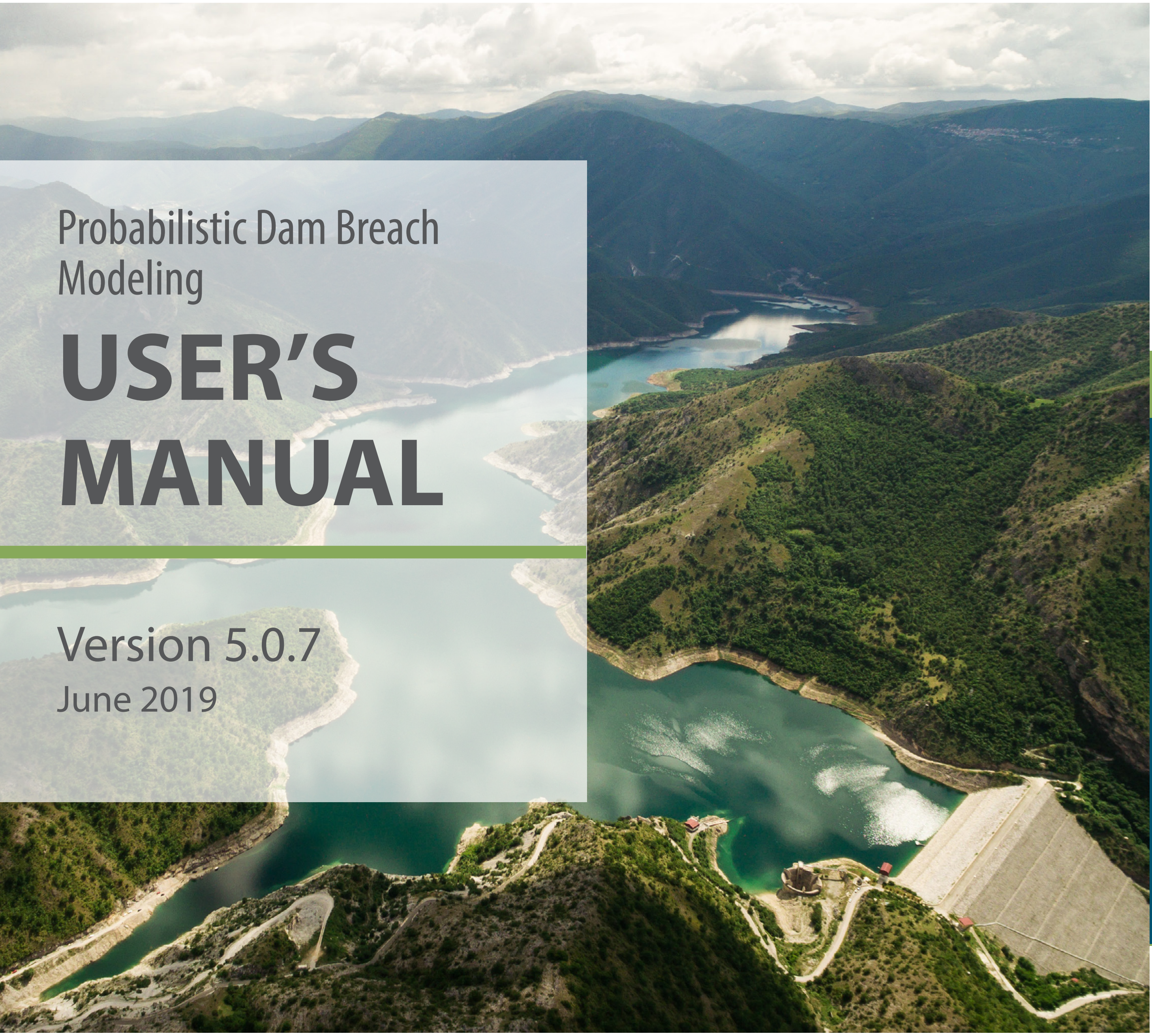
McBreach©
by Kleinschmidt



Probabilistic Dam Breach Modeling

USER'S MANUAL

Version 5.0.7

June 2019

Practical *Solutions* for Complex *Problems*
Affecting Energy, Water and the Environment

McBreach© User's Manual
Version 5.0.7

Written by Christopher Goodell and
Published in the United States of America by:

Kleinschmidt Associates
Portland, Oregon
www.KleinschmidtGroup.com

To download a copy of this manual and the McBreach software, please visit:
www.KleinschmidtGroup.com/mcbreach

Disclaimer: No information, written or implied in this book or any resource recommended should be considered advice for any individual or company, but constitutes a general education regarding the use of the software program McBreach©. Neither Kleinschmidt Associates, nor the author of McBreach and this User's Manual, Christopher Goodell, nor any affiliated entity accepts liability for anyone or anything that uses information presented in this manual.

