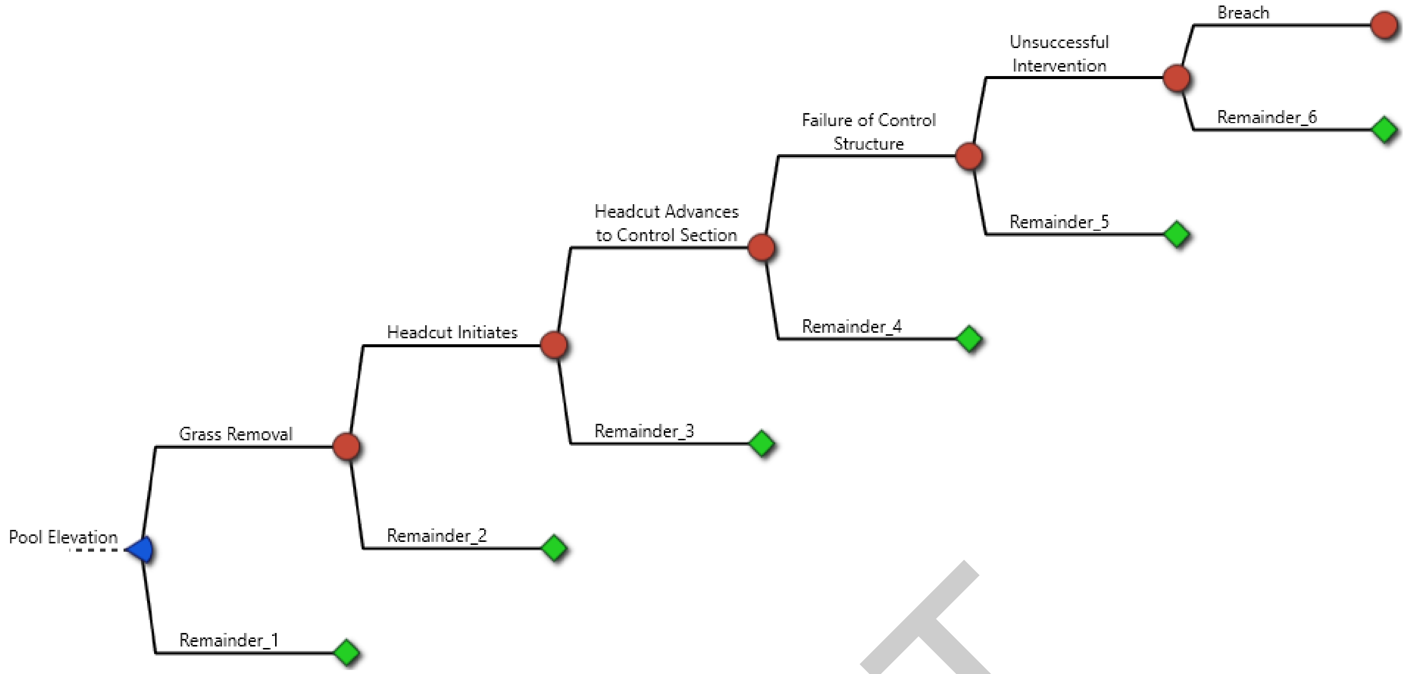


Figure 90 – Completed spillway erosion event tree.

Event Tree Results

The **Tabbed Document** contains three tabs: **Event Tree**, **Response**, and **Diagnostics**. RMC-TotalRisk provides several tools for exploring the results of the event tree analysis. The event tree is built and edited in the **Event Tree** tab as discussed in the sections above. The **Response** tab contains a graphical representation of the system response function for each hazard level. This is commonly referred to as a fragility curve and represents the probability of failure for each hazard level defined. The function data can be exported as tabular data using the export plot data button.

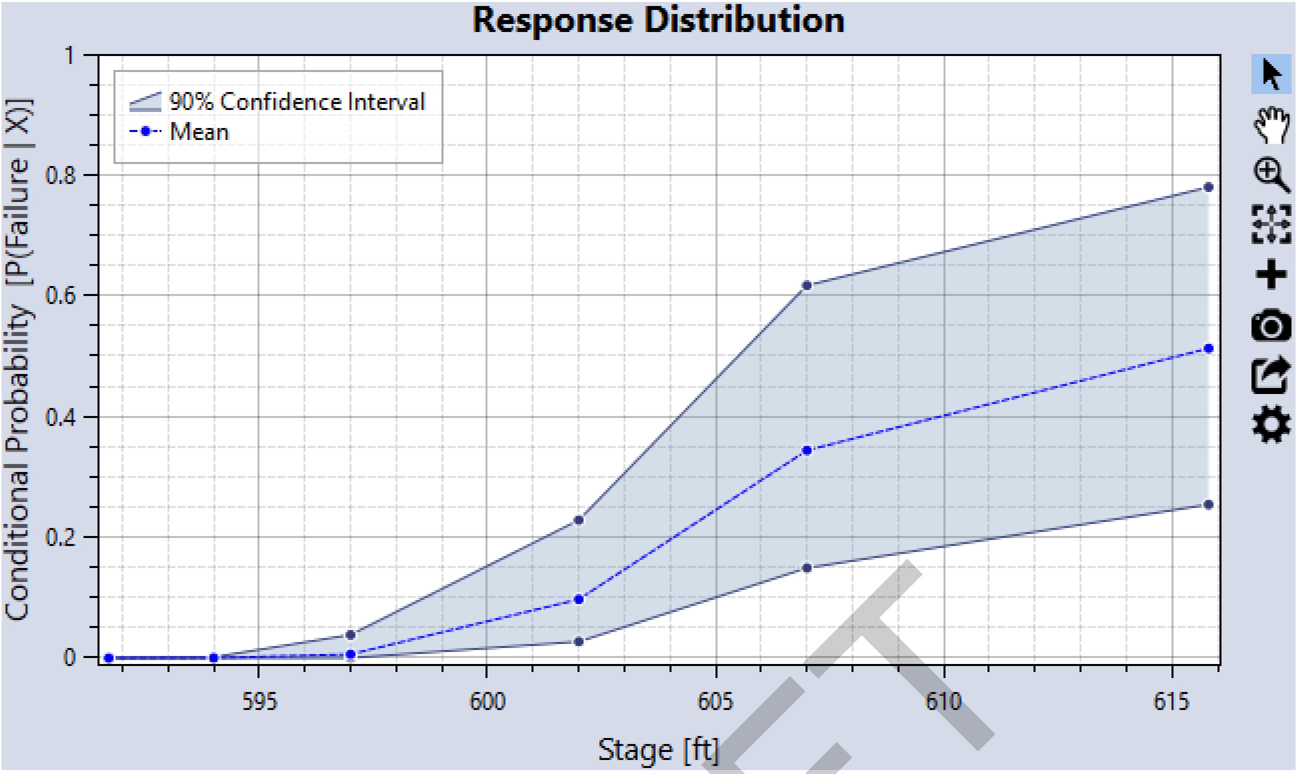


Figure 91 – System response probability function result from event tree.

The **Diagnostics** tab contains several tools for reviewing and validating the event tree calculations. Options for reviewing the event tree results are available on the left side of the **Diagnostics** tab. Options include **Node Filters**, **Model Parameters**, and **Plot Options** (Figure 92). Each viewing option is detailed below:

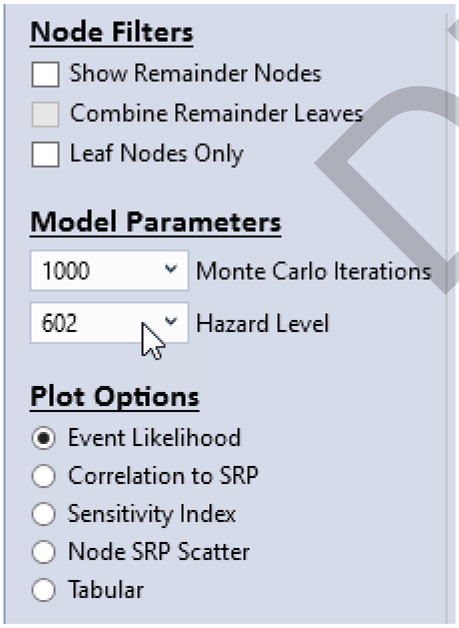


Figure 92 – Event tree diagnostic viewing options.

Node Filters Filter the visible plot data.

- **Show Remainder Nodes** Turns on or off displaying remainder nodes in the results.

- **Combine Remainder Leaves** If checked, the terminal remainder nodes are combined in the results. This is often akin to the probability of non-failure as each remainder node often represents non-fail conditions.
- **Leaf Nodes Only** If checked, only terminal leaf nodes are displayed. A leaf node is any node that doesn't have any child nodes.

Model Parameters Defines how the event tree is analyzed for review.

- **Monte Carlo Iterations** Defines the number of Monte Carlo iterations used to sample the event tree for diagnostic analysis. If no uncertainty is present, this option is disabled.
- **Hazard Level** Defines the hazard level that the diagnostic results are calculated at.

Plot Options Provides various plots and tables to analyze the event tree results.

- **Event Likelihood** Displays the likelihood of each node occurring in the event tree for the given hazard level (defined in the Model Parameters) as a box and whisker plot (Figure 93).
- **Correlation to SRP** Displays the Pearson's correlation coefficient for how each node's sampled probabilities correlate to the overall system response probability (SRP). Chance nodes will have a positive correlation with the SRP, whereas remainder nodes will have a negative correlation. The absolute size of the correlation coefficient indicates the strength of the association with SRP [1]. The nodal correlations to SRP are displayed as a ranked tornado plot shown in Figure 94 below.
- **Sensitivity Index** Displays each node's first-order sensitivity index, or main effect index (Figure 95). This is the contribution to the output variance. It measures the effect of varying a single node but averaged over variations in other input parameters. It is standardized by the total variance to provide a fractional contribution. A node with a high sensitivity index is a good indicator that reducing the nodes uncertainty will have a large impact on the overall SRP [10, 1].
- **Node SRP Scatter** This option allows the user to see the sampled values for a given node plotted against the overall SRP for each Monte Carlo iteration. A node with a strong correlation to SRP will show a clear trend between the sampled node probability and overall SRP as shown in Figure 96 below.
- **Tabular** This option allows the user to view the individual node's sampled probabilities and overall SRP for each Monte Carlo iteration in the model in table form (Figure 97). Using the table features, verification of node distribution sampling can be accomplished through the column statistics as shown in Figure 98 below.

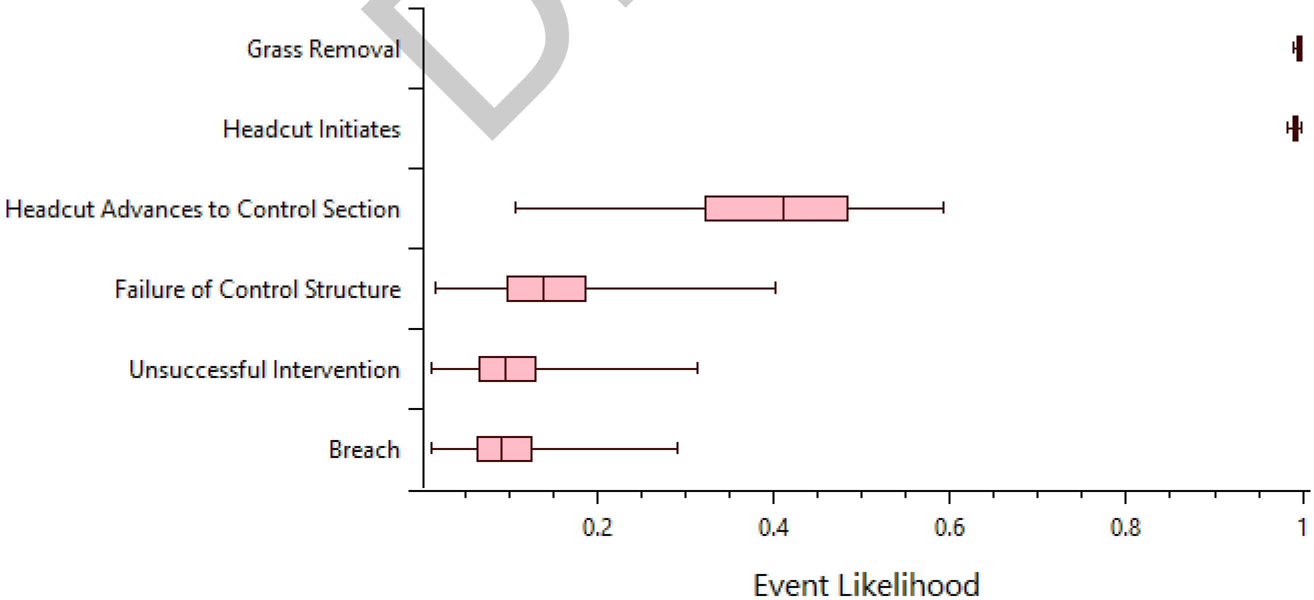


Figure 93 – Event tree diagnostics event likelihood plot option.

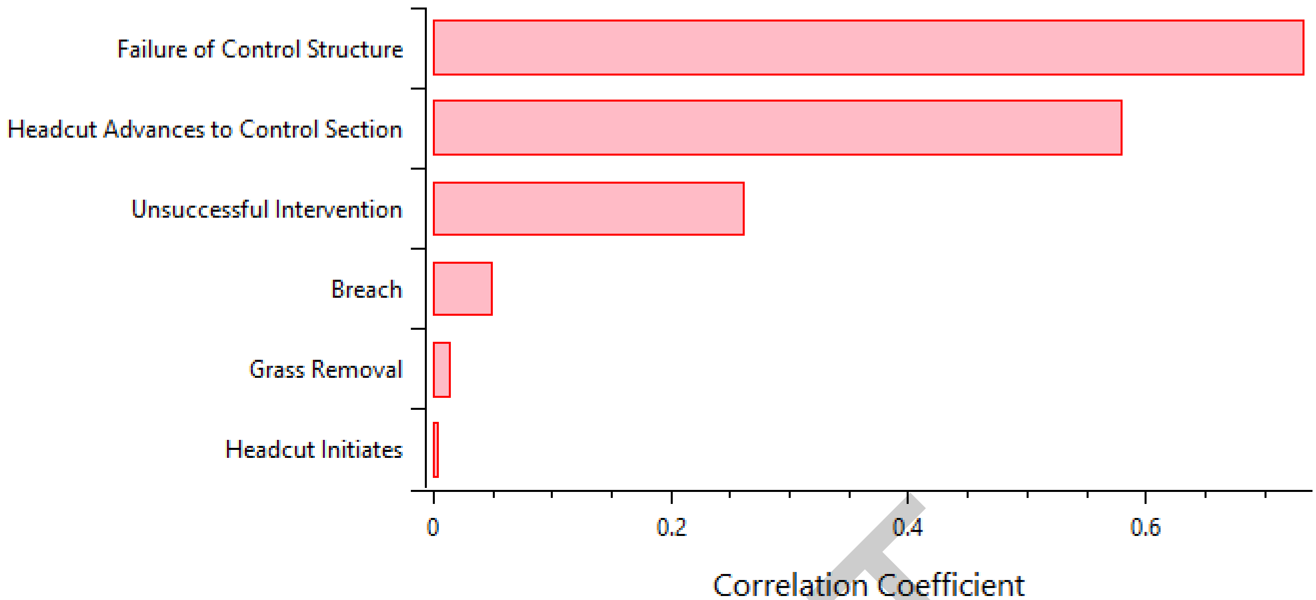


Figure 94 – Event tree diagnostics tree node correlation to SRP plot.

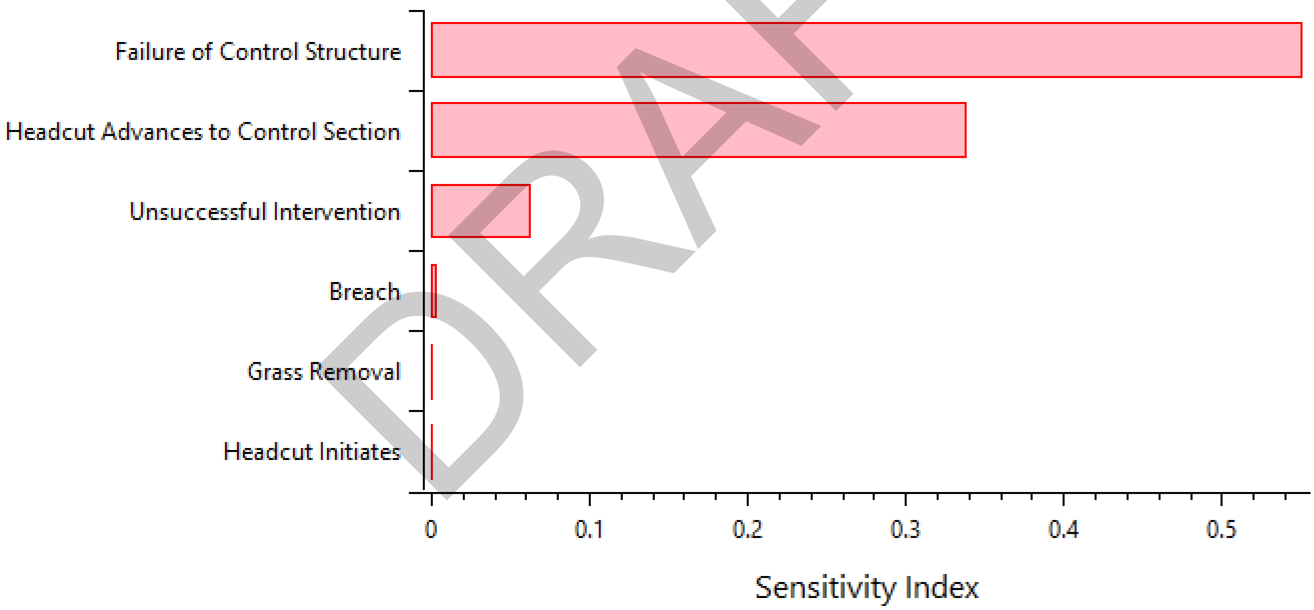


Figure 95 – Event tree diagnostics tree node sensitivity indices.

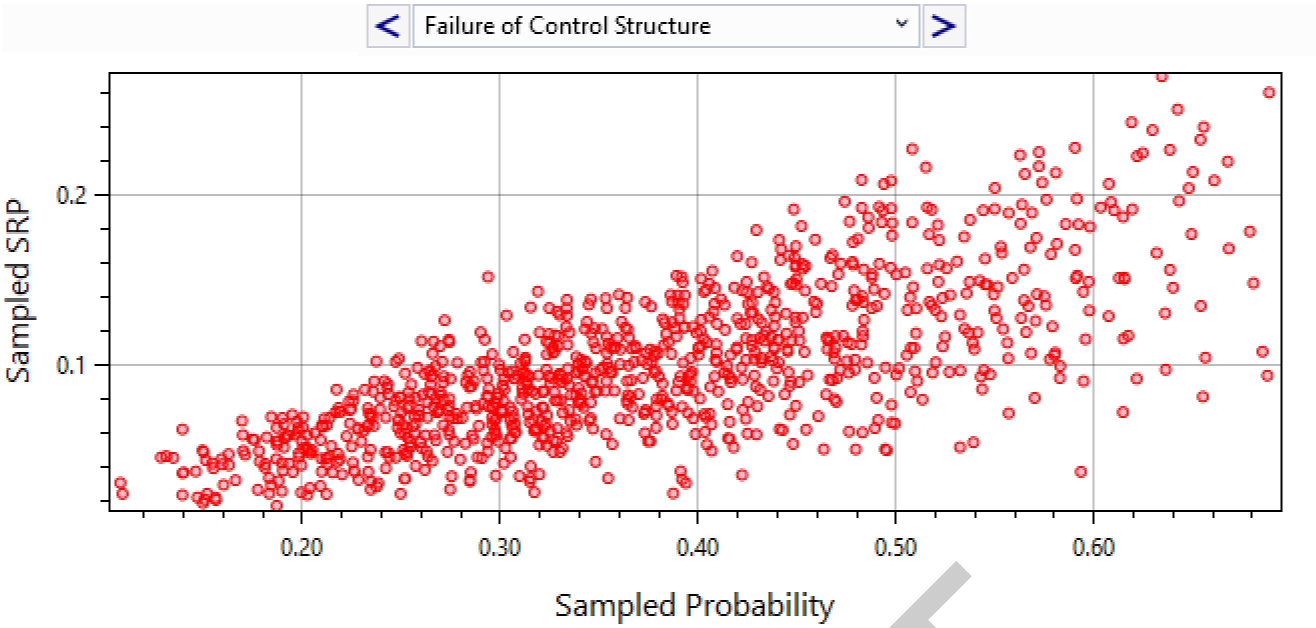


Figure 96 – Event tree diagnostics tree node probability to SRP scatter plot.

	Grass Removal	Headcut Initiates	Headcut Advances to Control Section	Failure of Control Structure	Unsuccessful Intervention	Breach	SRP
0	0.99232518853...	0.99238388762...	0.49364073344...	0.35747032902...	0.77271781224...	0.97474801716...	0.13088744576...
1	0.99366642365...	0.99772182494...	0.32812994751...	0.35567626317...	0.63572729196...	0.95073937275...	0.06993316358...
2	0.99418263431...	0.99129833804...	0.26421546961...	0.45059995199...	0.62492912163...	0.97862071335...	0.07175713666...
3	0.99835159563...	0.99539148125...	0.24401545766...	0.36399394704...	0.66941192800...	0.96859235708...	0.05722995714...
4	0.99685700090...	0.99708974006...	0.48275230415...	0.45401597124...	0.67804517645...	0.94038515377...	0.13890791465...
5	0.99745613511...	0.99412967815...	0.42172584186...	0.34856555608...	0.64221264441...	0.97166761406...	0.09095950921...
6	0.99045704932...	0.99626074127...	0.39931852710...	0.34893092186...	0.74809934579...	0.95477953428...	0.09820417664...
7	0.99467612456...	0.99478813968...	0.45643832208...	0.28807827501...	0.67193803448...	0.97629482977...	0.08535227756...
8	0.99377212283...	0.99830832384...	0.45898595393...	0.39635550307...	0.68794059390...	0.95747202803...	0.11888110191...
9	0.99156153332...	0.99659623184...	0.47720140297...	0.18983962642...	0.82552285551...	0.93430256358...	0.06904689219...
10	0.99277123517...	0.99581929209...	0.36072190654...	0.14236856125...	0.77988664645...	0.91145373585...	0.03608963156...

Figure 97 – Event tree diagnostics tabular output.

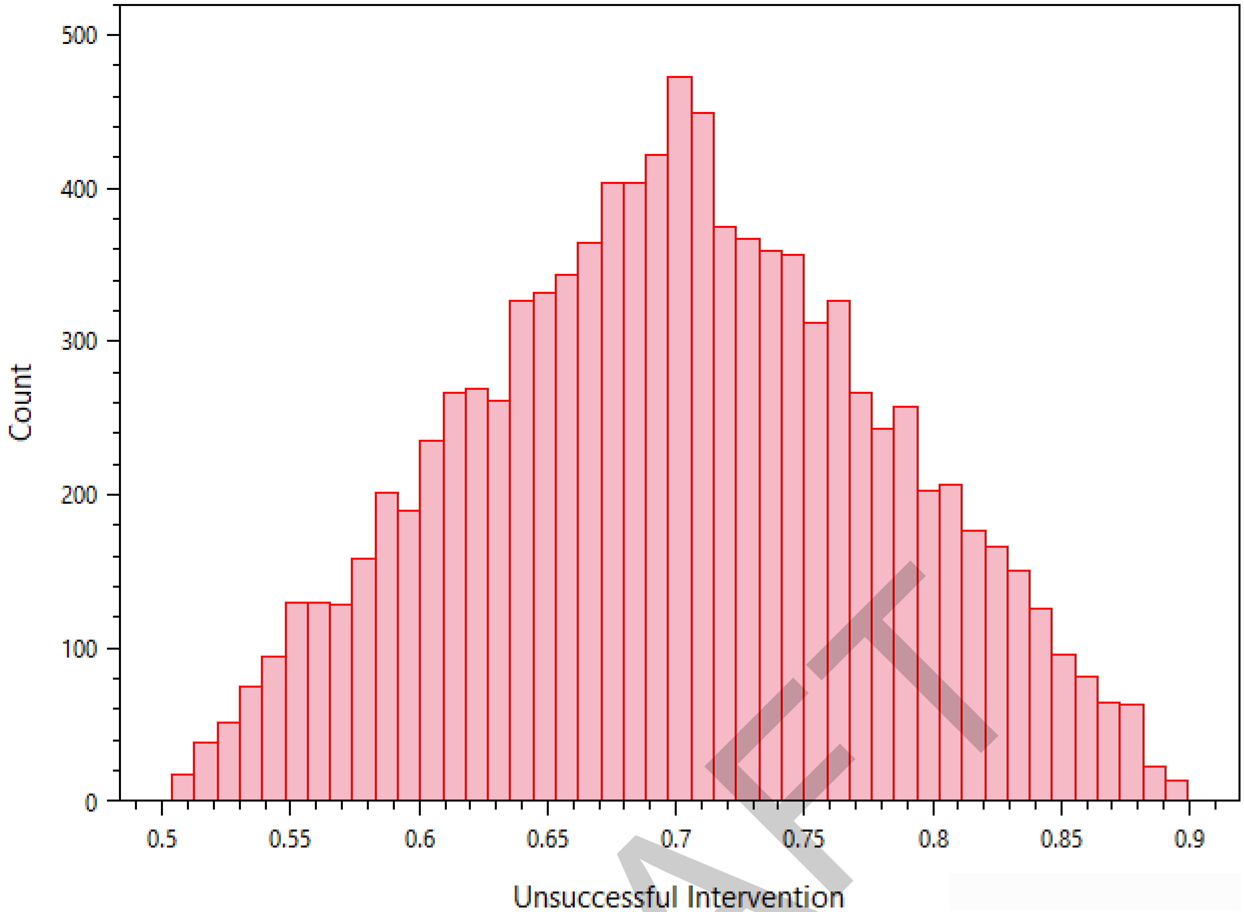


Figure 98 – Column statistics for the Unsuccessful Interventions node's sampled probabilities confirming that the node distribution (Triangular) is being sampled correctly.