Trademark notice: This manual uses various trademarked names within its text. In the interest of trademark holders, this manual cites their ownership of the trademarks, with no intention of infringement.

Software information: This book discusses strategies and techniques for using models created with the software program HEC-RAS. HEC-RAS is developed and distributed free-of-charge by the United States Army Corps of Engineers, Hydrologic Engineering Center in Davis, California. HEC-RAS and its supporting manuals may be downloaded from the Hydrologic Engineering Center's website, www.hec.usace.army.mil.

Cover photograph: Kozjak Dam and Reservoir by Petar Petkovski on Unsplash

Terms and Conditions for use of McBreach©

By installing McBreach to your computer, you agree to the following terms:

Kleinschmidt Associates, Inc ("Kleinschmidt") grants to you (“the User”) the rights to install McBreach "the Software" and to use the Software subject to the following Terms and Conditions for Use (“the Agreement”):

All copies of the Software received by user pursuant to the authority of the Agreement will be and remain the property of Kleinschmidt. User may not reproduce, distribute, rent, lease, or lend the Software without prior authorization from Kleinschmidt. Kleinschmidt is solely responsible for the content of the Software. The Software may not be modified, abridged, decompiled, disassembled, unobfuscated or reverse engineered. No part of the Software may be exported or re-exported in contravention of United States of America’s export laws or regulations.

Waiver of Warranty
KLEINSCHMIDT AND ITS AGENTS, OFFICERS, REPRESENTATIVES, AND EMPLOYEES, INCLUDING ITS CONTRACTORS AND SUPPLIERS PROVIDE THE SOFTWARE "AS IS," WITHOUT ANY WARRANTY OR CONDITION, EXPRESS, IMPLIED OR STATUTORY, AND SPECIFICALLY DISCLAIM ANY IMPLIED WARRANTIES OF TITLE, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT.

Limitation of Liability
IN NO EVENT SHALL KLEINSCHMIDT, ITS AGENTS, OFFICERS, REPRESENTATIVES, AND EMPLOYEES, INCLUDING ITS CONTRACTORS AND SUPPLIERS, BE LIABLE FOR LOST PROFITS OR ANY SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF OR IN CONNECTION WITH USE OF THE SOFTWARE REGARDLESS OF CAUSE, INCLUDING NEGLIGENCE EVEN IF KLEINSCHMIDT HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.
KLEINSCHMIDT AND THE LIABILITY OF ITS AGENTS, OFFICIERS, REPRESENTATIVES, AND EMPLOYEES, INCLUDING ITS CONTRACTORS AND SUPPLIERS, TO YOU OR ANY THIRD PARTIES IN ANY CIRCUMSTANCE IS LIMITED TO THE REPLACEMENT OF CERTIFIED COPIES OF THE SOFTWARE WITH IDENTIFIED ERRORS CORRECTED.

Indemnity
As a voluntary user of the Software you agree to indemnify and hold Kleinschmidt, and its agents, officers, 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 the Software or breach of the Agreement or your violation of any law or the rights of a third party.

Modifications
Kleinschmidt reserves the right to modify the product over time without notice and shall not be under any obligation to provide you with any notification of such change nor provide an archive of prior versions.

Support
The Software is provided with no support, either contractually or implied. Support services are available by contacting Kleinschmidt.

Duty of Care
As a user of the Software, you agree to use sufficient duty of care when using the Software. This includes not designing or constructing anything outside of your abilities and knowledge.

Entire Agreement
The Agreement, including any and all documents referenced herein, constitute the entire agreement between Kleinschmidt and the user. Kleinschmidt's failure to insist upon or enforce strict performance of any provision of the Agreement shall not be construed as a waiver of any provisions or right. If any of the provisions contained in the Agreement be determined to be void, invalid or otherwise unenforceable by a court of competent jurisdiction, such determination shall not affect the remaining provisions contained herein. The Agreement shall be governed by and construed in accordance with the laws of the state of Maine and the federal laws of the United States of America applicable therein.