Parametric Function

The parametric response function option allows the user to define a system response function using a parametric distribution. To create a parametric response function, right-click on the **System Responses** folder in **Project Explorer** (Figure 99) or from the **Project Menu→System Responses** and select **Add Parametric Response…**. Next, give the **Parametric Response** function a name and click **OK**.

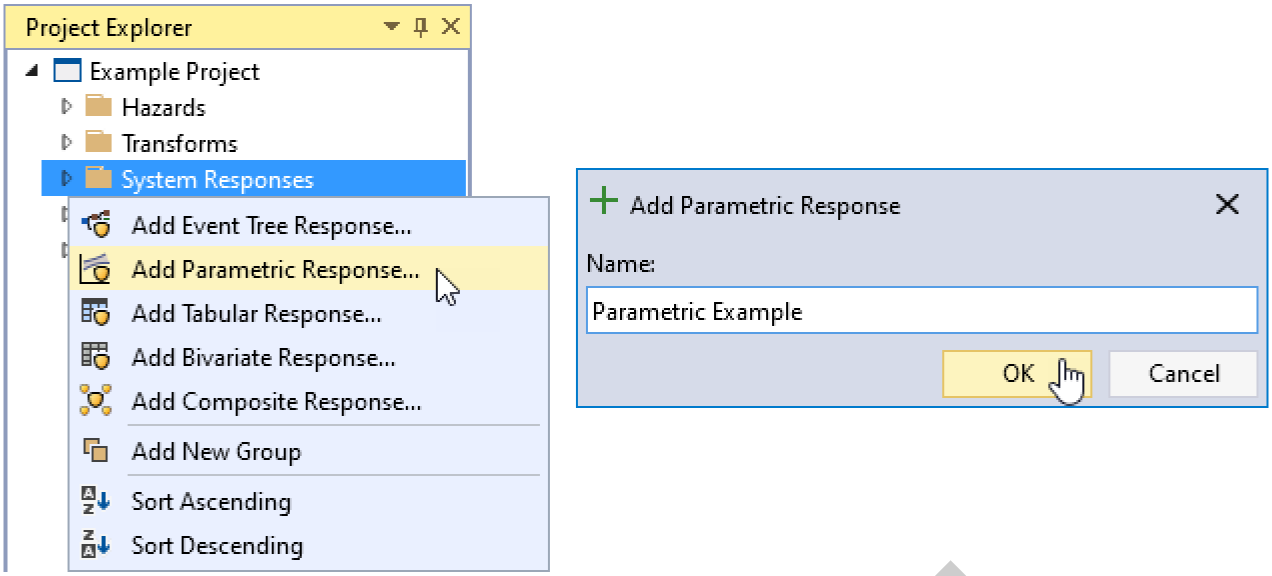


Figure 99 – Create New Parametric Hazard Function.

When the new Parametric Response function is created, it will be automatically opened into the **Tabbed Documents** area, and the parametric function properties will be displayed in the **Properties Window**. From here, you can set the **Name**, **Description**, **Hazard Type** and **Hazard Units**. The parametric function is defined in the properties window. Define the parametric distribution by setting the **Effective Record Length**, type of **Distribution**, and parameters for the distribution. Once the parameters have been set, click the **Compute** button to generate and view the parametric response function as shown in Figure 100. Further options for computing the parametric function are available in the **Options** tab which include bootstrap sampling **Confidence Interval**, number of **Realizations**, **PRNG Seed** for random number generation, and sample **Probability Ordinates**.

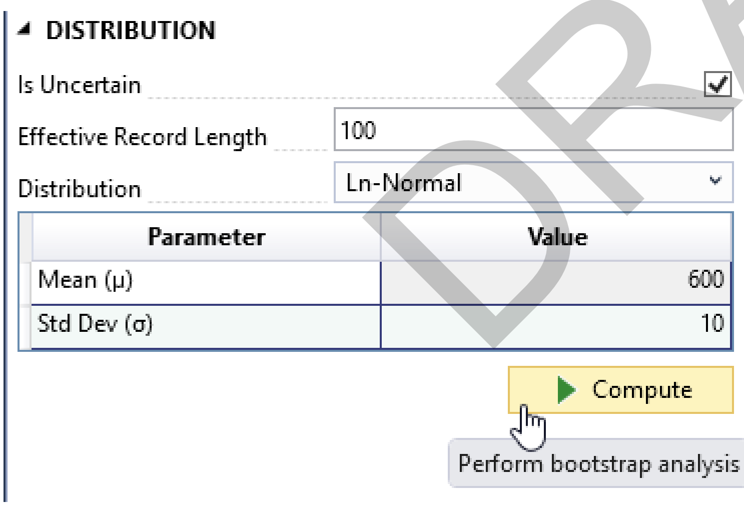


Figure 100 – Parametric Response Function properties.

Identical to the RMC-BestFit, RMC-RFA, and Parametric hazard functions, the frequency results can be viewed as graphical or tabular data. For more information on these viewing options, see the *Frequency Results* section under RMC-BestFit.

Tabular Function

The tabular response function provides an easy way to define a system response function using tabular data. The most common use case is copying and pasting from another application such as Microsoft Excel®. To create a tabular response function, right-click on the **System Responses** folder in **Project Explorer** (Figure 101) or from the **Project Menu→System Responses** and select **Add Tabular Response…**. Next, give the **Tabular Response** function a name and click **OK**.

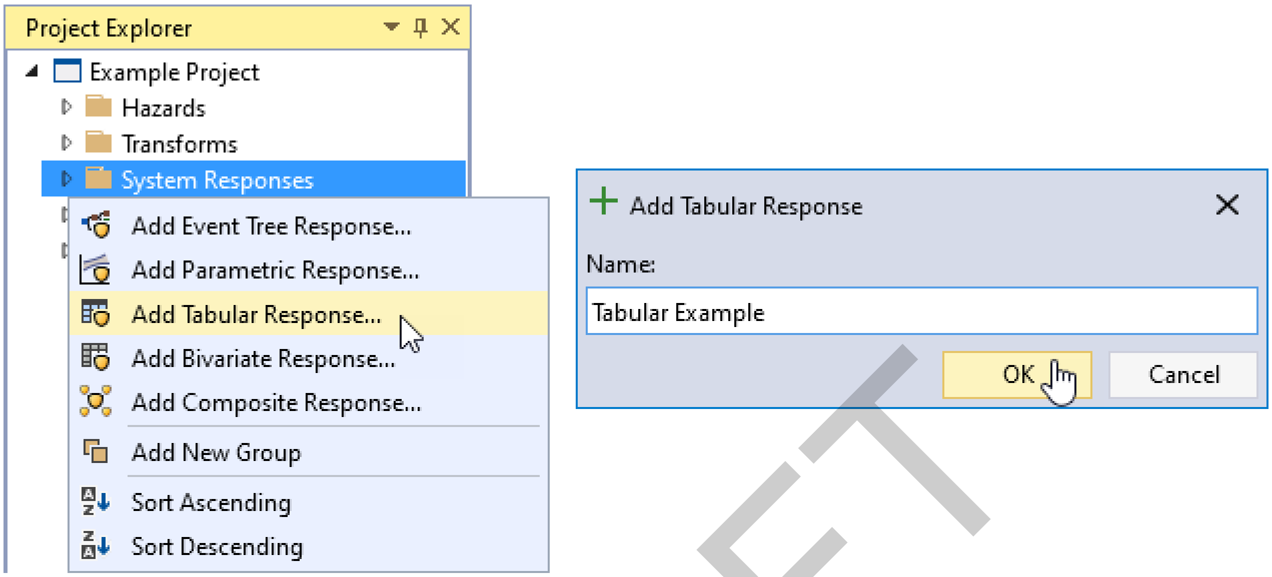


Figure 101 – Create New Tabular Response Function.

When the new Tabular Response function is created, it will be automatically opened into the **Tabbed Documents** area, and the tabular function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, and **Hazard** and **Probability** interpolation transforms as shown in Figure 102. The hazard and probability interpolation transforms define how the data is interpolated when sampling values between the specified tabular ordinates.

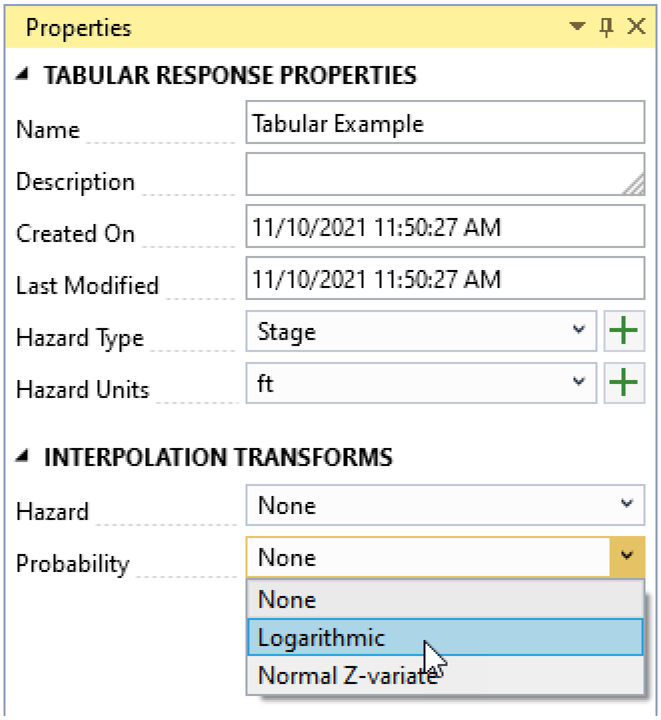


Figure 102 – Tabular Response Function properties.

The **Tabbed Document** for a tabular function contains the table where tabular data will be entered and a graphical representation of that data (Figure 103). A distribution must be selected to define uncertainty, parameters for the selected distribution can be entered for every ordinate in the tabular data. Data can be entered manually into the table or pasted from another source such as Microsoft Excel®.

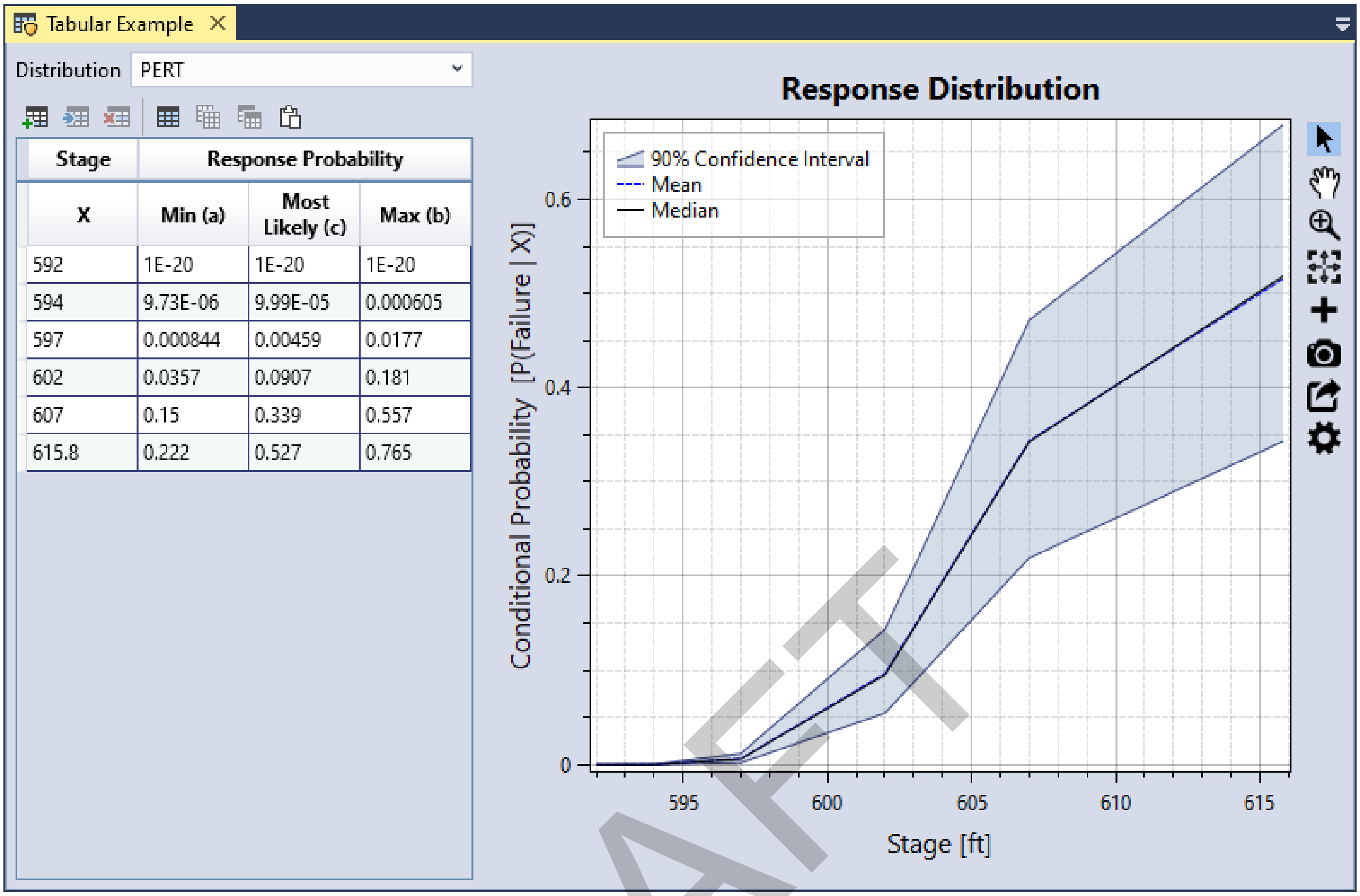


Figure 103 – Tabular Response Function completed tabular probability of failure given reservoir stage.

Data Validation

The input data table has built-in validation. The **Tabular Data** has the following requirements:

- Hazard values must be in ascending order.
- Probability values must be between 0 and 1.
- If uncertainty is defined, uncertain ordinates must contain valid distribution parameters.

When you enter invalid data, the table cell will turn red, and provide a tooltip indicating the source of the error as shown in Figure 104. In addition, an error message will appear in the **Message Window** indicating that you must resolve all errors in the data table.

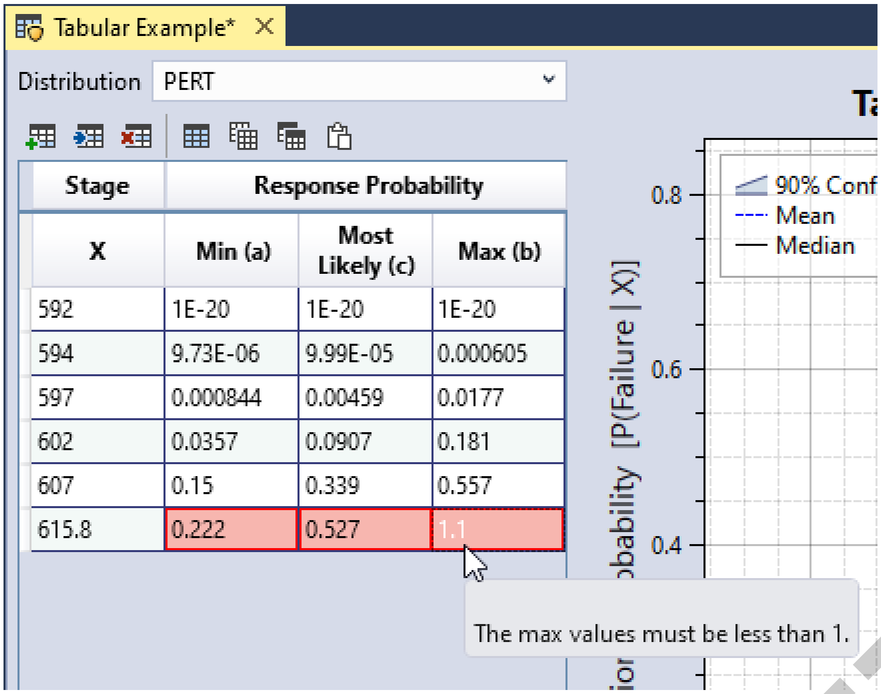


Figure 104 – Input Data Validation.

Bivariate Function

The Bivariate Response function option provides an easy way to define a system response function with two hazards using tabular data. In many cases a bivariate response function will be defined using the event tree tools. However, when available a bivariate probability table can be copied and pasted from another application such as Microsoft Excel®. To create a bivariate response function, right-click on the **System Responses** folder in **Project Explorer** (Figure 105) or from the **Project Menu→System Responses** and select **Add Bivariate Response…**. Next, give the **Bivariate Response** function a name and click **OK**.

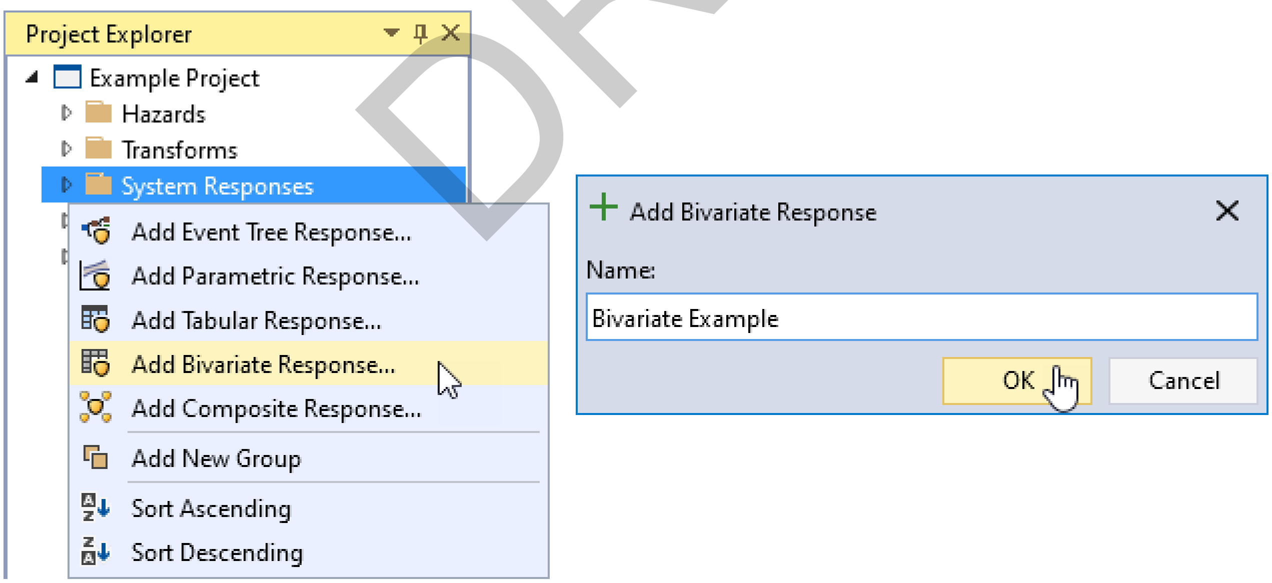


Figure 105 – Create New Bivariate Response Function.

When the new Bivariate Response function is created, it will be automatically opened into the **Tabbed Documents** area, and the bivariate function properties will be displayed in the **Properties Window** (Figure 106). From here, you can set the **Name**, **Description**, **Primary Hazard**, and **Primary Hazard Units**. You can also set the **Interpolation**

Transforms for the Primary Hazard and Probabilities. Finally, the properties window is where the primary and secondary **Hazard Levels** are defined. Use the table tools to add the desired hazard levels for the primary and secondary hazards. The primary and secondary hazard levels must be in ascending order. A weight is required for each secondary hazard level. The weights are used on the secondary hazard levels during the risk compute to define a weighted probability associated with each primary hazard level. The weight values must sum to 1. Weights can be manually entered or automatically calculated using a specified **Hazard Function**. See [1] for more details on bivariate hazard properties.

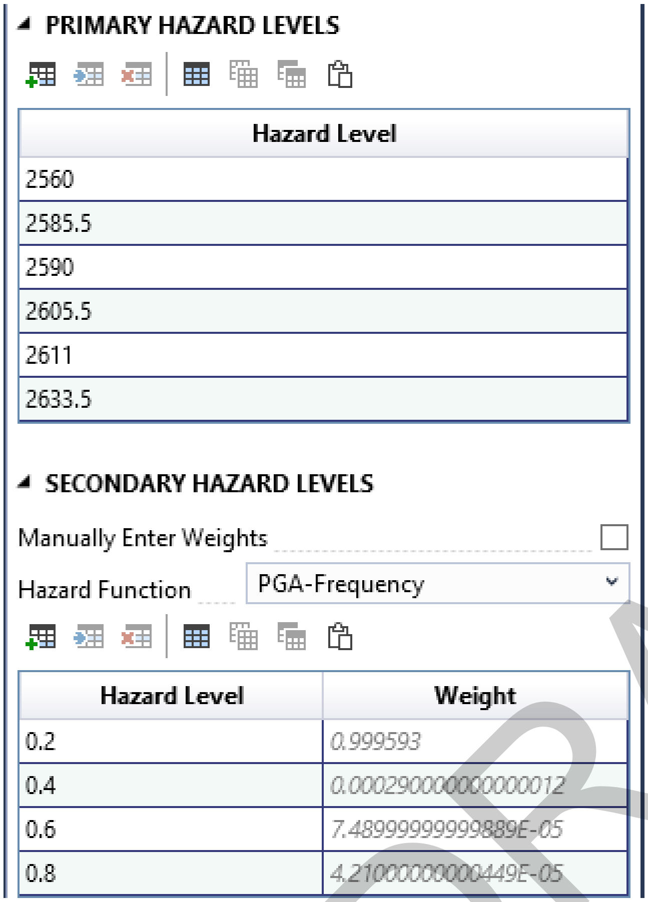


Figure 106 – Bivariate Response Function properties.

As the primary and secondary hazard levels are entered in the **Properties Window**, the table at the top of the **Tabbed Document** is automatically updated where each row is a primary hazard level and each column is a secondary hazard level. To complete the bivariate response function, enter the associated probability of failure in each cell given the primary hazard (row) and secondary hazard (column) as shown in Figure 107. Below the table is a graphical representation of the system response functions for each secondary hazard level.