Assent
Choosing the "I agree" option and selecting the "Next" button during installation of the McBreach software indicates that you have the authority to accept the Agreement and voluntarily accept the terms and conditions contained herein. If you do not agree or have the authority to agree to the Agreement, please delete all copies, and cease using the Software.

Table of Contents

I. Introduction

McBreach is a companion software application to the Hydrologic Engineering Center's River Analysis System (HEC-RAS) that performs probabilistic dam breach modeling. Using McBreach, the hydraulic modeler has the ability to randomly sample, about predefined statistical distributions, all breach parameters for inline structures, lateral structures and SA/2D Area Connections. In addition to breach parameters, the user can include the model's inflow hydrograph in the probabilistic analysis by randomly sampling hydrograph flow and duration multipliers.

Through a Monte Carlo simulation, McBreach produces exceedance probability peak discharges and their respective sampled breach parameters that can be used to produce exceedance probability inundation (EPI) maps. Ultimately a design exceedance probability peak discharge is selected for decision making. Several metrics are available for the user to gage statistical convergence during the probabilistic simulation.

Using the techniques presented by Goodell (2014), McBreach communicates with HEC-RAS and exchanges information at the realization level. The connection with HEC-RAS is managed through use of the HECRASController, as well as programmatic reading/writing of the HEC-RAS input files.

McBreach satisfies a need in the dam safety community to augment the overly conservative deterministic approach to dam breach modeling with a probabilistic approach that quantifies uncertainty in the analysis. McBreach allows for decision making based on risk and uncertainty and compliments dam safety jurisdictional desires to move towards risk-informed decision making.

II. Requirements

To use McBreach, the user must have a licensed copy. McBreach Version 5.0.7 software will run on Windows™ XP™, Vista™ SP2, 7 SP1, 8, 8.1, and 10 with Microsoft .Net™ Framework 4.6.1 or higher. Most new computer systems use .Net™ Framework 4.6.1 or higher; however, if necessary, .Net™ Framework 4.6.1 and higher can be downloaded for free from https://dotnet.microsoft.com/download/dotnet-framework. HEC-RAS Version 5.0.7 is required to use McBreach Version 5.0.7. Because McBreach is designed to run many thousands of HEC-RAS simulations autonomously, computer speed and efficiency is most important to minimize overall run-times. While not required, it is advised to use a computer with superior processing speed and random-access memory (RAM). At a minimum to handle .Net Framework 4.6.1 your computer must have the following:

Processor:	1GHz
RAM:	512 Mb
Free Disk Space:	4.5 Gb

McBreach Version 5.0.7 is available free of charge. However, to use McBreach Version 5.0.7, the user must agree to terms and conditions, as outlined on pages ii and iii of this manual. By installing McBreach Version 5.0.7 onto your computer, you agree to the terms and conditions included in this manual.

III. Installation

The McBreach installation file can be downloaded from the Kleinschmidt website at https://www.kleinschmidtgroup.com/mcbreach/. To install McBreach, double-click the McBreach507.msi installation file and follow the prompts on the install wizard. If a previous version of McBreach is already installed, the user may be required to uninstall the older version prior to installing the new version. Before McBreach can run, HEC-RAS Version 5.0.7 must be installed on the computer. HEC-RAS Version 5.0.7 can be downloaded from the Hydrologic Engineering Center's website (www.hec.usace.army.mil).

IV. Starting A New McBreach Project

To start a new McBreach project, double click the McBreach icon on the desktop or go to the Windows™ Start menu and navigate to McBreach, which normally will be located in the McBreach folder. Once McBreach has opened, click File…New. Then enter a name for the new McBreach project and save it in the directory of your choosing. All McBreach projects will have the file extension. mcb.

V. Interface

Main McBreach Window

Upon opening McBreach, the main McBreach window will become active. The main McBreach form is shown in Figure 1.

Most work for the McBreach project will be performed from the main McBreach window. It is a typical Windows™-style interface with a series of menu items and convenience short-cut buttons at the top. The main McBreach window is separated into five groups. At the top of the window, the first group includes the name of the current McBreach project and the unit system used for the current project.

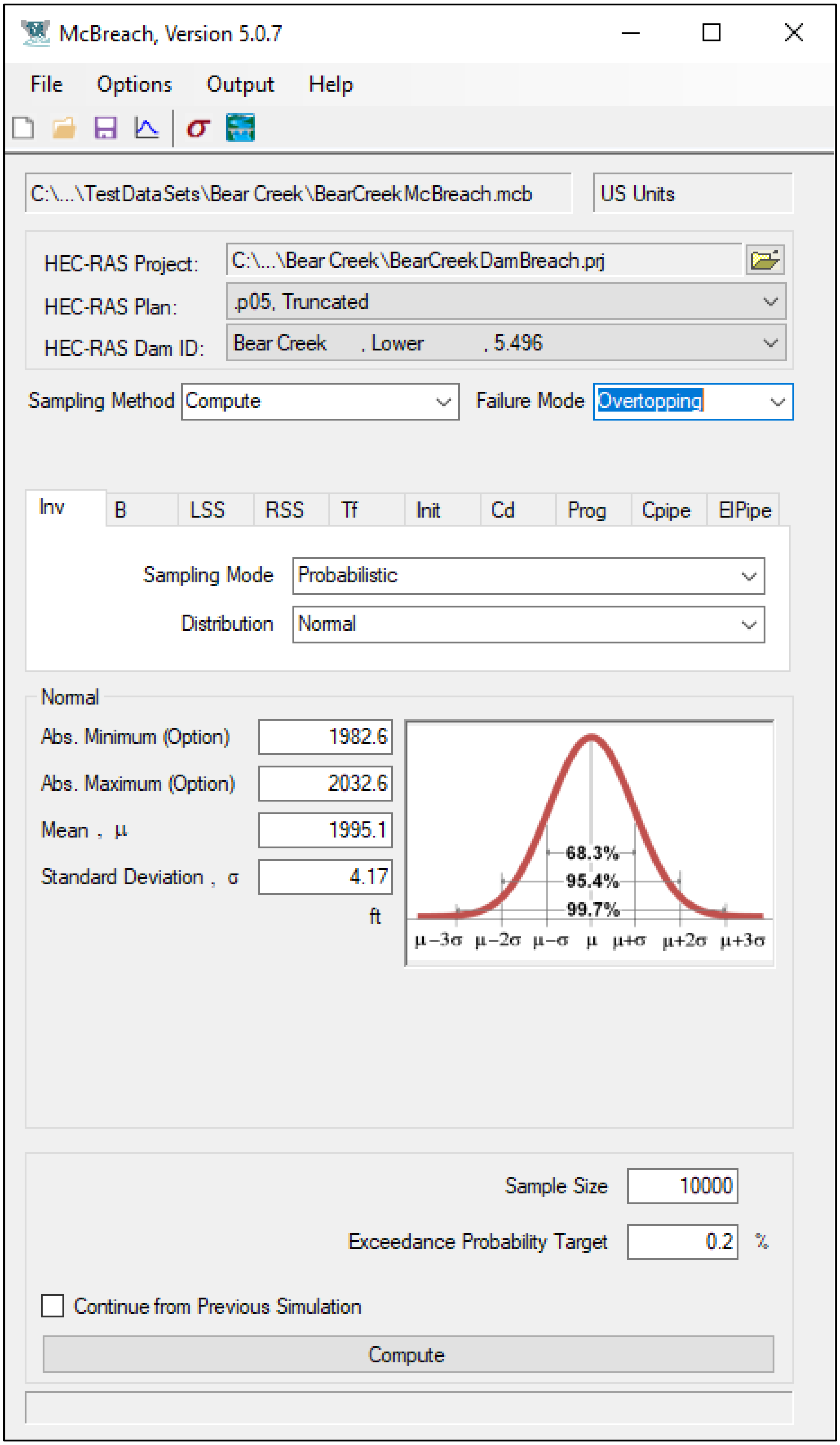


Figure 1. McBreach Main Window

HEC-RAS Association

The second group contains information about the associated HEC-RAS project and the dam or levee that will be simulated probabilistically (Figure 2).