Bivariate Example

	0.2	0.4	0.6	0.8
2560	1.8E-10	1.08E-07	9.18E-07	1.62E-06
2585.5	9.3E-09	5.58E-06	4.74E-05	8.35E-05
2590	1.69E-08	1.01E-05	8.61E-05	0.000151
2605.5	2.5E-08	1.5E-05	0.000127	0.000224
2611	1.17E-07	7.03E-05	0.000597	0.00105
2633.5	1.1E-06	0.000659	0.0056	0.00987

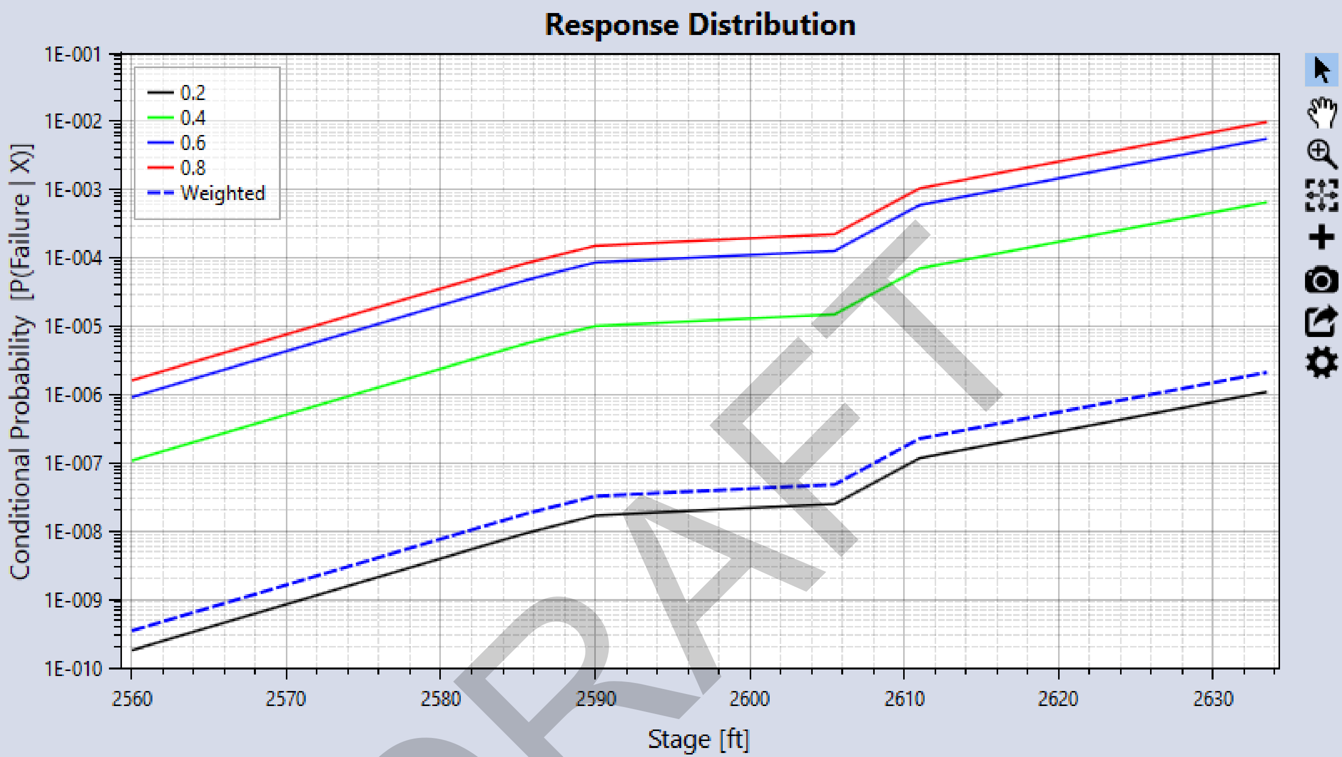


Figure 107 – Bivariate response function tabbed document.

Composite Function

The composite response function option allows the user to combine multiple response functions into a single function by weighting the individual input functions. To create a composite response function, right-click on the **System**

Responses folder in **Project Explorer** (Figure 108) or from the **Project Menu→Hazards** and select **Add Composite Response…**. Next, give the **Composite Response** function a name and click **OK**.

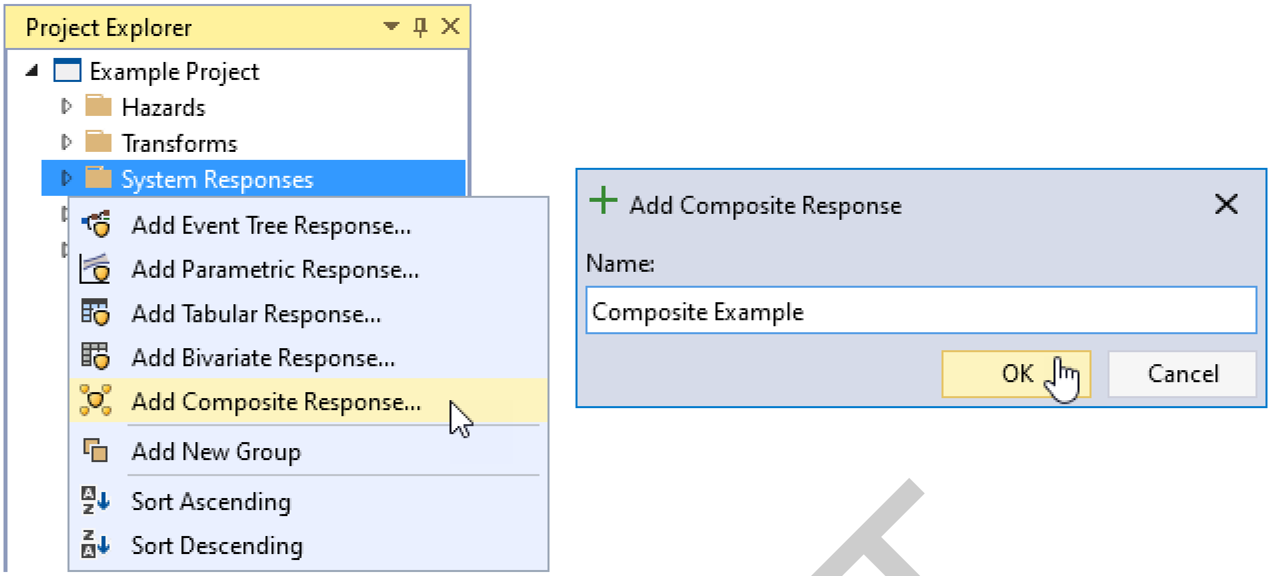


Figure 108 – Create New Composite Response Function.

When the new Composite Response function is created, it will be automatically opened into the **Tabbed Documents** area, and the composite function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, and input **Response Functions** as shown in Figure 109. The Response functions table is where the input functions are to be defined. Click the Add Row(s) button in the Response Functions table toolbar to add new rows for input to the composite. The response function weights must sum to 1. The user has the option to combine the functions using the probability of union assuming each response function is independent by unchecking the **Is Mixture** checkbox.

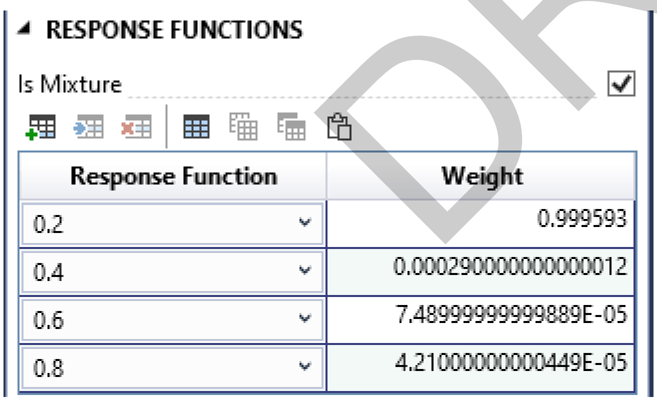


Figure 109 – Composite Response Function properties.

The **Tabbed Document** for a composite function contains a graphical representation of the composite function (Figure 110).

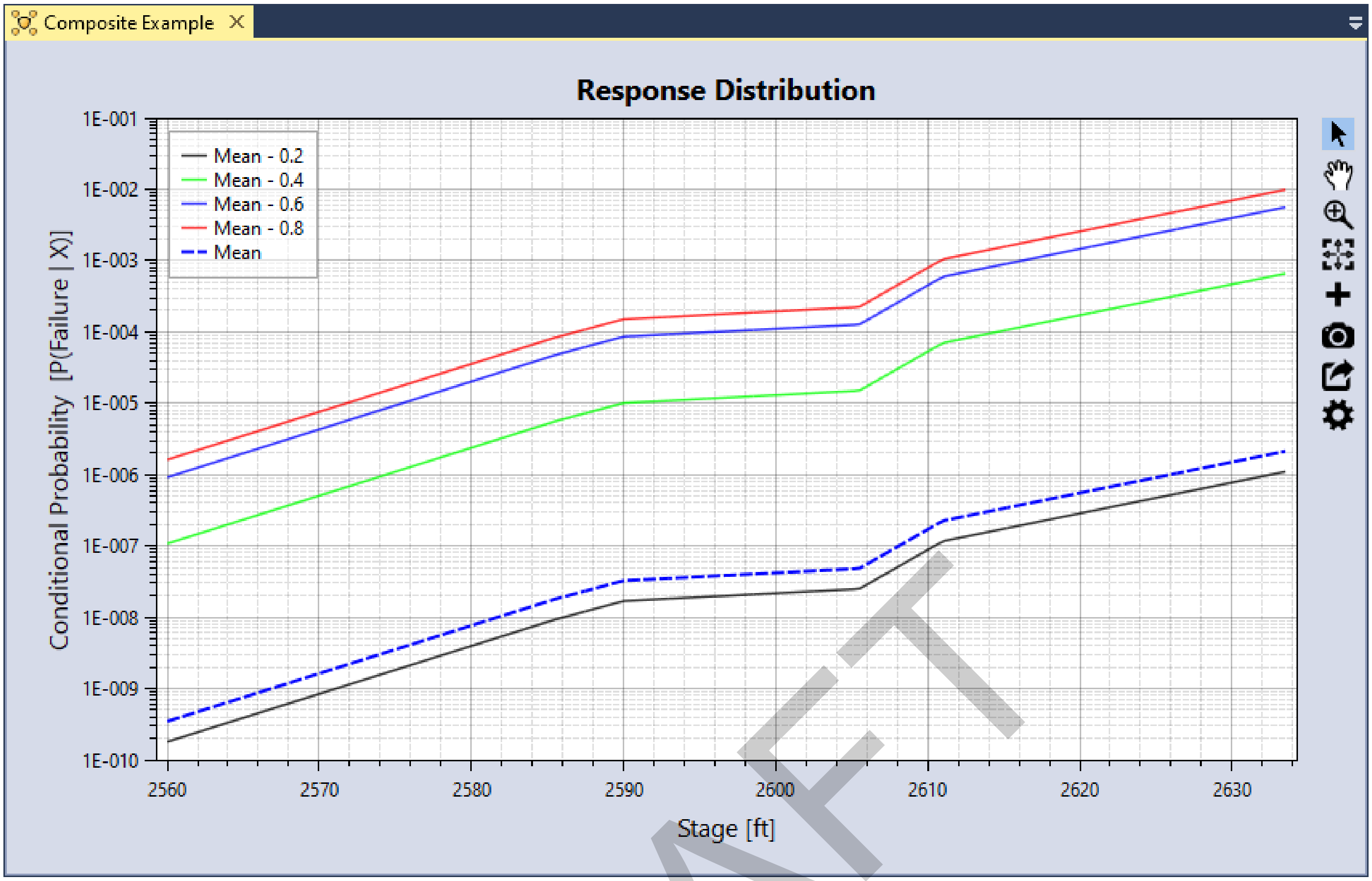


Figure 110 – Composite Response Function graphical display.

Consequence Functions

Consequence functions in RMC-TotalRisk represent the magnitude of consequences that will occur for a given range of hazards. In other words, how much life loss or economic damage is expected for a given hazard level and the associated system response. It is common in dam and levee safety risk analyses for consequence functions to be defined separately for each PFM because consequence estimates can change depending on which failure mode is being assessed. For example, an overtopping failure mode may have a very different warning time than an earthquake driven failure resulting in different life loss estimates. In RMC-TotalRisk, consequence functions can be defined by importing directly from a LifeSim v 2.0 model, as a tabular function, or as a composite function. The following will go over each input option in detail.

LifeSim

The USACE-RMC, in collaboration with the Hydrologic Engineering Center (HEC), developed the life loss and economic damage estimation software LifeSim [11] [12]. LifeSim is an agent-based system for estimating life loss with the fundamental intent to simulate population redistribution during an evacuation [13]. Life loss and economic damages are then determined by the hazard (e.g., flooding). LifeSim can be downloaded from the following link, https://www.rmc.usace.army.mil/Software/LifeSim/. Results from a LifeSim analysis can be imported directly into RMC-TotalRisk.

To import results of a LifeSim analysis, right-click on the **Consequences** folder in **Project Explorer** (Figure 111) or from the **Project Menu→Consequences** and select **Add LifeSim Consequence…**. A dialog will appear where you enter the name of the dataset and select the LifeSim project file that contains the desired results.

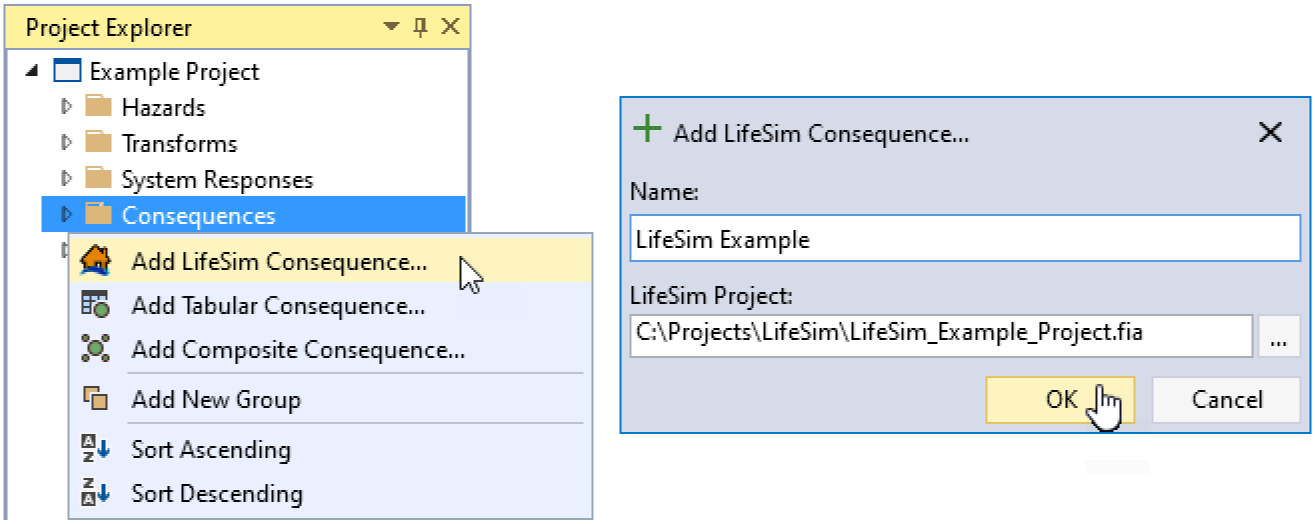


Figure 111 – Create New LifeSim Consequence Function.

Once satisfied with the import settings, click **OK** (Figure 111) and the LifeSim study results will be imported to the study**.** When the new LifeSim consequence function is created, it will be automatically opened into the **Tabbed Documents** area, and the function properties will be displayed in the **Properties Window** (Figure 106). From here, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, and **Hazard** and **Consequence** interpolation transforms as shown in Figure 112. The hazard and consequence interpolation transforms define how the data is interpolated when sampling values between the specified LifeSim results.

The **LifeSim Results** section contains three important parameters to consider when selecting results from a LifeSim analysis.

- **Consequence:** Determines what type of consequence will be selected from the LifeSim results. The options are *Life Loss* and *$ Damages*.
- **Starting Hazard:** The hazard level where consequences begin to occur. This parameter provides a lower bound for the consequence function. The starting hazard level must be below the lowest value defined in the imported LifeSim results.
- **Combine Zones:** If checked, selected LifeSim results are from the entire simulation area. If unchecked, specific summary zones (regions) must be selected from LifeSim results. LifeSim allows results to be geographically separated by summary zone allowing for more flexibility when creating consequence functions.

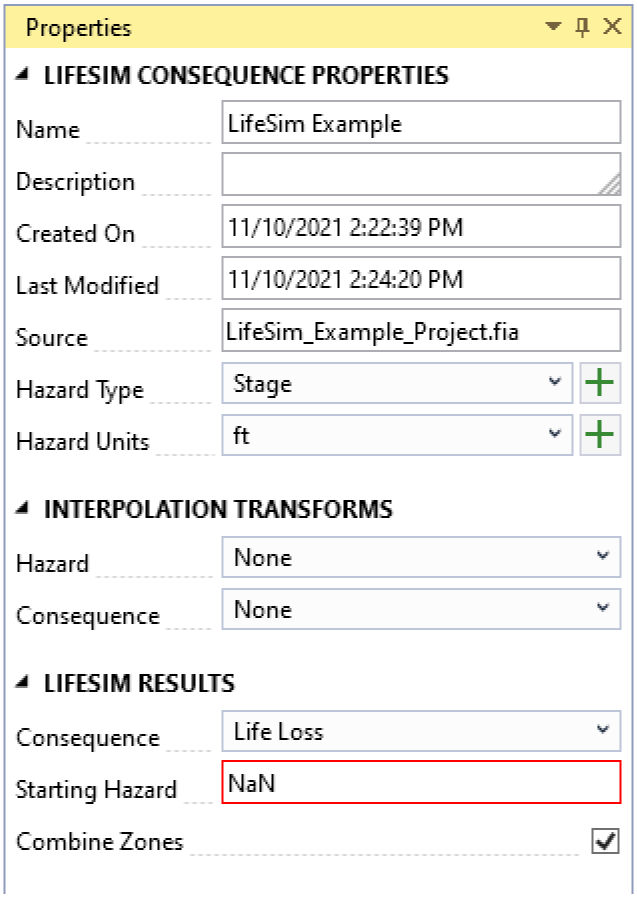


Figure 112 – LifeSim consequence function properties.

The LifeSim consequence function is created in the **Tabbed Document**. The consequence function is defined by entering hazard levels (e.g., reservoir pool elevations or river flows) and LifeSim simulation results using the table on the left. A graphical representation of the function is displayed to the right of the table (Figure 114). There are three steps to entering each LifeSim result:

1. Use the table tools to add rows for each desired hazard level (e.g., 2-yr, 10-yr, 50-yr, 100-yr floods). The hazard levels entered must be in ascending order.
2. For each defined hazard level, select a LifeSim simulation result from the dropdown menu(s). The **Filtered View** checkbox can make it easier to navigate LifeSim results by filtering the cell contents to only contain results from the selected Simulations/Alternatives/Times of day. For example, in Figure 114 below the only options in the Alternative column are from the *FWOP* simulations and the available Hazard Time(s) are based on the selected Simulation-Alternative combination.
3. Once a LifeSim simulation result has been selected, multiple distributions will be auto-fit to the data and a truncated normal distribution will be selected to represent potential consequences with uncertainty at the specified hazard level. To view, change, or edit the selected distribution click on the button in the **Distribution** column cell. A popup appears (Figure 113) that shows the selected distribution, the distributions PDF, and a histogram of the LifeSim results data for a visual comparison of the distribution fit. Summary statistics are provided for both the selected distribution and the LifeSim results data including goodness of fit tests for the distribution and the data.

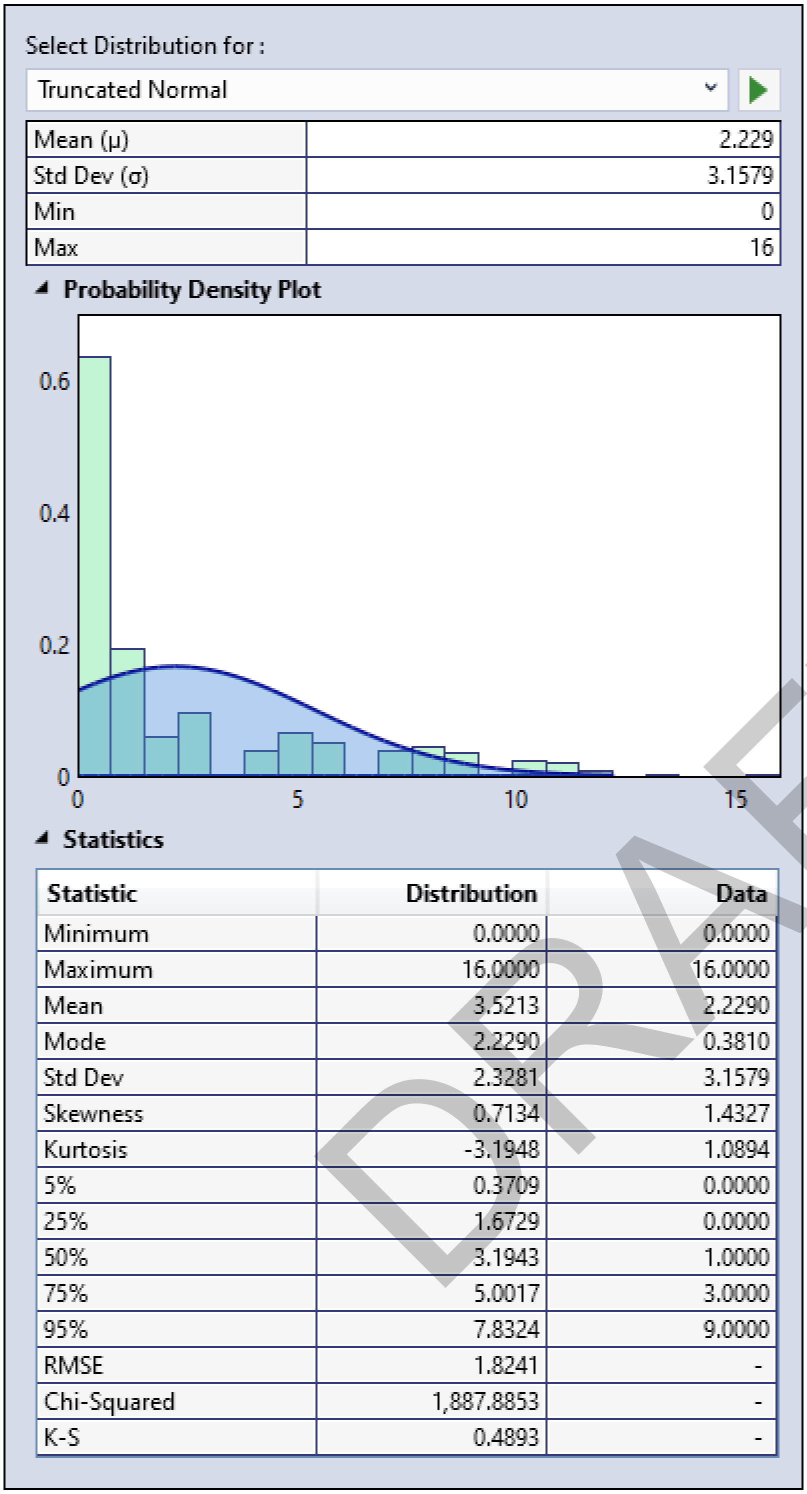


Figure 113 - LifeSim result distribution selector control.

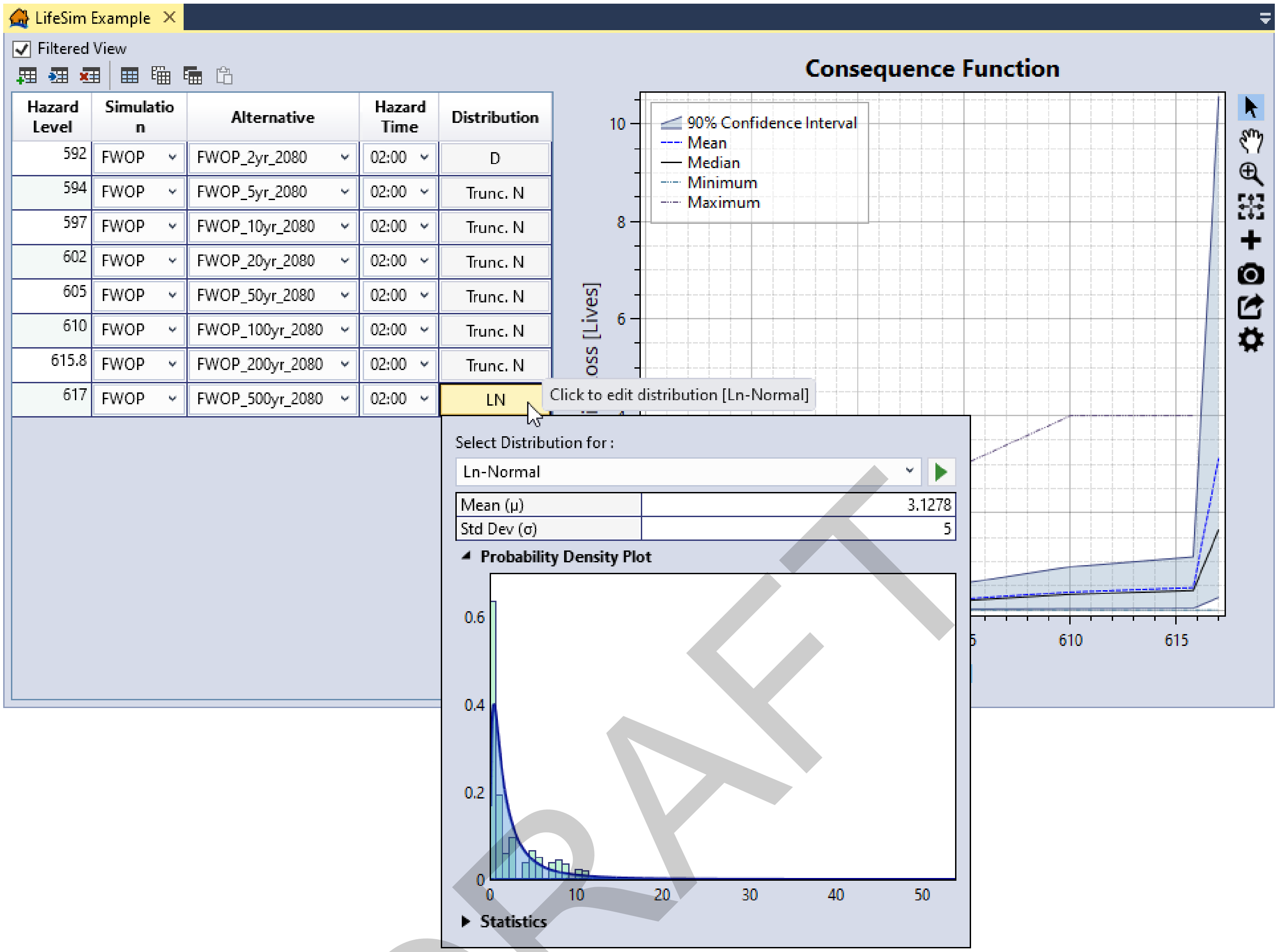


Figure 114 – LifeSim consequence function tabbed document.