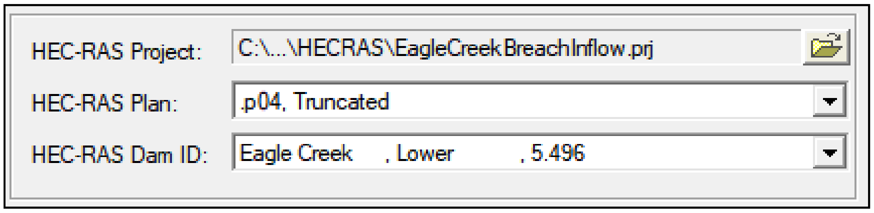


Figure 2. HEC-RAS Association Group

The HEC-RAS dam breach project must already be set up before McBreach can be associated with it. To associate a HEC-RAS project with your McBreach project, click the open button to the right of the HEC-RAS Project name label. This will open a Windows™ Explorer dialog. Navigate to the HEC-RAS project file (*.prj) that is desired to associate and select that project file. Once the HEC-RAS project is associated, the project path and file name will populate the HEC-RAS project label and McBreach will automatically assemble the HEC-RAS plans into the HEC-RAS Plan dropdown box. Select the plan to run with McBreach. Typically, a truncated plan (see Section VI. Truncated HEC-RAS Model) will be selected to run with McBreach. All inline structures, lateral structures, and SA/2D Area Connections included in the selected HEC-RAS plan will be assembled in the HEC-RAS Dam ID dropdown box. Select the dam or levee to be breached using McBreach.

Statistical Inputs

The next two groups allow the user to set statistical inputs for each of the dam breach parameters (Figure 3).

Sampling Method. By selecting "Compute", McBreach is instructed to randomly select the breach parameters of the statistical distributions defined by the user in the statistical inputs group. By selecting "Read From Sample File", McBreach will read in the breach parameter for all realizations from a sample file (*.smp). To use this option, a sample file must first be written in the correct format.

Each time the user computes (both a full Monte Carlo run or Compute Sample Only), McBreach will write a sample file (.smp) that contains all the sampled breach and hydrograph parameters. If the sample file is created manually, it must adhere to the format as follows:

Inv, B, LSS, RSS, Tf, Init, Cd, Prog, CPipe, ElPipe, InflowMult, InflowDur
##,##,##,##,##,##,##,##,##,##,##,##

The header row is required as shown above. The second row represents the first realization of breach parameters. There should be a row of comma delimited values for reach realization. Each ## represents the sampled value that corresponds to the breach parameter in the corresponding order on the header. If the user is unsure of the sample file format, the sample file (*.smp) created after each McBreach run can be viewed directly in a text editor.