Tabular Function

The tabular consequence function option provides an easy way to define a consequence function using tabular data. The most common use case is copying and pasting from another application such as Microsoft Excel®. To create a tabular consequence function, right-click on the **Consequences** folder in **Project Explorer** (Figure 115) or from the **Project Menu→Consequences** and select **Add Tabular Consequence…**. Next, give the **Tabular Consequence** function a name and click **OK**.

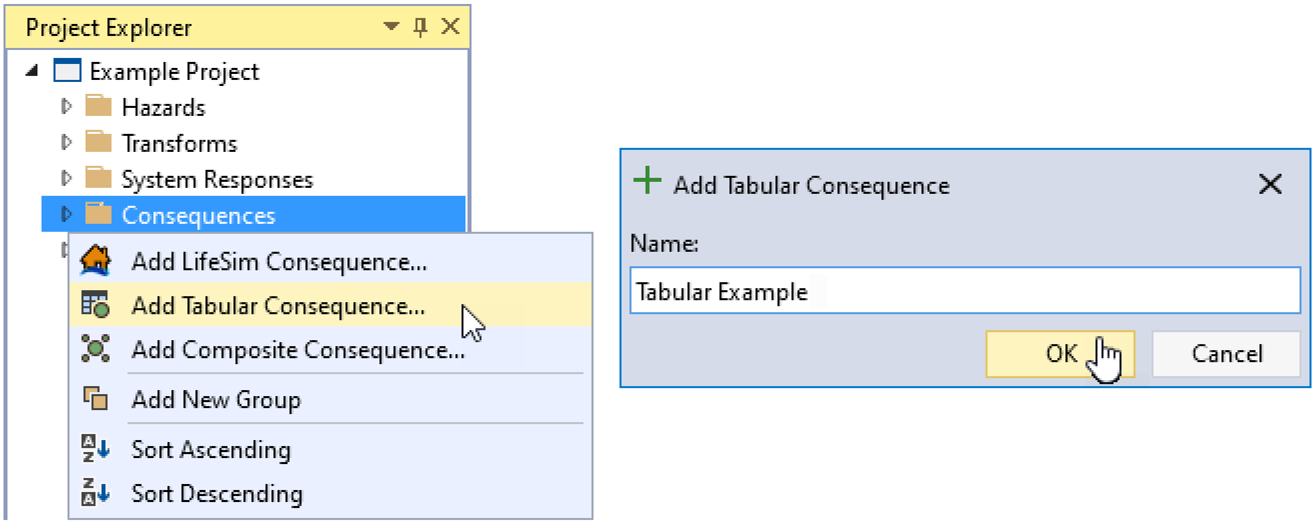


Figure 115 – Create new Tabular Transform Function.

When the new Tabular Consequence function is created, it will be automatically opened into the **Tabbed Documents** area, and the tabular function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, **Consequence**, **Consequence Unit**, and **Hazard** and **Consequence** interpolation transforms as shown in Figure 116. The hazard and consequence interpolation transforms define how the data is interpolated when sampling values between the specified tabular ordinates.

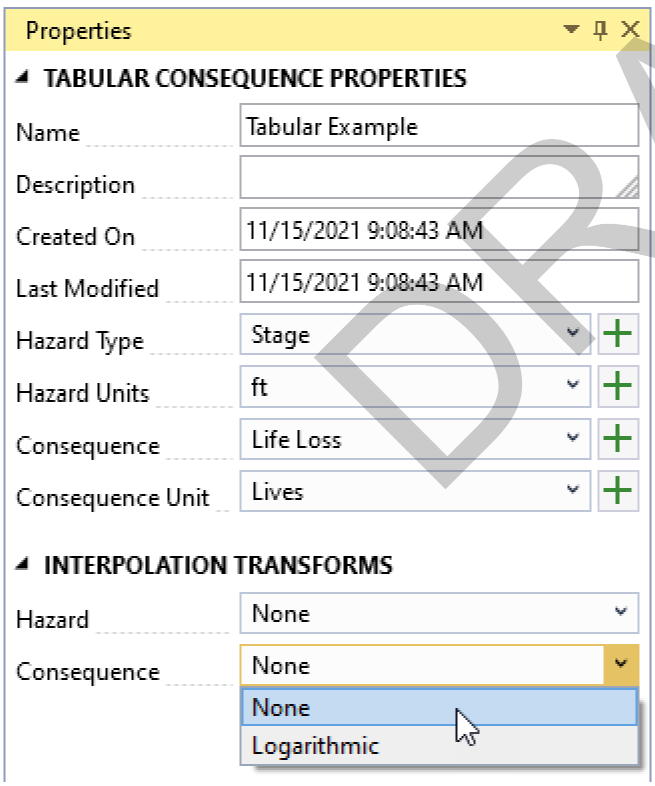
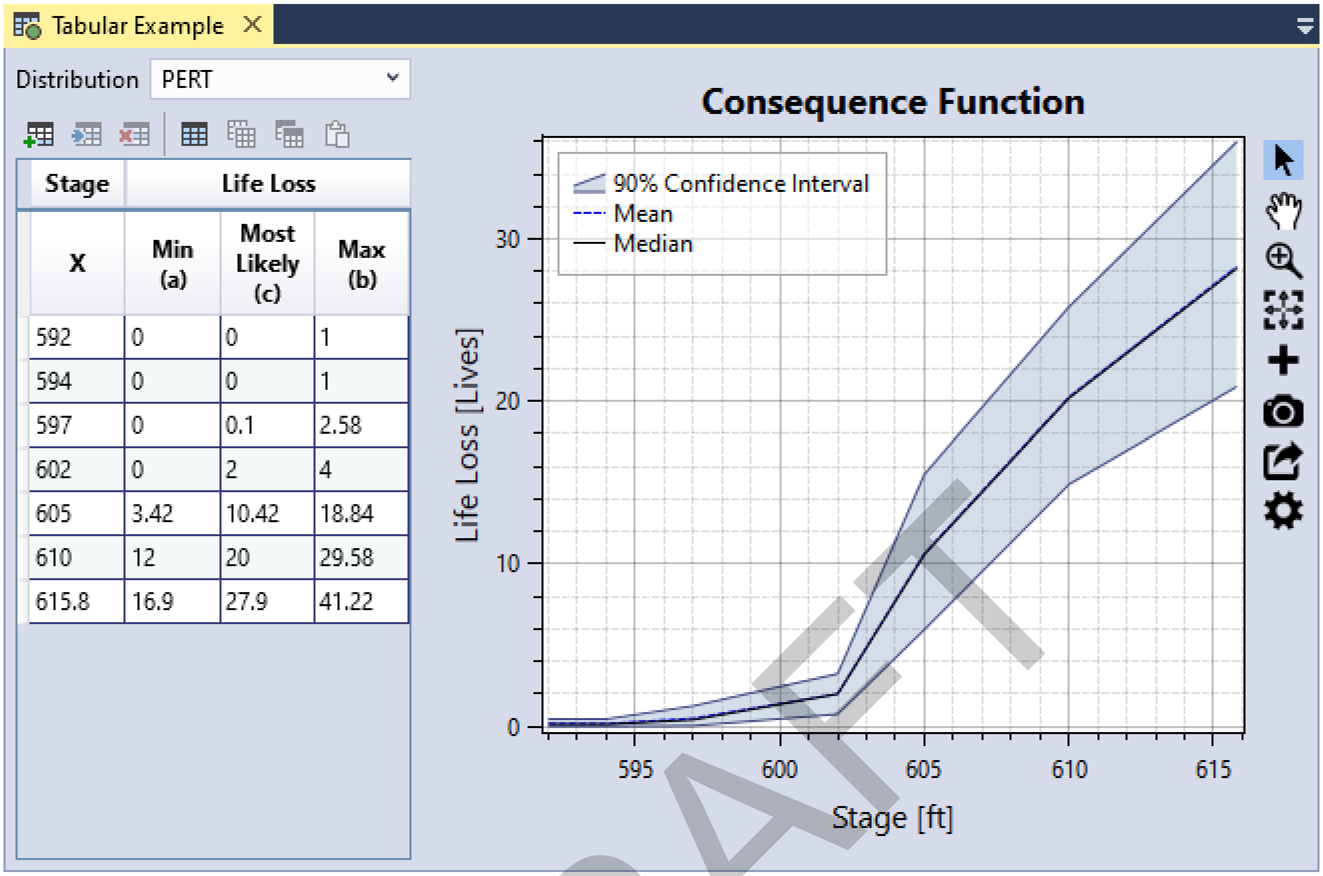


Figure 116 – Tabular Consequence Function properties.

The **Tabbed Document** for the Tabular Consequence Function contains the table where data will be entered and a graphical representation of that data (Figure 117). Uncertainty can be defined around the consequence for each tabular ordinate. A distribution must be selected to define uncertainty, parameters for the selected distribution must be entered for every ordinate in the tabular data. Data can be entered manually into the table or pasted from another source such as Microsoft Excel®.



Stage	Life Loss		
X	Min (a)	Most Likely (c)	Max (b)
592	0	0	1
594	0	0	1
597	0	0.1	2.58
602	0	2	4
605	3.42	10.42	18.84
610	12	20	29.58
615.8	16.9	27.9	41.22

Figure 117 – Tabular consequence function example.

Data Validation

The input data table has built-in validation. The **Tabular Data** has the following requirements:

- Hazard values must be in ascending order.
- If uncertainty is defined, uncertain ordinates must contain valid distribution parameters.

When you enter invalid data, the table cell will turn red, and provide a tooltip indicating the source of the error as shown in Figure 118. In addition, an error message will appear in the **Message Window** indicating that you must resolve all errors in the data table.

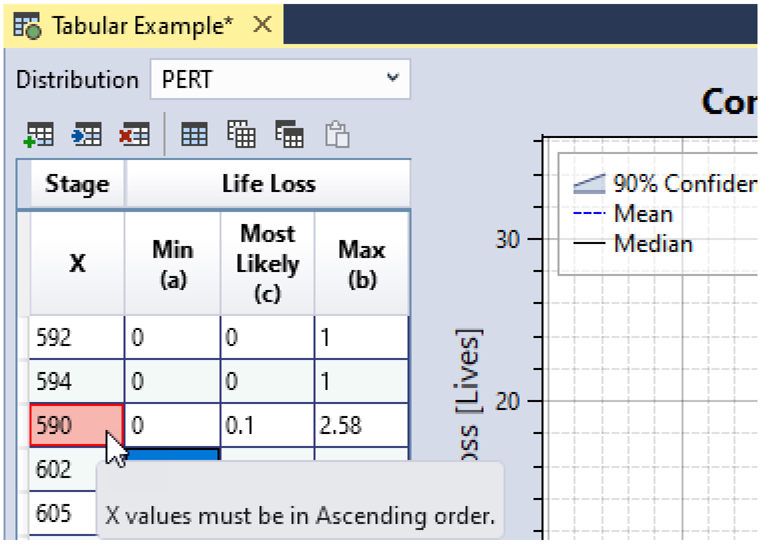


Figure 118 – Input Data Validation.

Composite Function

The composite consequence function option allows the user to combine multiple consequence functions into a single function by either weighting the individual input functions or making them additive. A common use case is taking a daytime consequence function and combining it with a night-time function using a day-night weight ratio. Another common use case is to take damage functions by structure damage category and aggregate them into a single damage function. To create a composite consequence function, right-click on the **Consequences** folder in **Project Explorer** (Figure 119) or from the **Project Menu→Consequences** and select **Add Composite Consequence…**. Next, give the **Composite Consequence** function a name and click **OK**.

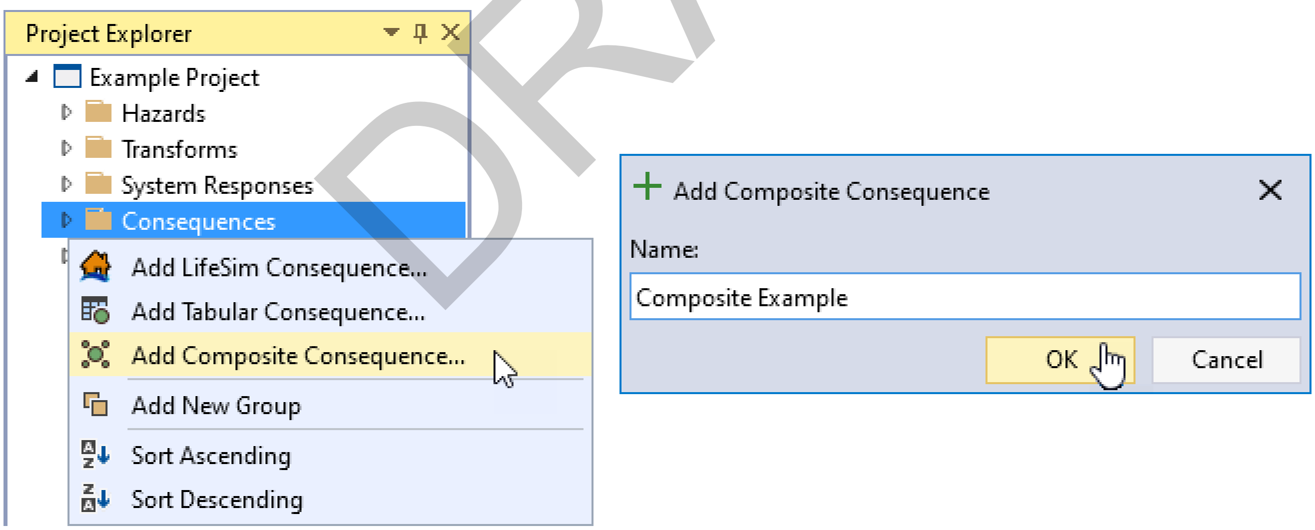


Figure 119 – Create new Composite Hazard Function.

When the new Composite Consequence function is created, it will be automatically opened into the **Tabbed Documents** area, and the composite function properties will be displayed in the **Properties Window**. From the properties window, you can set the **Name**, **Description**, **Hazard Type**, **Hazard Units**, **Consequence**, **Consequence Unit**, **Hazard** and **Consequence** interpolation transforms, **Additive** option for selected inputs, and input **Consequence Functions** as shown in Figure 120.

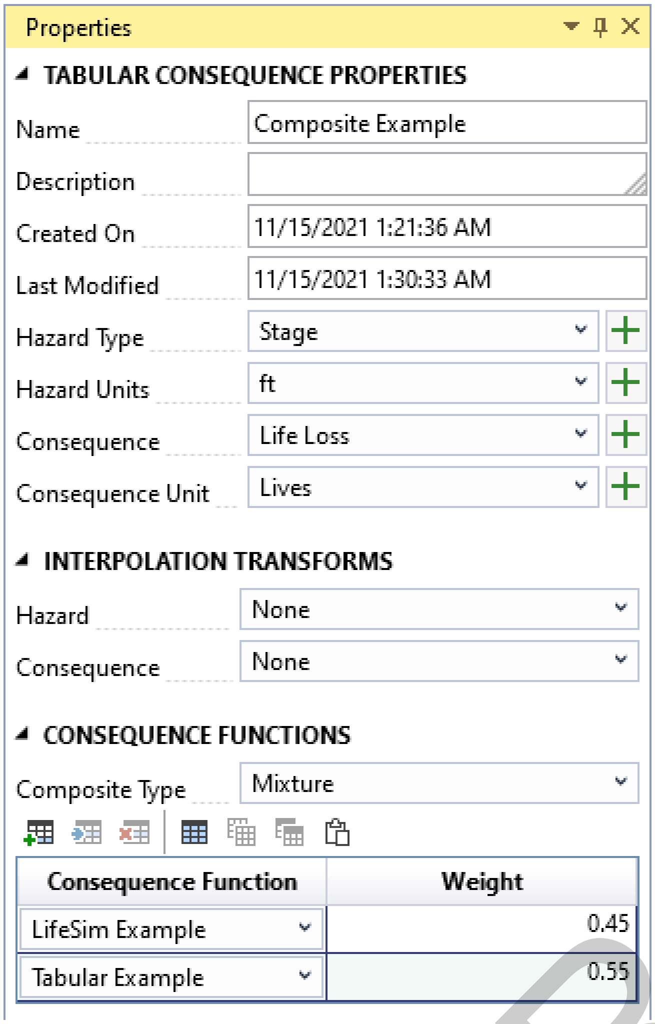


Figure 120 – Composite Hazard Function properties.

The **Composite Type** provides three options to define how the input functions will be composited:

- **Additive** The input functions will be added together, no weights are required.
- **Average** The input functions and their uncertainties are combined using a weighted average. The weights must sum to one.
- **Mixture** The input functions and their uncertainties will be combined as a mixture. The weights must sum to one. This option results in the same mean as the average method with wider bands of uncertainty in the composited function.

The **Consequence Functions** table is where the input functions are selected for composition. Click the Add Row(s) button in the table toolbar to add new rows for input to the composite.

The **Tabbed Document** for a composite function contains a graphical representation of the composite function (Figure 121).

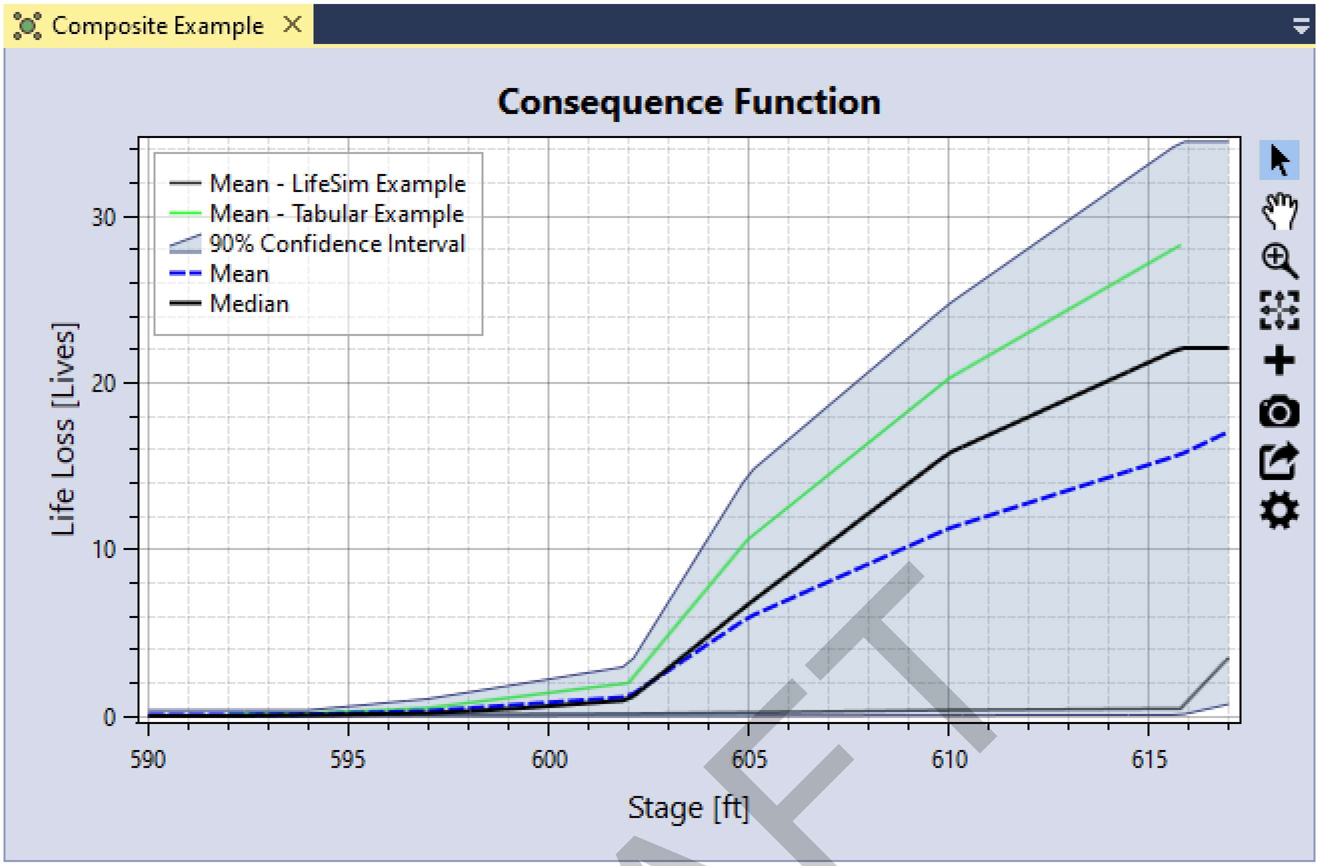


Figure 121 – Composite Hazard Function graphical display.

Risk Analyses

In RMC-TotalRisk, the risk analysis is composed of three fundamental components: the hazard, system responses to that hazard, and consequences given response and hazard. These fundamental components are called **System Components**. For a given hazard, there can be multiple system response functions, commonly called *failure modes*, where each failure mode could potentially have a different consequence outcome. For example, a dam a seepage failure mode may be slow to progress to breach, which provides more time for people downstream to evacuate; whereas for a seismic failure mode the population downstream have little time to evacuate. A *non-failure mode* does not have a response function. There can only be one non-failure mode per system component. A risk analysis can have multiple system components, which can represent multiple structures in a system or multiple hazard types for a single structure. A risk analysis must have at least one system component. A non-failure mode is required to calculate the risk of non-failure, background risk, and incremental risk. If no non-failure mode is supplied, the non-failure consequence is assumed to be zero. At least one failure mode is required to calculate incremental, failure, and non-failure risk. For more details on the quantitative risk analysis framework in RMC-TotalRisk, see the technical reference manual [1].

Create New Risk Analysis

To create a risk analysis, right-click on the **Risk Analyses** folder in **Project Explorer** (Figure 122) or from the **Project Menu** and select **Add Risk Analysis…**. Next, give the **Risk Analysis** function a name and click **OK**.

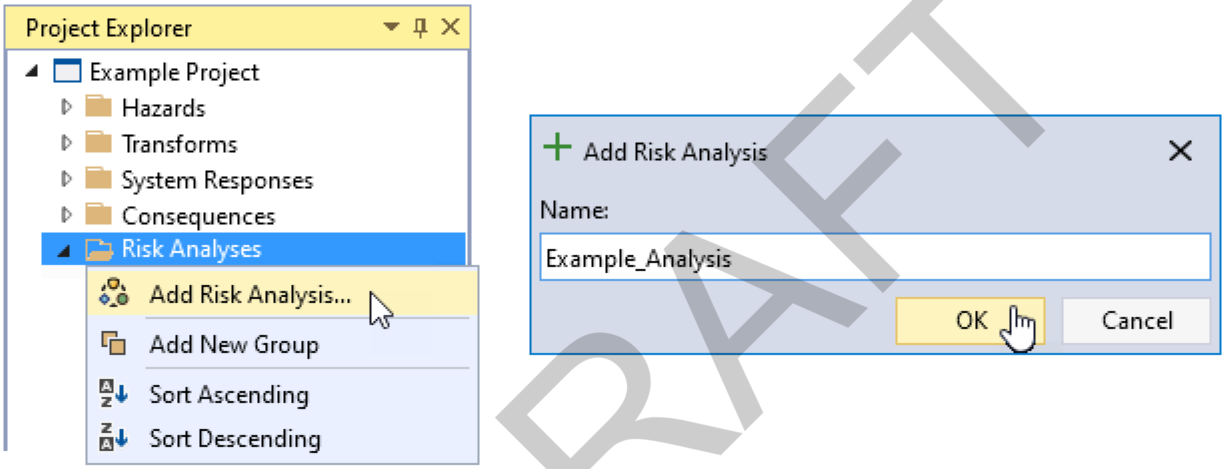


Figure 122 - Create new risk analysis.

When the new Risk Analysis is created, it will be automatically opened into the **Tabbed Documents** area, and the risk analysis properties will be displayed in the **Properties Window** (Figure 123).

Risk Analysis Properties

From here, you can set the **Name**, **Description**, **Consequence**, and **Consequence Units**. The consequence and consequence units are required, and each consequence function used in the analysis must match the selected consequence type. Here you can also run the risk simulation once it has been defined. When estimating risk, you can either **Simulate Mean Risk Only** which simply uses the mean result from each input function, or you can **Simulate Risk with Full Uncertainty** which uses Monte Carlo simulation to estimate risk using the full range of uncertainty from each input function. To calculate a risk estimate, click the **Estimate** button.

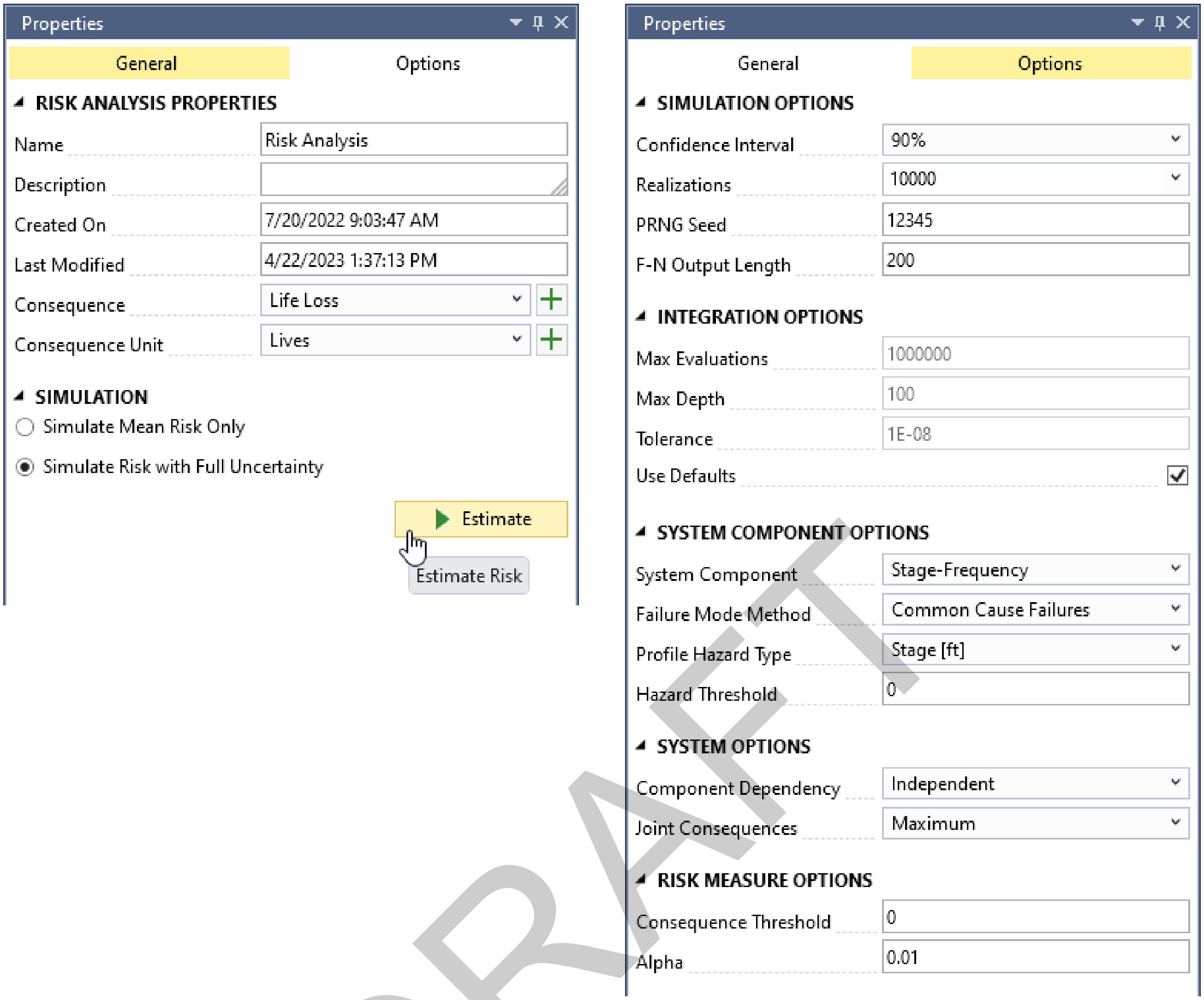


Figure 123 - Risk analysis properties. The general properties are shown on the left and the risk analysis options are shown on the right.

Risk Analysis Options

The risk analysis options can be accessed through the **Properties Window** in the **Options** tab (Figure 123). For typical applications, the default risk analysis options should provide reasonable results out of the box. The following subsections provided details on the available risk analysis options.

Simulation Options

The simulation options provide settings for the uncertainty analysis and the F-N curve results. The following options are available:

- **Confidence Interval (CI):** The width of the confidence interval. For a 90% confidence interval, the value of interest lies with a 90% probability in the interval. Confidence intervals are only computed after simulating risk with full uncertainty. The default CI is 90%.
- **Realizations:** Determines the number of Monte Carlo simulation realizations when simulating risk with full uncertainty. The default is 1,000 to ensure reasonably accurate confidence intervals and shorter runtimes. Due to runtime and file size limitations, the maximum number of Monte Carlo realizations allowed is 10,000. As such, there is a potential for minor sampling errors in the mean risk results and percentiles. It is recommended to run 10,000 realizations to get the most accurate results.
- **PRNG Seed:** The pseudo random number generator (PRNG) seed value used within the Monte Carlo simulation. Using the same seed value ensures repeatability. By changing the seed value, the sequence of random numbers will change.
- **F-N Output Length:** The number of points used to construct the F-N curves. An F-N curve plots the risk results with consequences (N) on the x-axis and the exceedance probability, or frequency of occurrence, (F) on the y-axis. It is recommended to use at least 200 points to improve the accuracy of the curves.

Integration Options

In RMC-TotalRisk, within every Monte Carlo realization, risk is computed using numerical integration. When there is just a single system component in the risk analysis, the Adaptive Simpson's Rule (ASR) is used to perform the numerical integration. The options for the ASR method are as follows:

- **Max Evaluations:** The maximum number of integrand evaluations allowed when performing numerical integration. This value must be between $10{,}000$ and $1{,}000{,}000$. The default value is $1{,}000{,}000$.
- **Max Depth:** The maximum recursion depth when performing ASR integration. The default is 100.
- **Tolerance:** The desired tolerance for the ASR integration. The default is 10^{-8}.

When there are two or more system components in the risk analysis, the adaptive importance sampling method VEGAS is used to perform the numerical integration. The options for the VEGAS method are as follows:

- **Max Evaluations:** The maximum number of integrand evaluations allowed when performing numerical integration. This value must be between $10{,}000$ and $1{,}000{,}000$. The default value is $1{,}000{,}000$.
- **Warmup Evaluations:** The number of integrand evaluations each warmup cycle. The default is $1{,}000 \cdot D$ warmup evaluations, where D is the number of integrand dimensions (i.e., system components).
- **Warmup Cycles:** The number of warmup cycles for the adaptive importance sampling method. The default is 5 warmup cycles.
- **Final Evaluations:** After the warmup is completed, the final number of integrand evaluations for the adaptive importance sampling method. The default is $10{,}000$ final integrand evaluations.

More details on the numerical integration methods employed by TotalRisk are provided in the technical reference [1].

System Component Options

The following system component options are available:

- **System Component:** A system component is composed of three fundamental inputs: the hazard, system response to that hazard, and consequences given the response and hazard. A system component is identified and labeled by the selected hazard function. The selected hazard function can only be used once per risk analysis. A single risk analysis is limited to 20 system components due to virtual memory and computer runtime limitations. Options are available for how each system component will be computed in the risk analysis.

- **Failure Mode Method:** Determines how multiple failure modes are modeled in the risk analysis. By default, the Common Cause Adjustment (CCA) method is used.

- **Joint Consequences:** If the joint failure mode method is selected, this option determines how the consequences of joint failures are treated in the risk analysis. The options are additive, average, maximum, and minimum. By default, when joint failures occur among failure modes in the system component, the maximum of the joint consequences will be recorded.

  In the context of dam and levee safety, additive consequences can be useful when each failure mode has a different inundation area where the consequences for the joint failure are best represented by adding the consequences for each inundation area. Average consequences can be used if the inundation areas are partially overlapping. If each failure mode has practically the same inundation area, then the maximum rule can be used so that consequences are not overestimated. The minimum rule can be used as a sensitivity or as a lower bound for risk.

- **Profile Hazard Type:** The hazard type used for constructing the risk profiles and used for estimating the probability of exceeding the hazard threshold. The user can choose from the primary hazard function or any of the hazard-to-response transform functions. For a levee accreditation analysis, the profile hazard type should be stage or water surface elevation.

- **Hazard Threshold:** The probability of hazard levels exceeding the threshold will be recorded in the risk simulation. The default hazard threshold is 0. For a levee accreditation analysis, the hazard threshold should be the top of levee height or elevation.

<u>**System Options:**</u>
The system options determine how the system components interact in the risk calculations. The following system options are available.

- **Component Dependency:** Determines the dependency between system components in the risk analysis. The dependency between system components is modeled by the joint probability of the hazard functions. The options are independent, perfectly negative, perfectly positive, or a user-defined correlation matrix. If the correlation matrix is selected, a table is presented for the user to enter correlation coefficients between components. By default, each system component is assumed to be independent of one another.

- **Correlation Matrix:** This is only available when correlation matrix is selected for component dependency. Clicking the button will display a table for the user to enter correlation coefficients between system components.

- **Joint Consequences:** Determines how the consequences of joint events are treated in the risk analysis. The options are Additive, Average, Maximum, Minimum, Multiplicative. By default, when joint events occur among components in the system, the maximum of the joint consequences will be recorded. However, there are cases where other methods are more appropriate. For example, if the system components have nonoverlapping inundation areas, then additive consequences would be more appropriate.

<u>**Risk Measure Options**</u>
RMC-TotalRisk provides additional risk measures that are useful for risk-based design of engineering structures. The risk measures are computed for the overall system, not the individual system components. The risk measure options are as follows:

- **Consequence Threshold:** The probability of consequences equal to or exceeding the threshold will be recorded in the risk simulation. The default consequence threshold is 0.

- **Alpha:** The exceedance probability for computing the Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR). The default exceedance probability is 10^{-2}.

More details on the additional risk measures in TotalRisk are provided in the technical reference [1].

Risk Analysis Tabbed Document

The **Tabbed Document** for the Risk Analysis contains five tabs: The risk **Diagram**, **F-N Plot**, **α-η Plot**, **Summary Statistics**, and **Diagnostics**. The contents of each tab are detailed below.

Risk Diagram

A risk analysis in RMC-TotalRisk is defined through a diagram as shown in Figure 124 below. The diagram provides an intuitive way to create and connect the various components of the modeled system.

A risk analysis computes the risk associated with a collection of potential failure modes for each component in the system. A failure mode is composed of a hazard, the system response to the hazard, and the consequences given the response to the hazard. A non-failure mode is composed of a hazard and the non-failure consequences given the hazard.

Figure 124 shows a single system component for a dam safety risk analysis. There is a non-failure mode, shown at the top of the diagram with the purple line, 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 [1]. There are two failure modes: 1) A spillway erosion failure mode, labelled PFM 1, shown in the center of the diagram connects the hazard function at Dam A to the PFM 1 response function and consequence function; and 2) A concentrated leak erosion failure mode, labelled PFM 2, shown in the bottom of the diagram with the same respective connections.

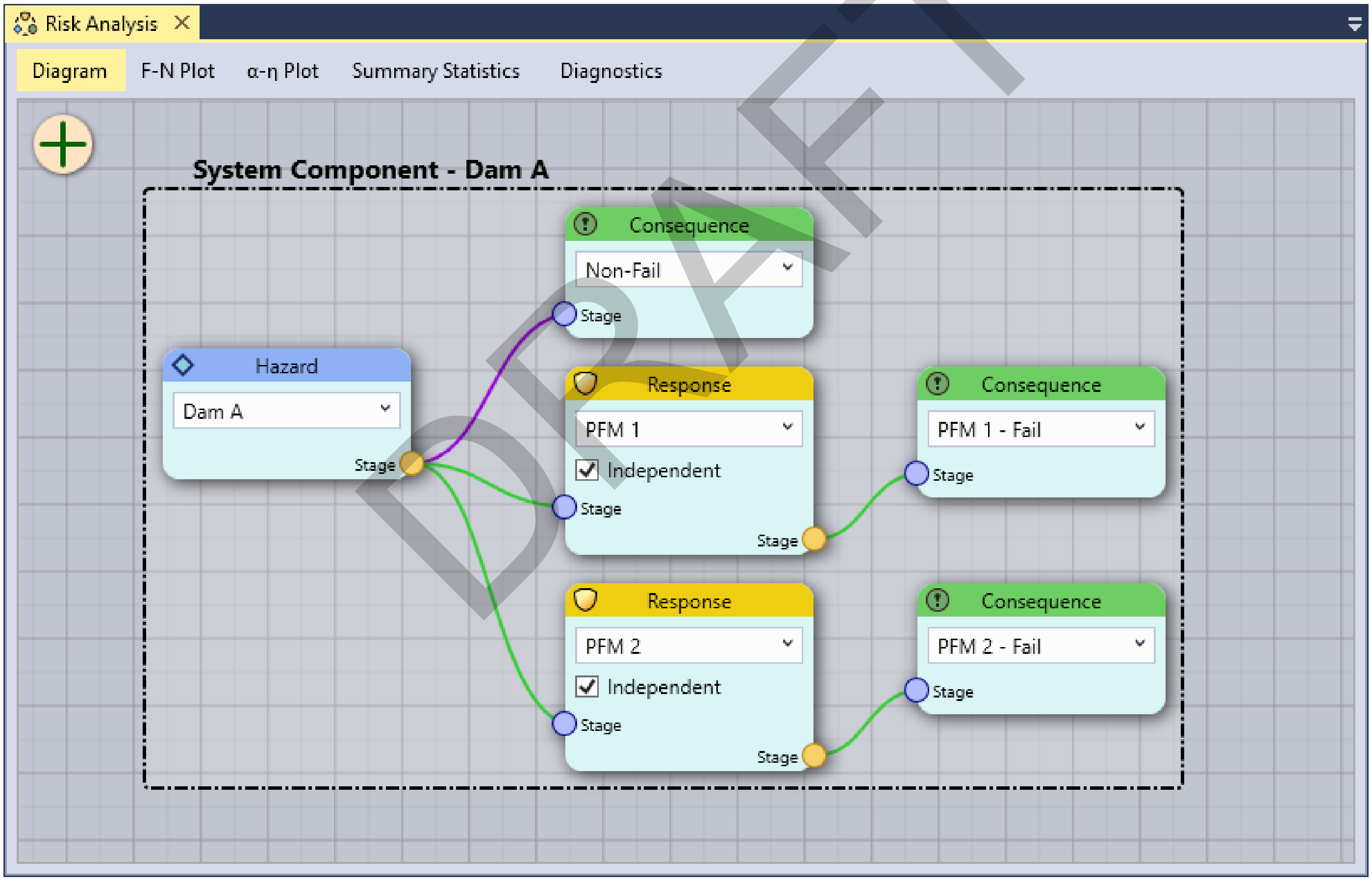


Figure 124 – RMC-TotalRisk risk diagram.

In the risk diagram, the input functions are connected from left to right, and linked together based on the hazard type (e.g., stage, flow, etc.) and units (e.g., ft, cfs, etc.) of each function. There cannot be any circular or redundant connections. As such, the risk diagram is a type of directed acyclic graph (DAG).

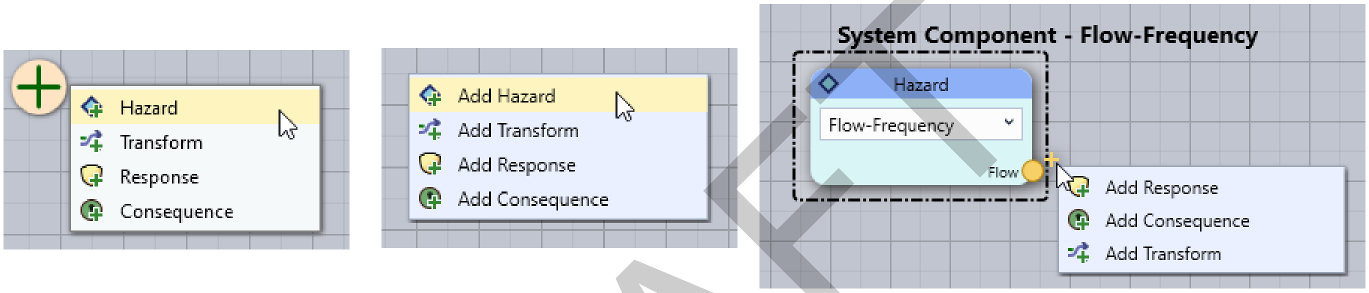
The system components are identified and labeled by the selected hazard function. The failure modes within a component are identified and labeled by the selected response functions. RMC-TotalRisk permits an unlimited number of failure modes per component, depending on the selected failure mode method. 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.

Creating a Diagram

First, get a feel for working with the diagram. Left-click-drag any open area in the diagram to pan the diagram surface. Mouse-wheel in and out to zoom the diagram.

Inputs to the risk analysis are designated using nodes in the diagram. Select the desired input function for a node using the selection box. Left-click-drag on any node to move the node around the diagram. Each node will have required inputs, shown as a blue circle on the bottom-left side of the node. Node output is shown as an orange circle on the lower-right side of the node.

There are three ways to add a node to the risk diagram as shown in Figure 125: a) place the mouse cursor over the large plus symbol in the upper left hand corner of the diagram; b) right-click on any empty space in the diagram to add at that location; and c) left-click on a node output. The third option has the added benefit of automatically connecting the new node to the clicked node output.



a) b) c)

Figure 125 - Options to add a new input node to the risk diagram: a) Move cursor over the plus symbol in the upper left corner of the diagram; b) Right-click on any empty space in the diagram to add at that location; and c) left-click on a node output, this option will also connect the nodes.

To connect two nodes, left-click-hold on a node output and drag towards the node you want to connect. A line will appear from the node output to the mouse cursor. Move the mouse cursor over the input of the desired node and release the mouse button to connect.

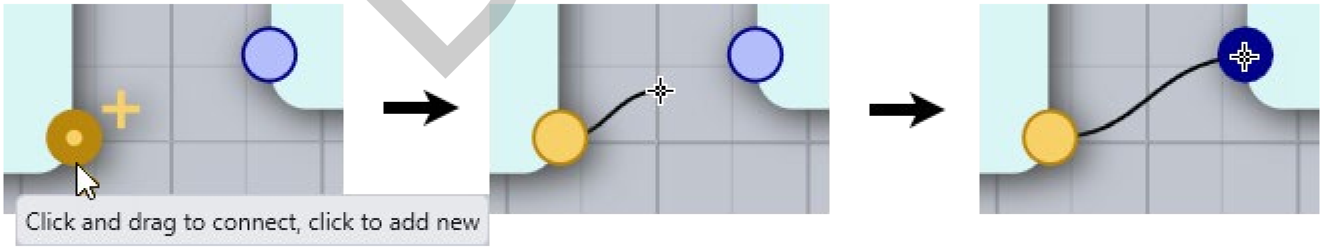


Figure 126 - Instructions for connecting a node to another node. left-click-hold on a node output and drag to the desired node input. Release the mouse button to finish the connection.

To delete a node, you can either right-click on the node and select delete or click the x that appears in the top-right corner when the cursor is over the node. To disconnect two nodes, left-click-drag on the input to the connected node and move the cursor to either another nodes input or remove the connection by clicking in any open space of the diagram.

There are four fundamental node types in the diagram:

Hazard: A hazard function describes the exceedance probabilities of various hazard levels. Examples include annual maximum peak flow-frequency, peak reservoir pool stage-frequency, and peak ground acceleration. The system component is identified and labeled by the selected hazard function. There can be multiple connections made to selected hazard function.

Transform: A transform function can be used to transform (or convert) the hazard levels from one type of function to another. The required input to this node is the hazard type to be transformed. The node output is the hazard type that the function is transforming into. Multiple connections can be made from a transform function unless it is transforming a response function. Multiple transforms can be connected in sequentially. For example, an unregulated flow-frequency may need to be transformed into a regulated flow and then transformed again from flow to stage to assess probability of failure on hydraulic structures downstream.

Response: A system response function describes the conditional probability of failure for various hazard levels, such as water surface elevations. The failure modes within a system component are identified and labeled by the selected response function. There can be multiple failure modes within a system component, each with different consequences. The required input is the hazard type that was defined by the selected response function. The output type is the same as the input. There can only be one connection from the output. The response function also has the option to select if the failure mode is independent of other failure modes within the system component. If unchecked, the failure mode will be modeled as perfectly negatively dependent of the other failure modes.

Consequence: A consequence function describes the consequences of failure or non-failure for various hazard levels, such as annual maximum peak water surface elevations. Note that each response node can have a different consequence node. Also important, a consequence function connected to the hazard node without a response function is considered the non-failure component of the element. A consequence node has one required input, the hazard defined by the selected consequence function.

The risk diagram provides the following visual feedback on input data validation:

A node with no input selected will be highlighted red.

A black connection indicates nothing is wrong with the connection, and the units match. But there is not a completely connected failure mode or non-failure mode. So, this connection will not be included in the risk calculations.

A red connection means the connection is not valid. Either the hazard units do not match, or an input hasn't been defined for one of the nodes. The risk analysis cannot be computed if there is an invalid connection.

A green connection is for valid failure modes. It indicates that every connection in a system component is valid and failure modes are complete. A system component with green connections for the failure modes indicates that the component will be included in the risk calculations.

A purple connection is for valid non-failure modes. It indicates that every connection in a system component is valid and the non-failure mode is complete. A system component with purple connections for the non-failure mode indicates that the component will be included in the risk calculations.

Figure 124 shows the risk diagram for a levee risk analysis. The hazard function is a river peak flow-frequency curve. Peak flow is transformed to a peak river stage using a flow-to-stage rating curve derived from a hydraulic routing model. There is a prior to overtopping failure mode (Prior OT) from backwards erosion piping, and an overtopping (OT) failure mode. There are two failure modes shown with green connectors. The non-failure mode is shown at the top with the purple connectors. Non-fail consequences are connected directly to the hazard transform function with no response function in between.

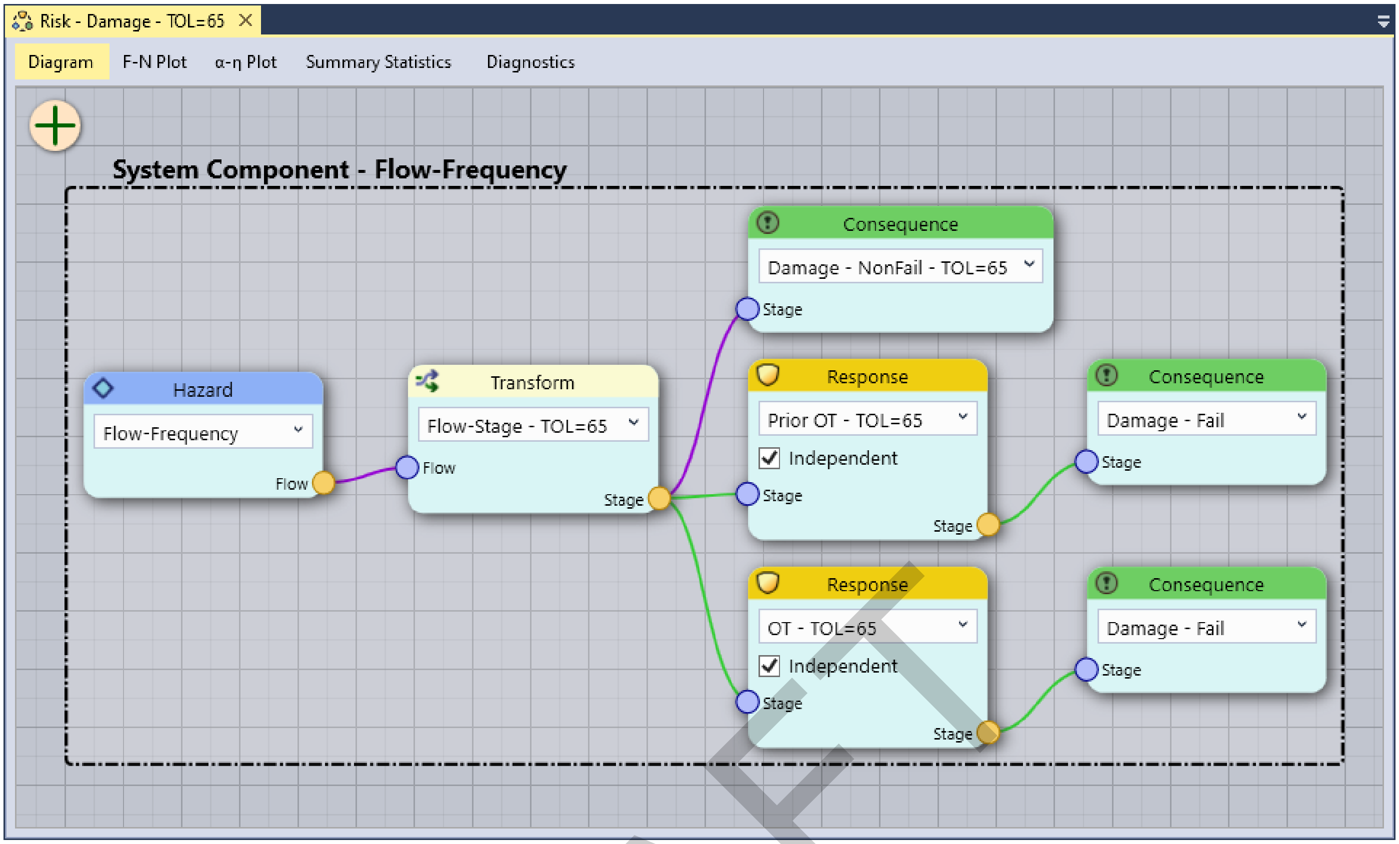


Figure 127 – Example levee risk diagram.