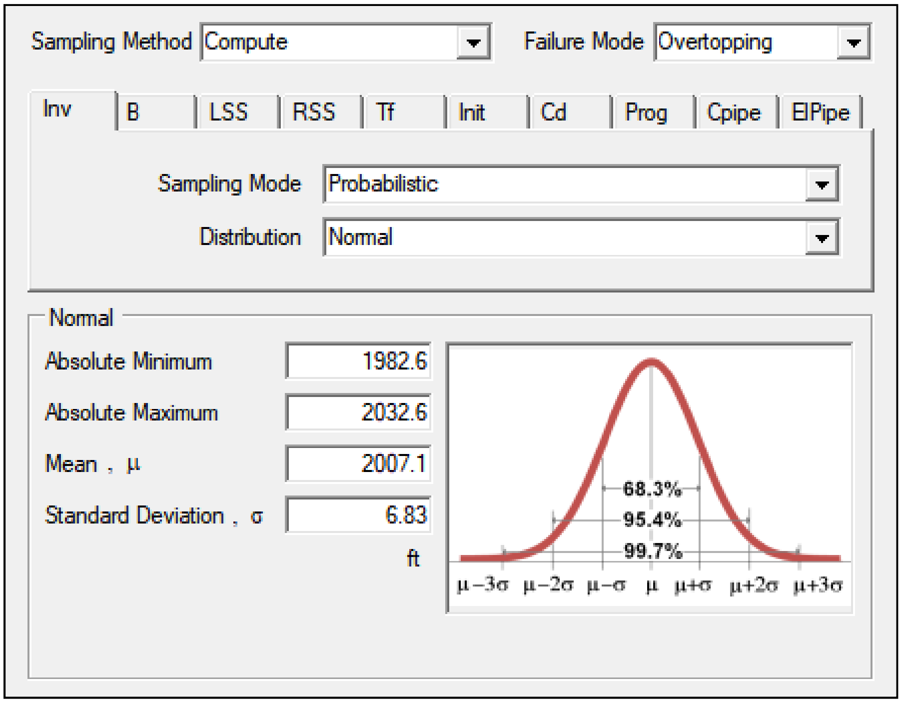


Figure 3. McBreach Statistical Input Groups

Failure Mode. Select either Overtopping or Piping. This must be consistent with the failure mode selected in the associated HEC-RAS project. See the HEC-RAS manuals for more information on failure mode.

Breach Parameter Tabs. Select the tab for the breach parameter and enter the data. Breach centerline is not a parameter used in McBreach.

- **Inv**. Final Bottom Elevation
- **B**. Final Bottom Width
- **LSS**. Left Side Slope
- **RSS**. Right Side Slope
- **Tf**. Breach Formation Time
- **Init**. Starting WS Elevation for failure initiation. Only used if Trigger Failure is set to WS Elev
- **Cd**. Breach Weir Coefficient
- **Prog**. Breach Progression. If probabilistic sampling mode is selected, breach progression is set to a uniform distribution, representing a “coin flip” between linear function and sine function. In other words, McBreach will randomly select either linear or sine.
- **Cpipe**. Piping Coefficient. Only used if the failure mode in HEC-RAS is set to piping.

- **ElPipe**. Initial Piping Elevation. Only used if the failure mode in HEC-RAS is set to piping.

Sampling Mode. For each breach parameter, select between Deterministic and Probabilistic. If Deterministic is selected, enter the value to be used for the selected breach parameter for each realization and McBreach will use that exact value for every realization in the Monte Carlo run. If Probabilistic is selected, choose the desired distribution and enter the required data. When Probabilistic is selected, McBreach will randomly sample values about the defined statistical distribution for each realization.

Distribution. Choose a statistical distribution for the selected breach parameter. Uniform, normal, triangular and lognormal are the statistical distributions available in McBreach Version 5.0.7. More information on the statistical distributions available in McBreach is presented in VII. Theory

Statistical Inputs. These values are entered by the user to define the shape of the selected statistical distribution. Each distribution has its own set of inputs.

- **Value**. Deterministic Sampling Mode. This is the value that McBreach will assign for the given breach parameter for all realizations.
- **Minimum**. Probabilistic Sampling Mode. Uniform Distribution. This sets the minimum bound for a uniform sampling domain.
- **Maximum**. Probabilistic Sampling Mode. Uniform Distribution. This sets the maximum bound for a uniform sampling domain.
- **Abs. Minimum (Option)**. Probabilistic Sampling Mode. Normal and Lognormal Distributions. Allows the user to set an absolute minimum value that McBreach can select during the sampling process. For a given realization, if a number less than the absolute minimum is sampled, McBreach will use the absolute minimum value.
- **Abs. Maximum (Option)**. Probabilistic Sampling Mode. Normal and Lognormal Distributions. Allows the user to set an absolute maximum value that McBreach can select during the sampling process. For a given realization, if a number greater than the absolute maximum is sampled, McBreach will use the absolute maximum value.
- **Mean**. Probabilistic Sampling Mode. Normal and Lognormal Distributions. Enter the mean (average) value for the normal distribution.
- **Standard Deviation**. Probabilistic Sampling Mode. Normal Distribution. Enter the standard deviation for the normal distribution.
- **Min**. Probabilistic Sampling Mode. Triangular Distribution. Enter the minimum value for the triangular distribution.
- **Max**. Probabilistic Sampling Mode. Triangular Distribution. Enter the maximum value for the triangular distribution.
- **Mode**. Probabilistic Sampling Mode. Triangular and Lognormal Distributions. Enter the mode for the triangular distribution. The mode is the statistically most frequently occurring value in the sampled set.