Risk Results

Results of the risk analysis can be viewed in the **F-N Plot**, **α-η Plot**, and **Summary Statistics** tabs (Figure 128). The risk results tabs contain results of the risk analysis shown graphically and in tabular form.

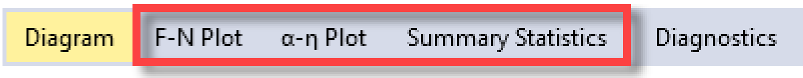


Figure 128 – Risk results can be viewed in the F-N Plot, α-η Plot, and Summary Statistics tabs.

F-N Plot

The **F-N plot** has consequences (N) on the x-axis and the exceedance probability, or frequency of occurrence, (F) on the y-axis [14]. If the hazard function probabilities are defined as an annual frequency, F is an annual exceedance probability. This type of plot is also commonly referred to as an *F-N curve*, *survival function*, or *Farmer diagram.* A log-log scale is typically used because the range of probabilities and consequences can span multiple orders of magnitude.

An example F-N plot is provided below in Figure 129. After simulating risk with full uncertainty, the 90% confidence interval is shown as a shaded bound. The mean and median curves are also provided. By default, the USACE tolerable risk limit [8] is also plotted. The tolerable risk limit (or guideline) can be customized or removed from the plot.

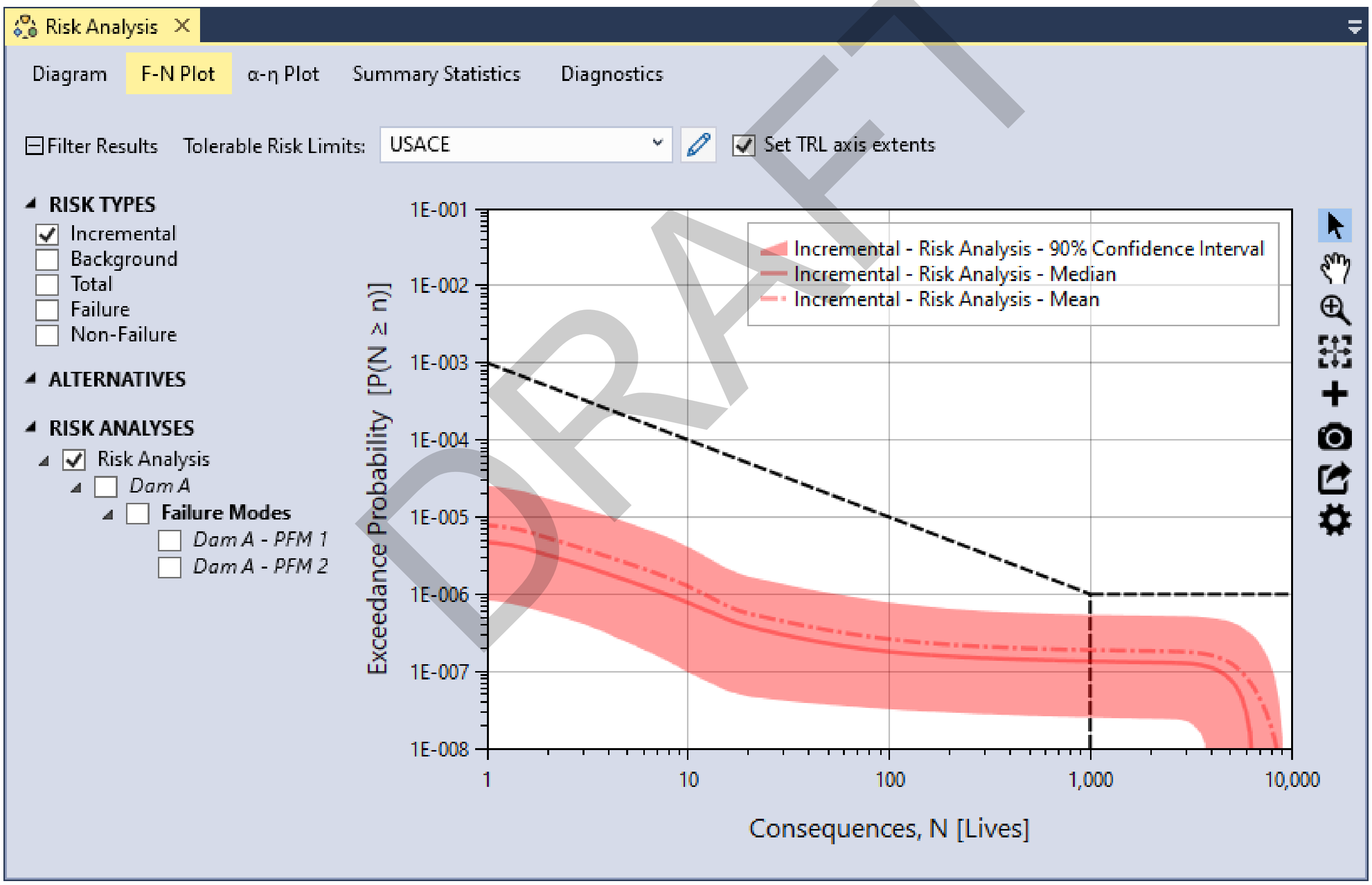


Figure 129 – Example of F-N plot results with confidence intervals and the USACE tolerable risk limit.

Tolerable risk limits (TRL) can be displayed by selecting from the **Tolerable Risk Limits** dropdown menu (Figure 129). You can select **None**, **USACE**, **ANCOLD**, or create your own. To add or edit custom limits, press the Edit/Add Tolerable Risk Limits button (Figure 130). The tolerable risk limit editor will appear (Figure 131). Finally, the plot extents can be automatically set to the selected TRL extents by checking the **Set TRL axis extents** checkbox.

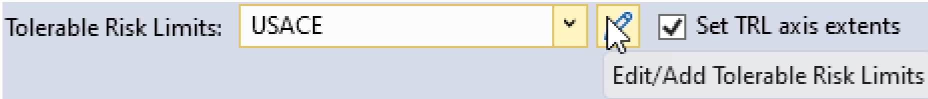


Figure 130 - Tolerable risk guideline viewing options for graphical risk results in RMC-TotalRisk.

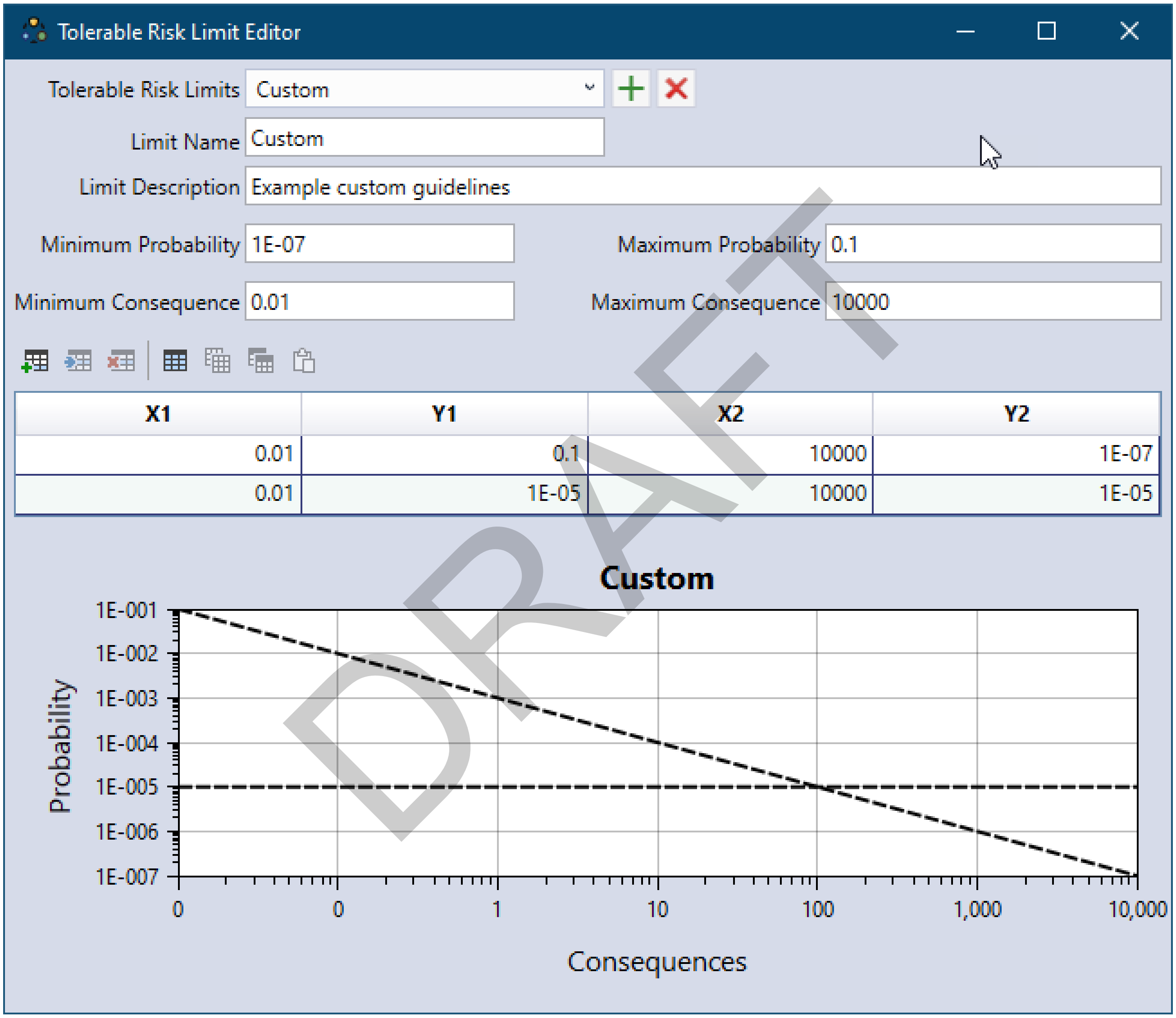


Figure 131 - Tolerable risk guideline editor.

Each risk result tab has options to filter which results are available. To filter results, click the button ⊞ next to **Filter Results** near the top of the risk results tab. Use the checkboxes (Figure 132) to display which risk components and types to show in both the graphical and tabular results. Risk components include the overall system risk, all elements within the system, and all failure modes within each element. There are 5 types of risk reported in RMC-TotalRisk [1]. Each risk type is calculated for a range of probable hazard events.

- **Incremental Risk:** The incremental risk of failure of the system. Incremental consequences are the incremental losses or damages that failure might inflict over and above any damage which might occur for the same event assuming the structure does not fail. The incremental risk is computed with the product of the probability of the hazard $P(H)$, the probability of failure given hazard $P(F|H)$, and the incremental consequences from failure ($C_\Delta = C_F - C_{NF}$).
- **Background Risk:** Background risk is defined as the risk of the structure assuming that it has no structural flaws or vulnerabilities. In other words, if all the structural vulnerabilities were eliminated, the remaining risk would be the background risk from natural hazards. Background risk is computed with the product of the probability of the hazard $P(H)$ and the consequences from non-failure (C_{NF}).
- **Total Risk:** The overall risk of the system (or component), which is the sum of the failure risk and non-failure risk. In some USACE publications, total risk has been referred to as *residual risk*, i.e., the risk that remains [4] [8] [15]. Proper estimation takes into consideration all the potential hazard sources, their likelihoods of occurrence, and their potential consequences.
- **Failure Risk:** The risk from failure of the system. The failure risk is computed with the product of the probability of the hazard $P(H)$, the probability of failure given hazard $P(F|H)$, and the consequences from failure (C_F).
- **Non-Failure Risk:** The risk from non-failure of the system. For infrastructure such as dams and levees, 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 risk is computed with the product of the probability of the hazard $P(H)$, the probability of non-failure given hazard $\{1 - P(F|H)\}$, and the consequences from non-failure (C_{NF}).

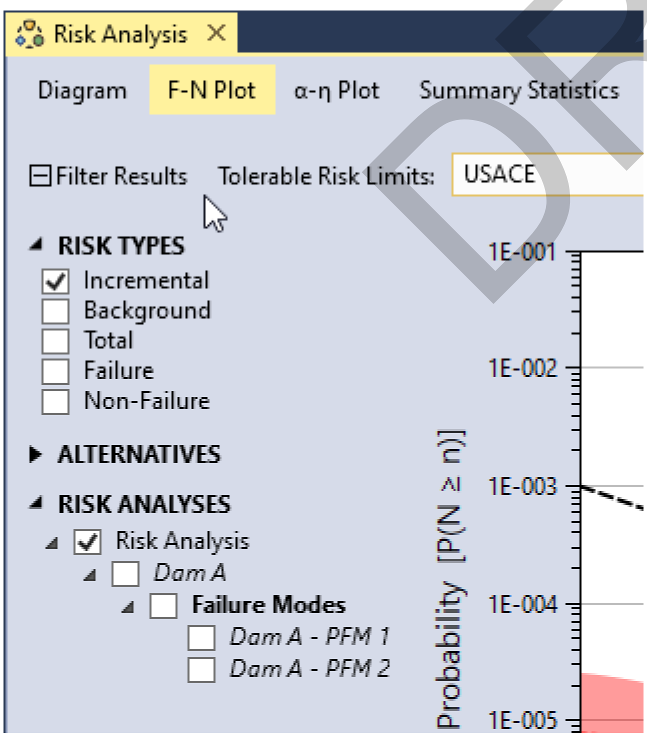


Figure 132 - Options to filter what risk results you want to view. Clicking a checkbox will show the results of that component of risk in the graphical and tabular risk results.

α-η Plot

Risk results can be viewed with the **α-η Plot** (pronounced as “alpha-N”), which is a commonly used in the USACE dam and levee safety programs for plotting incremental risk. In this plot, the conditional mean consequences (η) are plotted on the x-axis and the exceedance probability (α) on the y-axis. Like the F-N plot, a log-log scale is typically used because the range of probabilities and consequences can span multiple orders of magnitude.

In the USACE dam and levee safety programs, this plot has been traditionally called the $f \cdot \bar{N}$ plot. However, in probability and statistics, f is universally used as the symbol for the probability density function, not an exceedance probability. Therefore, to avoid any unnecessary confusion and to be consistent with other disciplines, RMC-TotalRisk uses α as the symbol for exceedance probability.

The α-η plot is only available for the risk of failure and incremental risk. Both risk types have the same exceedance probability, $\alpha_{\mathrm{F}} = \alpha_{\Delta}$. Total risk and background risk are both unconditional expectations where $\alpha = 1$. The risk of non-failure is a conditional expectation, where $\alpha_{NF} = 1 - \alpha_F$. However, α_{NF} is typically very close to 1, so there is no reason to plot it.

Figure 133 shows an α-η plot after simulating risk with full uncertainty. The uncertainty is portrayed as a scatter cloud. To improve the visibility of this plot, the uncertainty scatter is thinned down to ensure a maximum of 1,000 points per system risk component. The mean incremental risk result for the overall system is shown as a red diamond. The incremental risk has an exceedance probability $\alpha_{\Delta} = 8.7621e^{-6}$ and conditional mean incremental consequences $\eta_{\Delta} = 127.9035$. Stated another way, the mean annual probability of failure is $8.7621e^{-6}$, and if the dam were to fail, the expected incremental life loss would be 127.9035. The diagonal of the α-η plot is equal to the product of α and η, which is the unconditional mean consequences, $\mathbb{E}[\mathrm{N}] = \alpha \cdot \eta = 1.1207e^{-3}$.

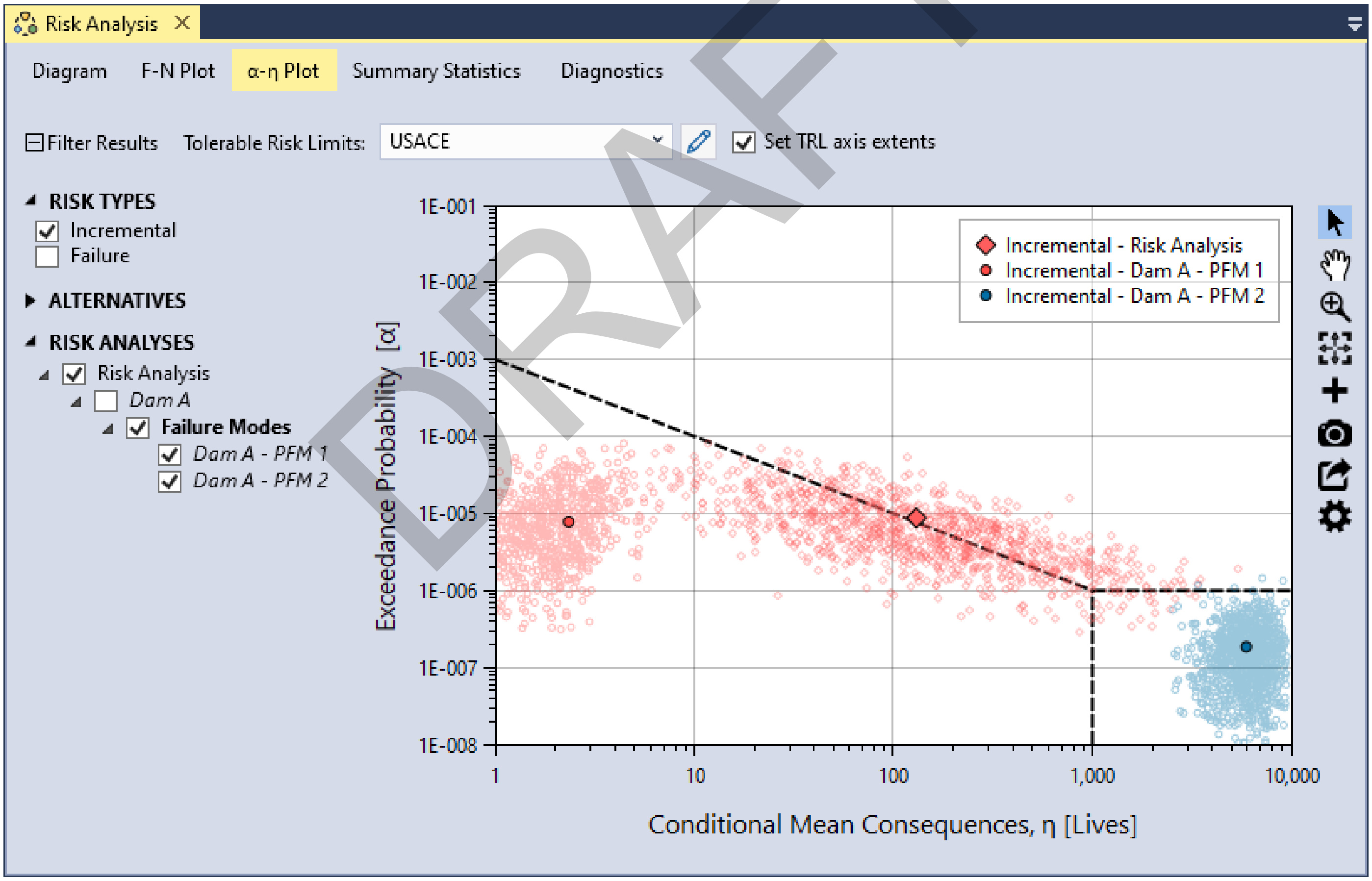


Figure 133 – α-η plot displaying incremental risk results as the exceedance probability (α) and conditional mean consequences (η). USACE Tolerable Risk Limits are being shown in the plot.

Summary Statistics

The Summary Statistics tab displays result statistics for each of the filtered risk measures (Figure 134). Each column in the table is explained below:

- **Component:** The overall system, the individual system components, and each failure mode within each system component. The overall system is labelled by the name of the risk analysis. The system components are labelled by the name of the selected hazard function. The failure modes are labelled by the hazard function and the selected response function.

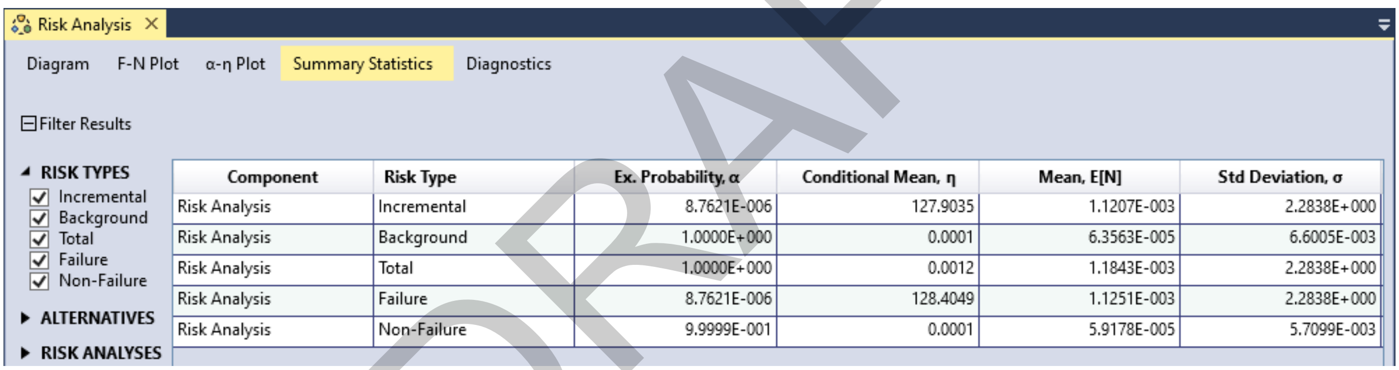
- **Risk Type:** There are 5 types of risk reported in RMC-TotalRisk: Incremental, Background, Total, Failure, and Non-Failure.

- **Exceedance Probability, α:** The exceedance probability of system failure. This probability is 1 for Background Risk and TotalRisk. For Non-Fail Risk, this is 1 minus the failure probability, which is often very close to 1.

- **Conditional Mean, η:** The mean (or expected) consequences given system failure. The product of the exceedance probability (α) and the condition mean (η) is equal to the unconditional mean, E[N] = α · η. This measure is applicable for Incremental and Failure Risk where the probability of failure is explicitly considered.

- **Mean, E[N]:** The mean (or expected) consequences are a probability weighted average over all hazardous events. In flood damage assessments this term is commonly called Expected Annual Damage (EAD).

- **Standard Deviation, σ:** The standard deviation of the consequences N. This provides a measure of deviation from the mean, E[N]. If two alternatives have the same mean, E[N], the one with the smaller standard deviation is considered less risky.



Component	Risk Type	Ex. Probability, α	Conditional Mean, η	Mean, E[N]	Std Deviation, σ
Risk Analysis	Incremental	8.7621E-006	127.9035	1.1207E-003	2.2838E+000
Risk Analysis	Background	1.0000E+000	0.0001	6.3563E-005	6.6005E-003
Risk Analysis	Total	1.0000E+000	0.0012	1.1843E-003	2.2838E+000
Risk Analysis	Failure	8.7621E-006	128.4049	1.1251E-003	2.2838E+000
Risk Analysis	Non-Failure	9.9999E-001	0.0001	5.9178E-005	5.7099E-003

Figure 134 - Summary statistics from a risk analysis - risk results in RMC-TotalRisk.

Diagnostics

RMC-TotalRisk provides several diagnostics for exploring the 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. The following subsections describe the available risk analysis diagnostics.

Integration

The integration diagnostics include an estimate of the standard error of the computed total risk for the system, and the number of integrand function evaluations performed during the risk simulation. The diagnostics are graphically displayed as a kernel density or cumulative distribution plot. Summary statistics, including the mean, standard deviation, and key percentiles are provided in a table. Figure 135 shows an example of the integration diagnostics for the number of function evaluations performed during the simulation. For this example, 121 function evaluations were performed on average for each Monte Carlo realizations.

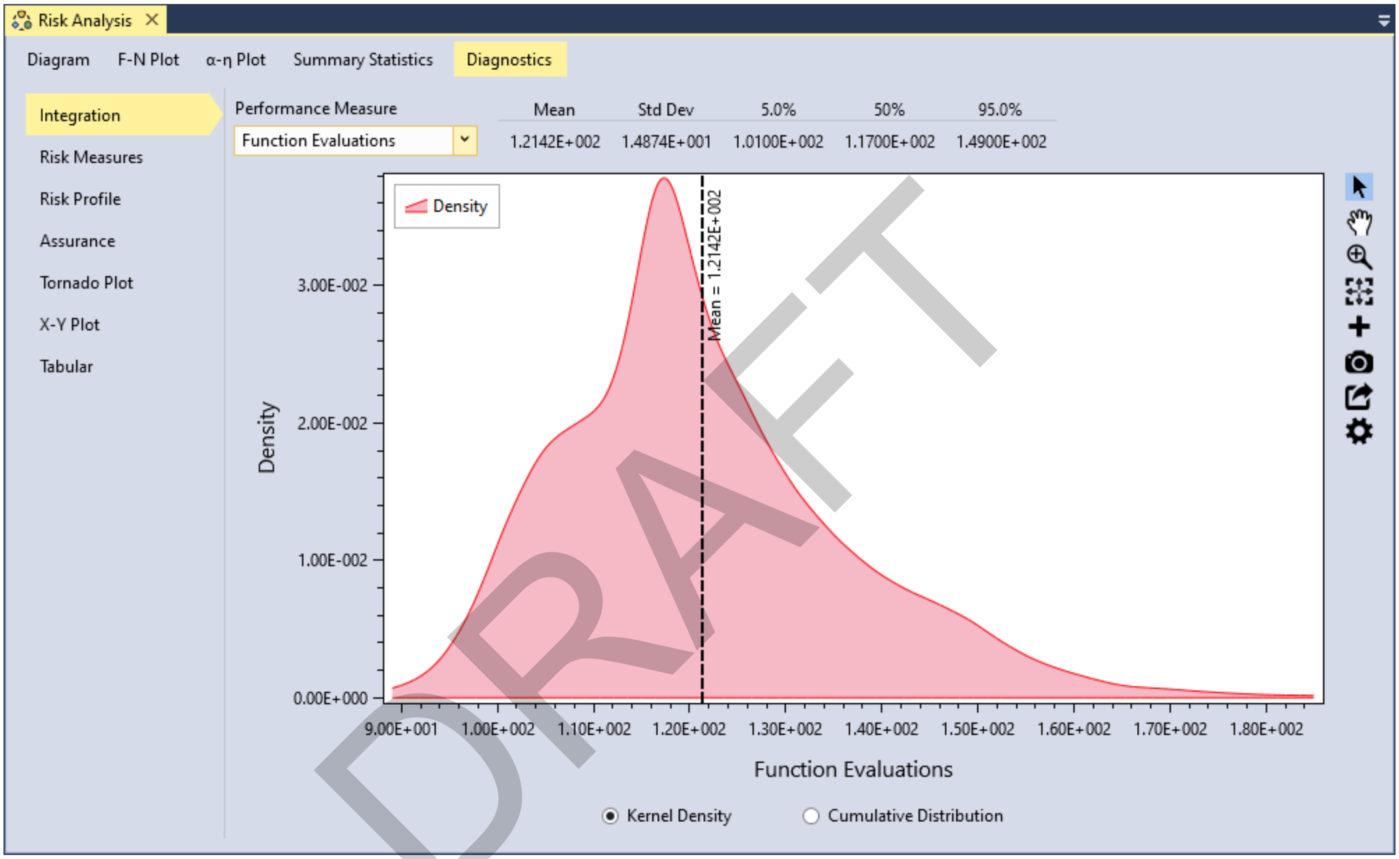


Figure 135 - Example of integration diagnostics.

Risk Measures

RMC-TotalRisk computes six risk measures for all five risk types:

- **Exceedance Probability, α:** The exceedance probability of system failure. This probability is 1 for Background Risk and TotalRisk. For Non-Fail Risk, this is 1 minus the failure probability, which is often very close to 1.
- **Conditional Mean, η:** The mean (or expected) consequences given system failure. The product of the exceedance probability (α) and the condition mean (η) is equal to the unconditional mean, $E[N] = \alpha \cdot \eta$. This measure is applicable for Incremental and Failure Risk where the probability of failure is explicitly considered.
- **Mean, E[N]:** The mean (or expected) consequences are a probability weighted average over all hazardous events. In flood damage assessments this term is commonly called Expected Annual Damage (EAD).
- **Standard Deviation, σ:** The standard deviation of the consequences N. This provides a measure of deviation from the mean, E[N]. If two alternatives have the same mean, E[N], the one with the smaller standard deviation is considered less risky.
- **Consequence Threshold Probability:** The probability that the user-specified consequence threshold will be exceeded.
- **Value-at-Risk (VaR):** A risk measure that estimates the minimum consequences for a user-specified exceedance probability (α).
- **Conditional Value-at-Risk (CVaR):** A risk measure that estimates the conditional mean (or expected) consequences for a user-specified exceedance probability (α).

Please see the technical reference manual [1] for mathematical details on these risk measures.

As shown in Figure 136, select the desired **Risk Type** and the **Risk Measure** from the dropdowns to view the results. You can view the distribution as a **Kernel Density** or as a **Cumulative Distribution** using the radio buttons at the bottom of the plot (Figure 137). Summary statistics of the distribution are displayed in the upper right-hand corner (Figure 137).

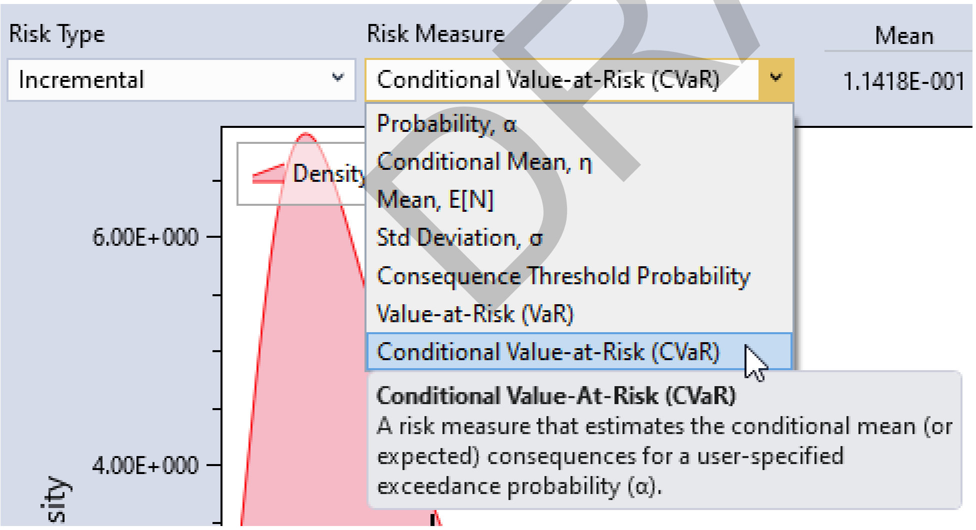


Figure 136 - Select the risk type and risk measure to display results.

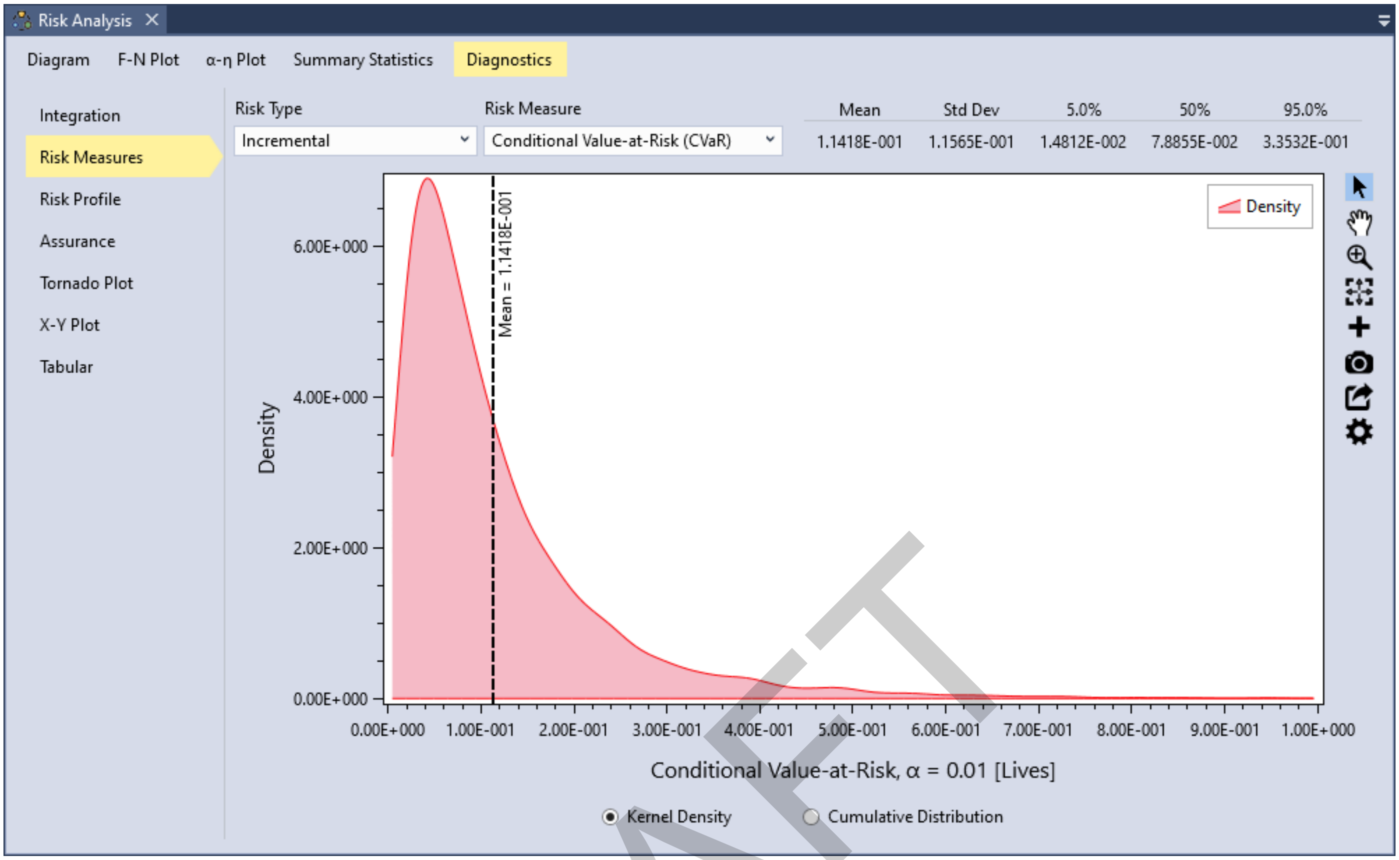


Figure 137 - Risk measure diagnostic tools in RMC-TotalRisk showing the kernel density of the Incremental Conditional Value-at-Risk (CVaR).

Risk Profile

A risk profile plots the exceedance probabilities or conditional mean consequences against increasing hazard levels. The risk profile results can be filtered by **System Component** and **Risk Type**. This plot is useful for identifying critical hazard levels where the probability of failure or risk sharply increases. Figure 138 shows the hazard exceedance probability for the background risk of Dam A. Since background risk represents the remaining risk from the natural hazard, this risk profile will match the input reservoir stage-frequency hazard function.

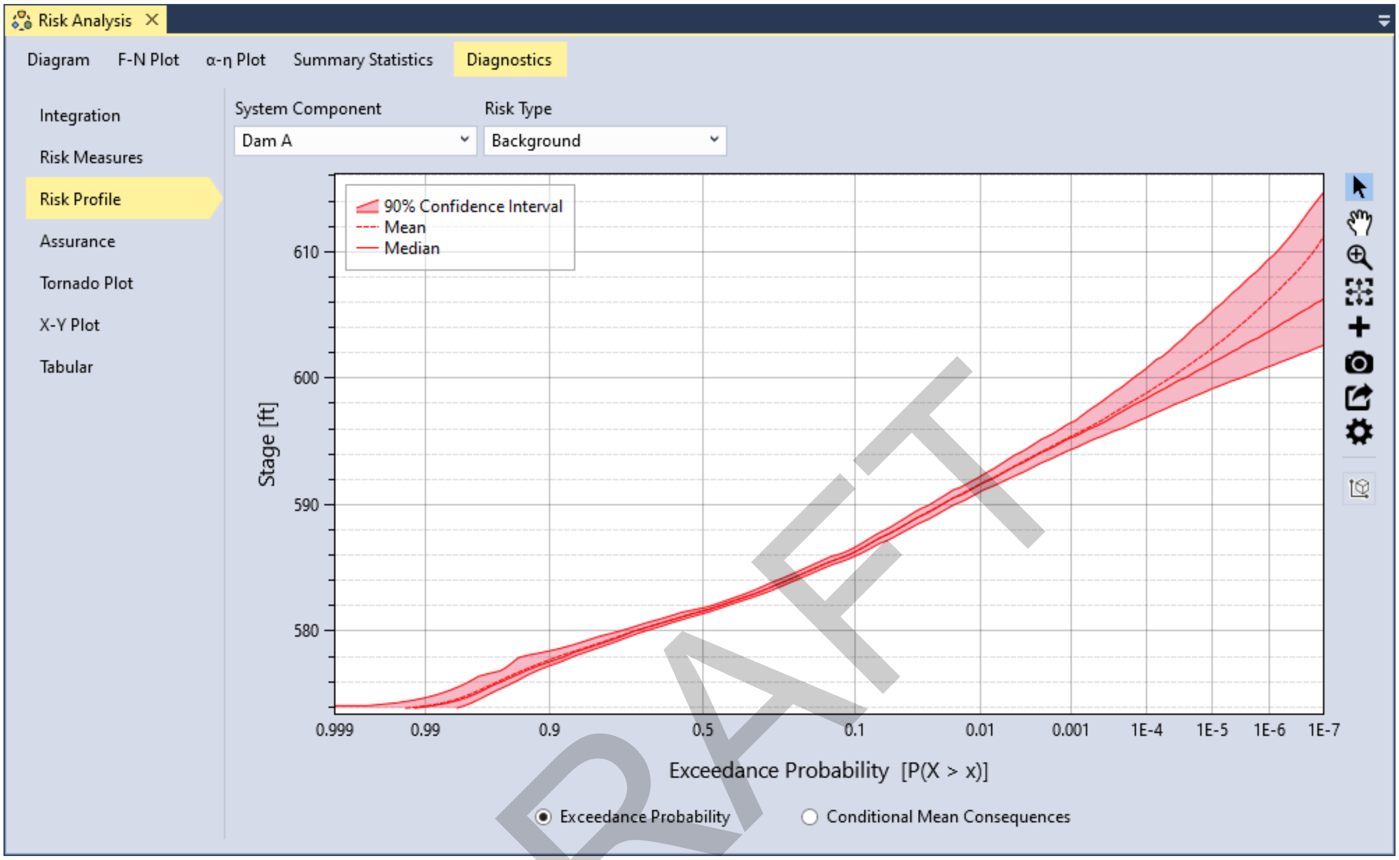


Figure 138 - Example of a risk profile plot showing the hazard exceedance probability for the background risk at Dam A.

Figure 139 below shows the hazard exceedance probability for the incremental risk at Dam A. There is an inflection point in the profile near a reservoir stage of 595 ft. The is because PFM 1 (spillway erosion) has a non-zero probability of failure beginning near this hazard level. This is the point where incremental risk will begin to occur.

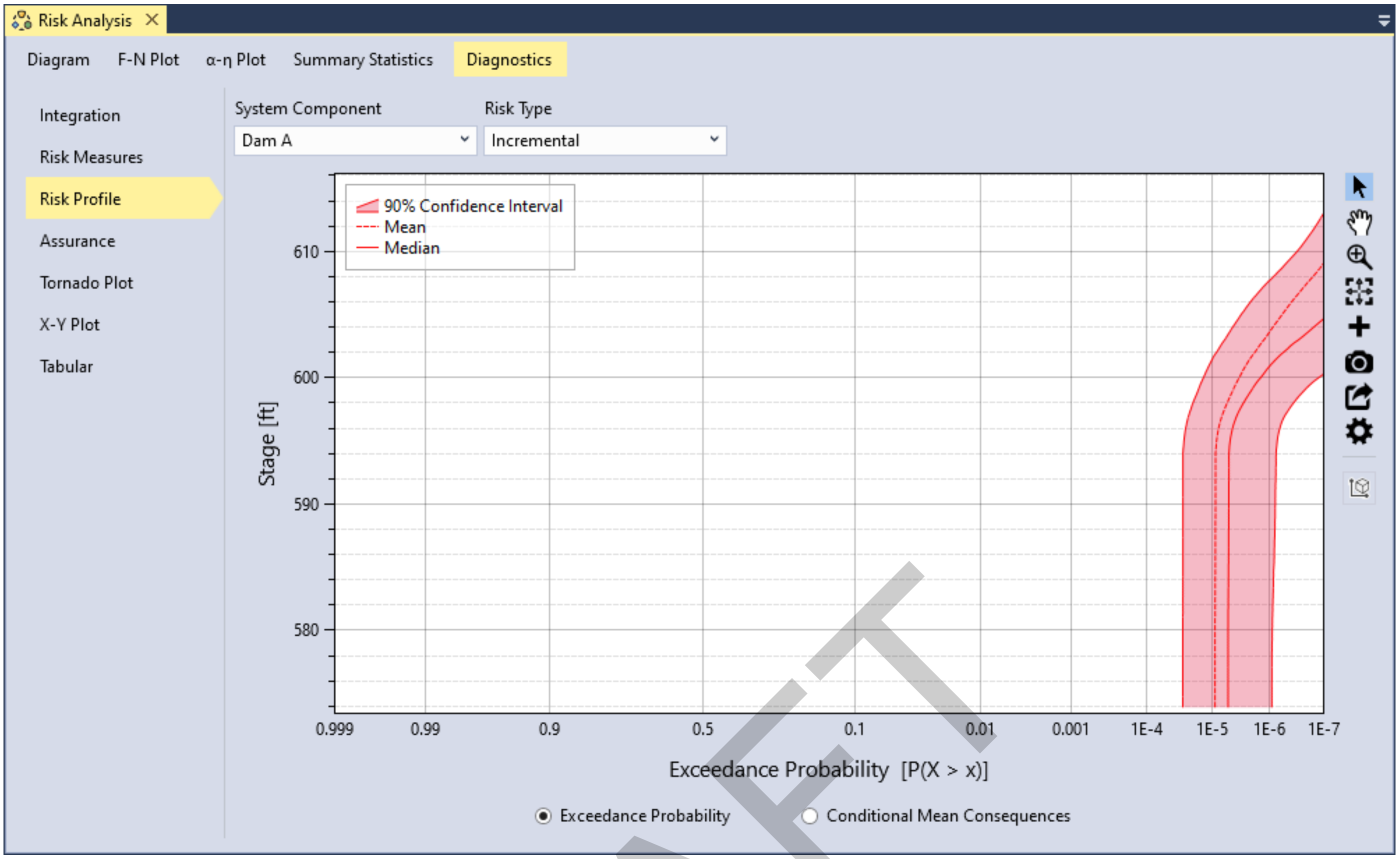


Figure 139 - Example of a risk profile plot showing the hazard exceedance probability for the incremental risk at Dam A.

Assurance
An assurance plot and summary statistics are provided based on a user-defined profile hazard type and hazard threshold. This diagnostic is intended to support the National Flood Insurance Program for levees. Please see the technical reference for more details [1].

Figure 140 below shows an example risk diagram for a levee risk analysis. The primary hazard is river peak flow-frequency. Peak flow is transformed to a peak river stage using a flow-to-stage rating curve derived from a hydraulic routing model. There is a prior to overtopping failure mode (Prior OT) from backwards erosion piping, and an overtopping (OT) failure mode. The top of levee is at a river stage of 65 ft.

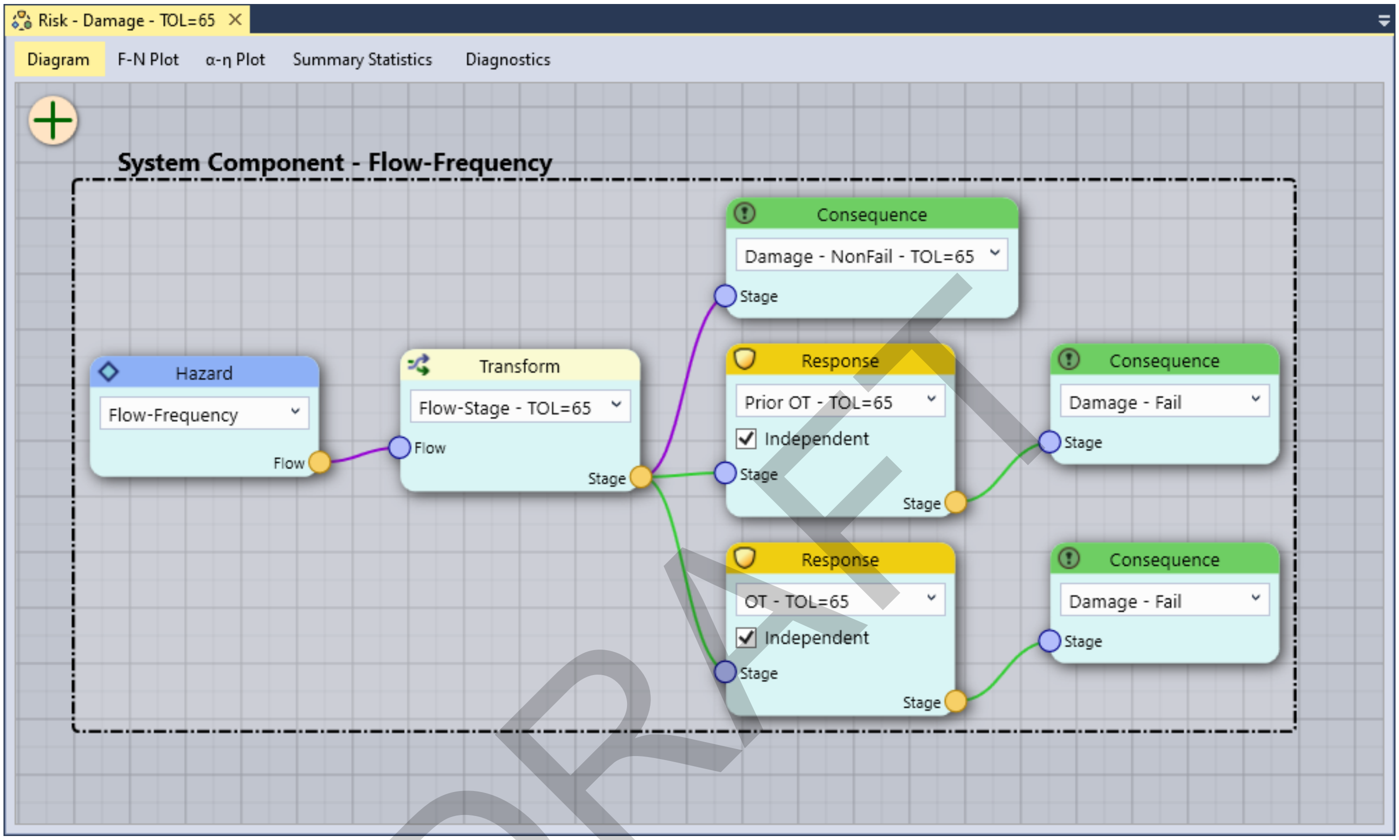


Figure 140 - Example risk diagram for a levee risk analysis.

To compute the assurance, the user must select the **Profile Hazard Type** and specify the **Hazard Threshold** for the desired system component in the risk analysis options as shown in Figure 141:

- **Profile Hazard Type**: The hazard type used for constructing risk profiles and used for estimating the probability of exceeding the hazard threshold. For a levee accreditation analysis, the hazard type should be stage or water surface elevation.

- **Hazard Threshold**: The probability of hazard levels exceeding the threshold will be recorded in the risk simulation. For a levee accreditation analysis, the hazard threshold should be the top of levee height or elevation.

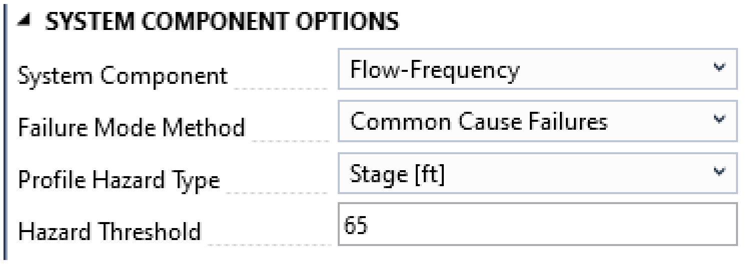


Figure 141 - Setting the profile hazard type and threshold level for the system component.

The assurance diagnostic estimates the uncertainty in the annual probability of inundation (API). The level of assurance (e.g., the levee can be accredited with 85% assurance) is synonymous with the confidence level, i.e., the leveed area is inundated with a probability of 0.01 or less, with 85% confidence. To assess the level of assurance with RMC-TotalRisk, the risk analysis must be simulated with full uncertainty.