Options. The following optional methods are available:

- **Monolith Width (Option).** Breach width (B) parameter. This option will use whatever is sampled for the breach width and round it to the nearest multiple of the monolith width value entered. This is more appropriate when simulating breaches of concrete dams that typically breach as multiples of monolith widths.
- **Multiple of Breach Height (Option).** Breach width (B) parameter. This option allows the breach width to be defined as a multiple of the breach height. Several breach parameter equations are a function of breach height. If this option is selected, enter in values that represent multiples of breach height instead of breach widths. When selecting this option, a dam crest elevation will be required. McBreach determines the breach height by subtracting the dam crest elevation from the sampled breach invert elevation.
- **Erosion Rate (Option).** Breach formation time (Tf) parameter. Selecting Erosion Rate will change the units for the formation time inputs from hours to feet or meters per hour (ft/hour or m/hour). If Erosion Rate is selected, enter erosion rates (in ft/hour or m/hour) instead of breach formation time. McBreach will divide each sampled breach width by the erosion rate. This provides a sampled formation time that is a function of breach width.

Computational Control

The last section of the main McBreach window includes computation control information (Figure 4).

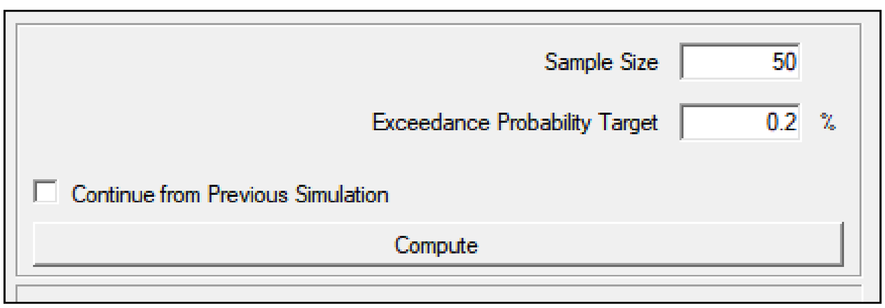


Figure 4. Computational Control Options

Sample Size. Enter the number of realizations to be run for the McBreach simulation. The number of realizations should be large enough so that statistical convergence on peak discharge is achieved. Before running a large number of realizations, it is advised to test the performance of McBreach with a small number or realizations first (10 or 20). Statistical convergence is discussed in detail in Section VII. Theory

Exceedance Probability Target. By default, McBreach provides output for seven standard exceedance probabilities for peak discharge: 1%, 5%, 10%, 50%, 90%, 95% and 99%. McBreach has the ability to produce an additional exceedance probability beyond the seven default values. If output for another exceedance probability is desired, enter it in this input box.

Continue from Previous Simulation. If upon completion of a McBreach simulation, it is determined that more realizations are desired, the user can continue the previous McBreach simulation by checking this box. The number of realizations in the Sample Size input box will be added to the previous simulation. This function is particularly useful once a simulation of a large number of realizations is completed, and the user determines the desired level of statistical convergence has not been achieved. There is no limit to how many times the user can continue from a previous simulation. When this option is selected, after selecting Compute, McBreach will read the previous simulation from the McBreach log output file (*.mcblog.out). Therefore, the user must already have an existing log output file in the McBreach project directory to use this option.

Compute. Once all input data is entered, select Compute to run a McBreach simulation. It is good practice to save data prior to selecting Compute.

Menu Items

The menu items include typical Windows™-type menu items: File, Options, Output and Help. The convenience buttons below the menu items gives the user quick one-touch access to some of the more common tools or options that will be used.

File Menu

The File menu contains typical options for creating, opening and saving McBreach projects (Figure 5).

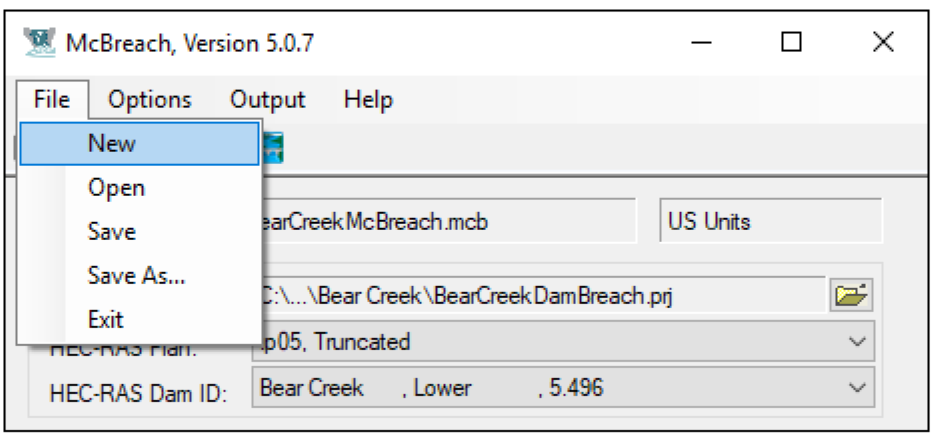


Figure 5. File Menu

New. Creates a new McBreach project. All input boxes will be cleared, and defaults will be reset.