After the risk analysis is complete, the user can navigate to the **Diagnostics** tab, and then the **Assurance** tab. Figure 142 shows the standard cumulative distribution plot for assurance. The API is on the x-axis, and the non-exceedance probability of the uncertainty in the API is on the y-axis. For this example, the mean API is shown as a vertical, dashed blue line at 0.00643. The target level of 0.01 (100-yr), which is shown as a vertical orange line, is shown to have an assurance level of 84.6%.

If the assurance level is less than 65%, the target level line will be plotted as a vertical red line. If the assurance is between 65% and 85%, the target level line will be plotted as an orange line. If the assurance is greater than 85%, it will be plotted as a greed line. In the example below, the assurance of containing the 0.01 AEP event falls between 65% and 85%. Therefore, the levee accreditation recommendation must be supported based on uncertainty, past system performance, and other factors [16].

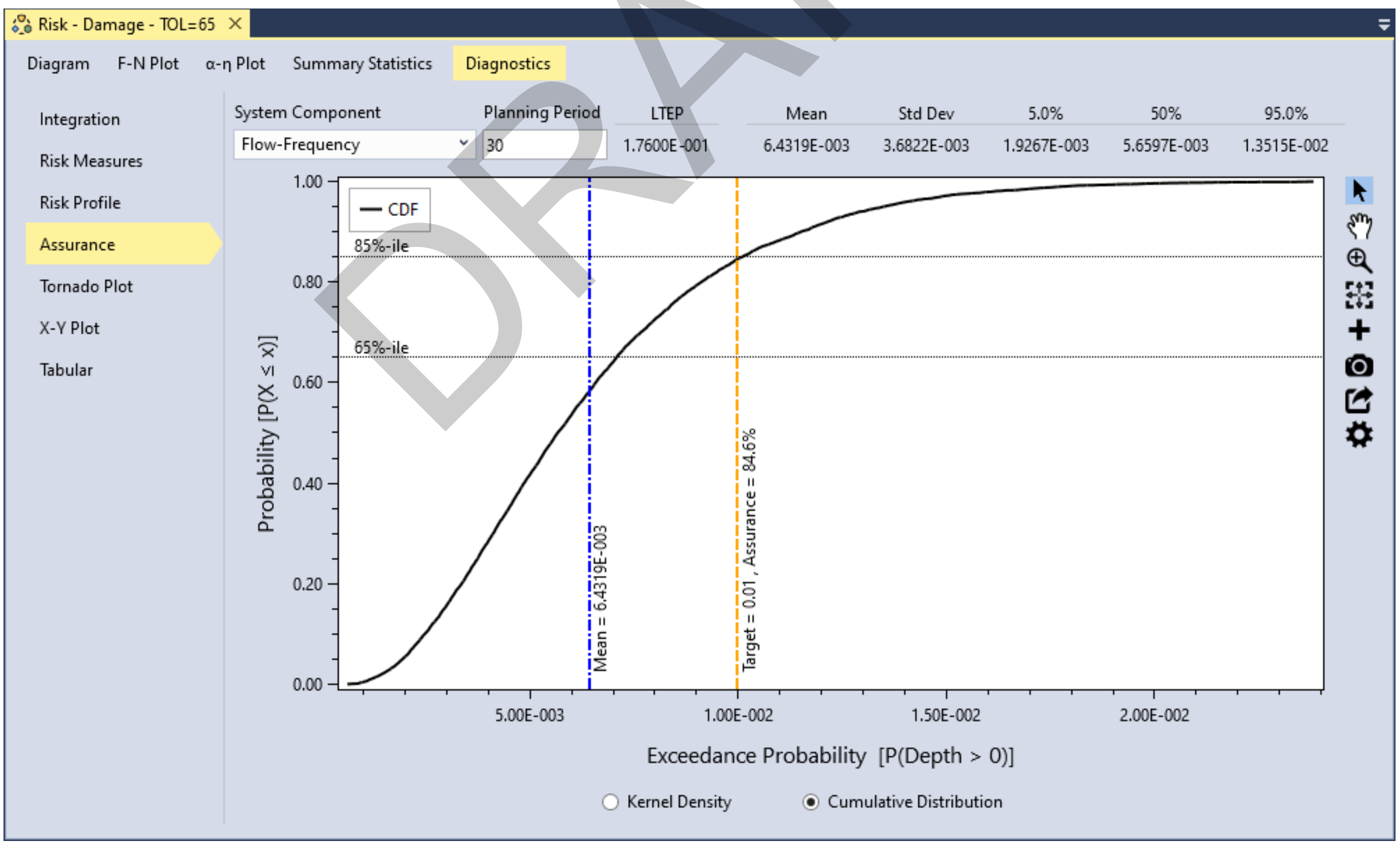


Figure 142 - Example of the cumulative distribution plot for NFIP assurance.

Tornado Plot

A tornado plot (Figure 143) is provided so you can visually assess how sensitive the risk results are to the input functions at each hazard level. The tornado plot is constructed based on the selected **System Component**, **Risk Type**, **Sensitivity Measure**, and **Hazard Level**. The inputs are ranked from most sensitive at the top to least sensitive at the bottom. The sensitivity measure options are *Sensitivity Index*, *Pearson's Correlation*, and *Spearman's Correlation* [1]. The risk sensitivity will typically vary with the hazard level. For example, at low hazard levels, the risk results might be most sensitive to the uncertainty in response, whereas at higher hazard levels, the results are more sensitive to the uncertainty in the hazard probability. Change the hazard level to see how the component sensitivity changes as hazard goes from low to high.

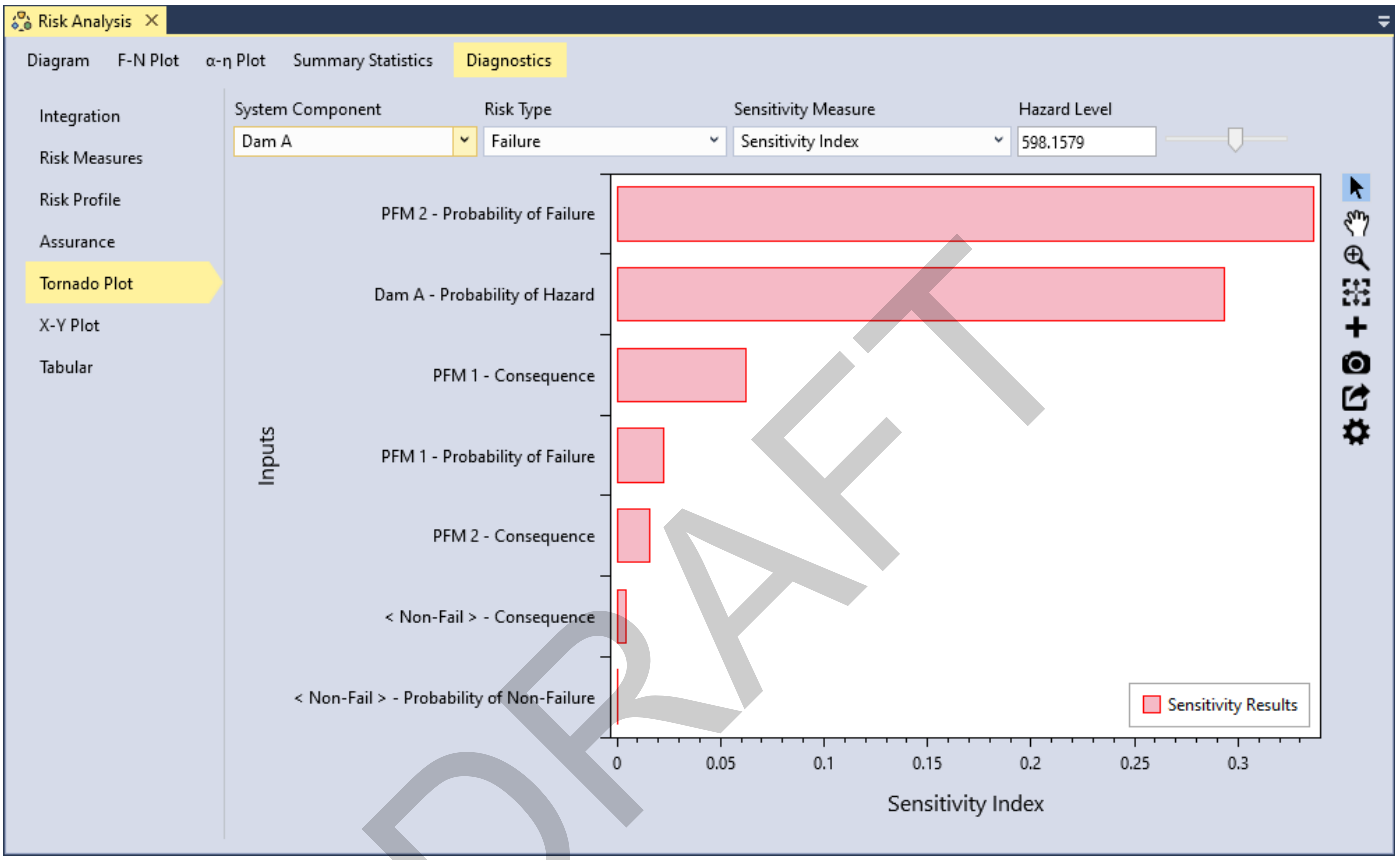


Figure 143 - Example of a tornado plot for risk diagnostics.

X-Y Plot

The X-Y plot (Figure 144) is provided to assess the correlation between the different system risk components and inputs. Results can be filtered by the **Risk Type**, **Risk Measure**, **X Parameter**, and **Y Parameter** components. For example, the overall risk of failure at the dam could be the Y parameter, and the risk of failure from an individual failure mode could be the X parameter. As shown below, the incremental risk of failure mode PFM 2 (concentrated leak erosion) is very strongly correlated to the incremental risk of the overall system. This means that large changes to the PFM 2 failure mode will be associated with large changes in the overall system risk. These results align with the sensitivity results shown in Figure 143.

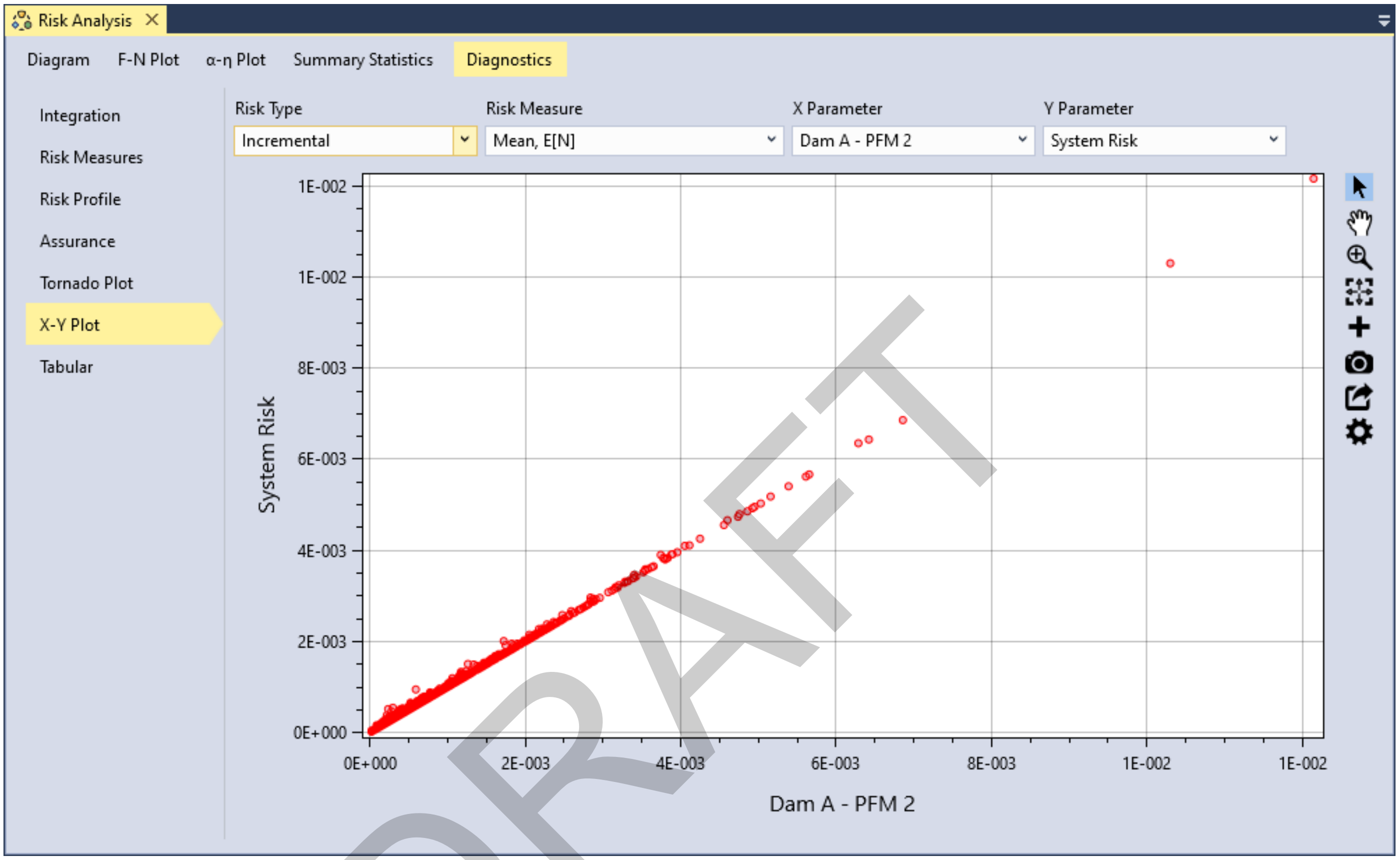
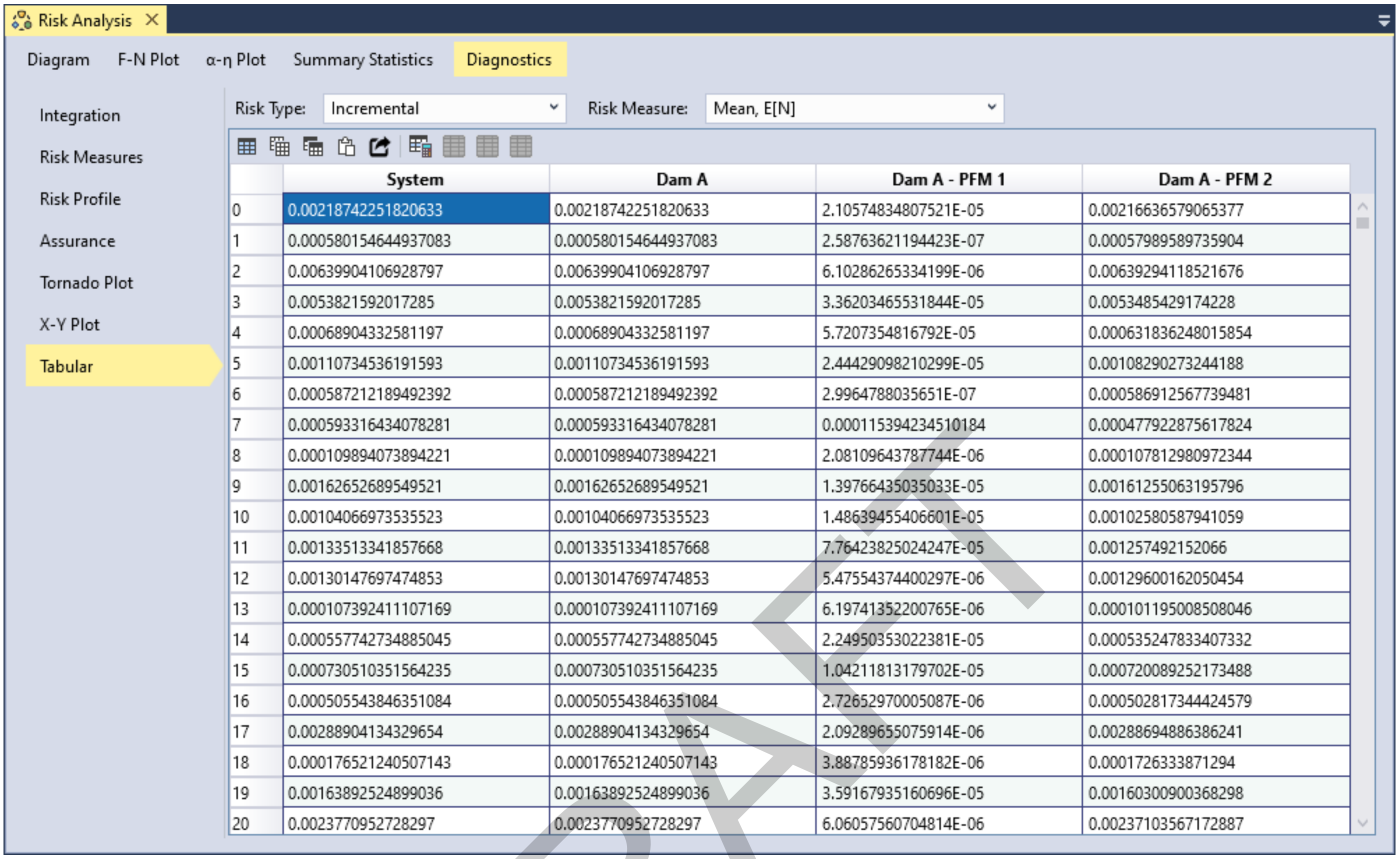


Figure 144 - Example of a X-Y plot for risk diagnostics.

Tabular

Tabular results are provided based on the selected **Risk Type** and **Risk Measure** (Figure 145). The table has 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.



	System	Dam A	Dam A - PFM 1	Dam A - PFM 2
0	0.00218742251820633	0.00218742251820633	2.10574834807521E-05	0.00216636579065377
1	0.000580154644937083	0.000580154644937083	2.58763621194423E-07	0.00057989589735904
2	0.00639904106928797	0.00639904106928797	6.10286265334199E-06	0.00639294118521676
3	0.0053821592017285	0.0053821592017285	3.36203465531844E-05	0.0053485429174228
4	0.00068904332581197	0.00068904332581197	5.7207354816792E-05	0.000631836248015854
5	0.00110734536191593	0.00110734536191593	2.44429098210299E-05	0.00108290273244188
6	0.000587212189492392	0.000587212189492392	2.9964788035651E-07	0.000586912567739481
7	0.000593316434078281	0.000593316434078281	0.000115394234510184	0.000477922875617824
8	0.000109894073894221	0.000109894073894221	2.08109643787744E-06	0.000107812980972344
9	0.00162652689549521	0.00162652689549521	1.39766435035033E-05	0.00161255063195796
10	0.00104066973535523	0.00104066973535523	1.48639455406601E-05	0.00102580587941059
11	0.00133513341857668	0.00133513341857668	7.76423825024247E-05	0.001257492152066
12	0.00130147697474853	0.00130147697474853	5.47554374400297E-06	0.00129600162050454
13	0.000107392411107169	0.000107392411107169	6.19741352200765E-06	0.000101195008508046
14	0.000557742734885045	0.000557742734885045	2.24950353022381E-05	0.000535247833407332
15	0.000730510351564235	0.000730510351564235	1.04211813179702E-05	0.000720089252173488
16	0.000505543846351084	0.000505543846351084	2.72652970005087E-06	0.000502817344424579
17	0.00288904134329654	0.00288904134329654	2.09289655075914E-06	0.00288694886386241
18	0.000176521240507143	0.000176521240507143	3.88785936178182E-06	0.0001726333871294
19	0.00163892524899036	0.00163892524899036	3.59167935160696E-05	0.00160300900368298
20	0.002377095272829 7	0.0023770952728297	6.06057560704814E-06	0.00237103567172887

Figure 145 - Tabular diagnostics tab displays every Monte Carlo realization for the selected risk type and risk measure.

Select a column of interest and right-click on the column header. Then, left-click on the **Summary Statistics…** option. A histogram plot and detailed summary statistics will be calculated for the selected column as shown in Figure 146 below.

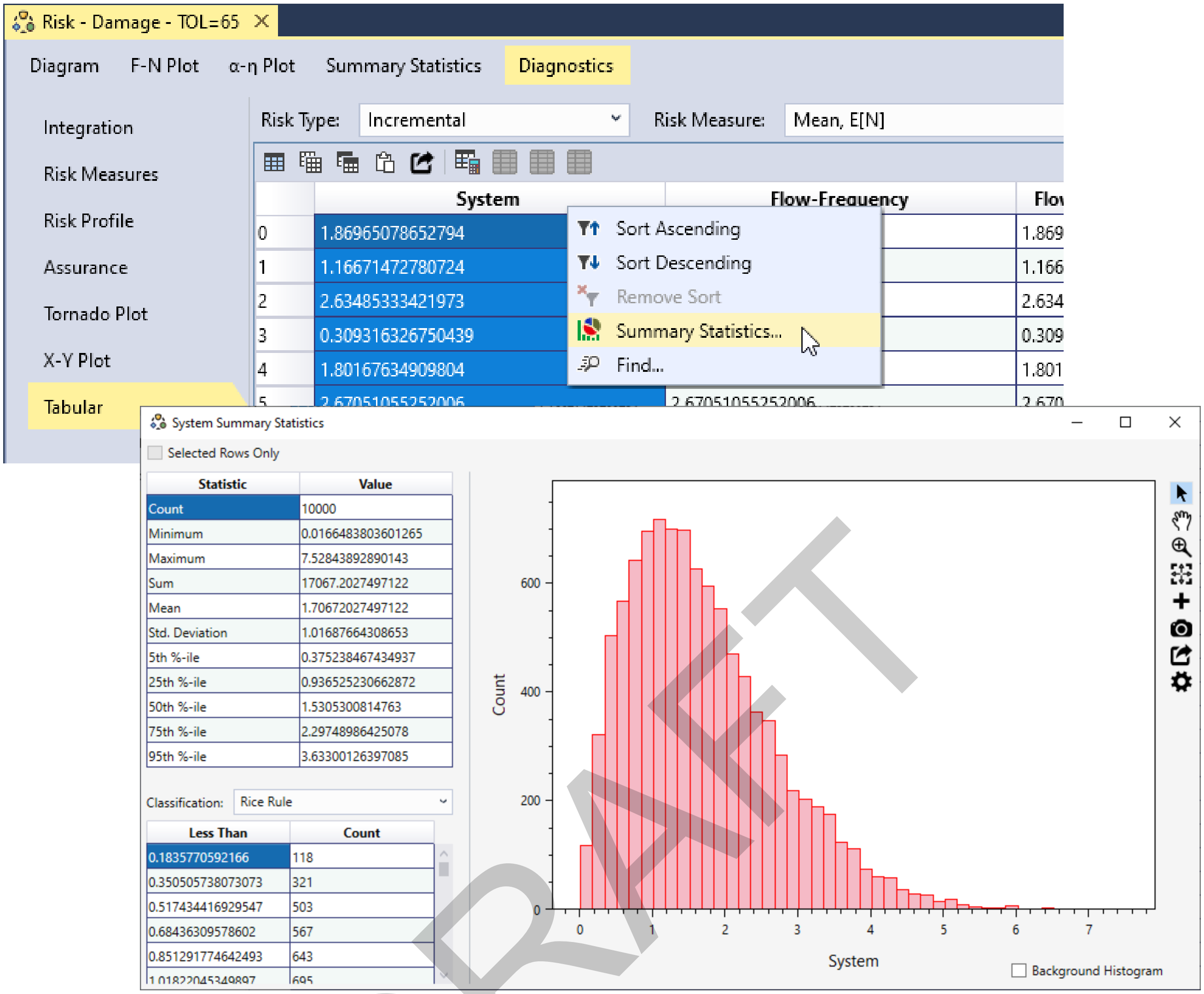


Figure 146 - Example of the histogram and summary statistics output for tabular results.

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[1] C. H. Smith, W. L. Fields and D. A. Margo, "(DRAFT) RMC-TR-2022-XX Quantitative Risk Analysis with the RMC-TotalRisk Software," U.S. Army Corps of Engineers, Lakewood, CO, 2022.

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[12] U.S. Army Corps of Engineers, "HEC-LifeSim Technical Reference Manual," Institute for Water Resources, USACE, Davis, CA, 2020.

[13] W. L. Fields, "Life Loss Estimation from Flood Events: A New Approach to Population Redistribution with Uncertainty," in *ANCOLD*, Adelaide, 2016.

[14] Center for Chemical Process Safety, Guidelines for Developing Quantitative Safety Risk Criteria, Hoboken, New Jersey: John Wiley & Sons, Inc., 2009.

[15] U.S. Army Corps of Engineers, "Key USACE Flood Risk Management Terms," U.S. Army Corps of Engineers, Davis, CA, 2015.

[16] U.S. Army Corps of Engineers, "ECB 2019-11 Transition Guidance for Levee System Evaluations for the National Flood Insurance Program (NFIP)," U.S. Army Corps of Engineers, Washington, DC, 2019.