Open. Opens a file-select dialog window which will allow the user to search for and open existing McBreach projects with the file extension *.mcb.

Save. Saves the current McBreach project and all the input data both on the Main McBreach window and the Inflow Hydrograph window.

Save as. Creates a new McBreach project while preserving all of the current input data.

Exit. Closes McBreach. If McBreach has any unsaved changes, the user will be prompted to save before McBreach exits.

Options Menu

The Options menu contains a range of options for the user to consider (Figure 6).

Unit System. Select between US (United States customary) units and SI (System International) units. This must be consistent with the unit system used in the HEC-RAS project.

Open Last Project on Startup. Provides a link in the Window™'s registry for the last saved McBreach project. When this is selected, the last saved McBreach project will automatically open when starting McBreach.

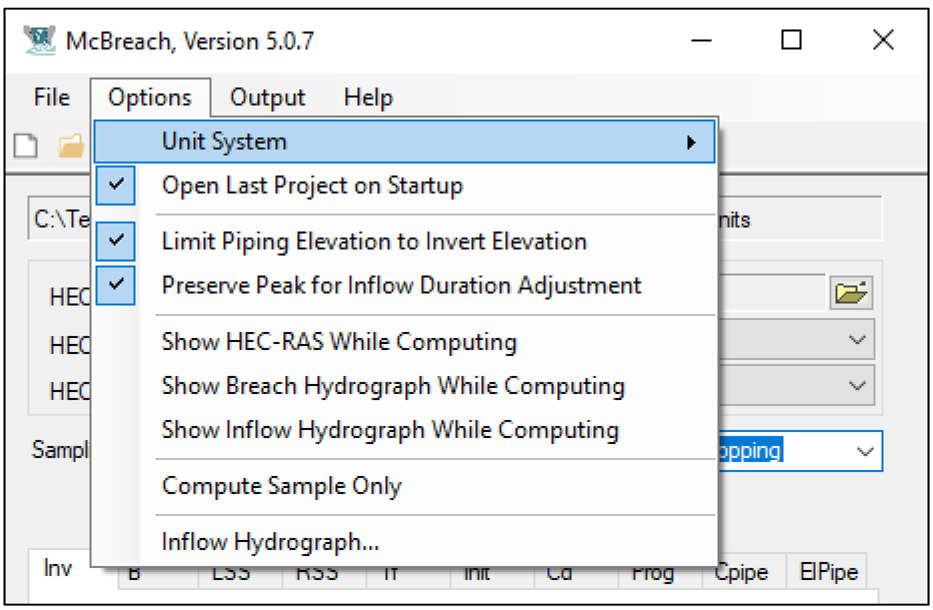


Figure 6. Options Menu

Limit Piping Elevation to Invert Elevation. Depending on the statistical ranges provided in the dam breach parameters, it may be possible for McBreach to randomly sample an initial piping elevation that is lower than the randomly sampled dam breach invert elevation. Although this is not a logical occurrence, this option is available to prevent this from occurring. When this option is selected, if McBreach returns an initial piping elevation lower than the sampled breach invert elevation, the piping elevation will be set to the breach invert elevation.

Preserve Peak for Inflow Duration Adjustment. When performing probability on the duration of the inflow hydrograph, the peak discharge for the sampled inflow hydrograph can be adjusted (downward) slightly due to the new spacing of hydrograph points. By selecting this option, McBreach will replace the peak discharge in the newly sampled hydrograph with the original hydrograph's peak discharge. All other points on the sampled hydrograph will remain as sampled.

Show HEC-RAS While Computing. While McBreach is running, the HEC-RAS computations will show for each realization. This can be useful to verify that HEC-RAS is computing successfully and to get a sense for how long each HEC-RAS run is taking for each McBreach realization. While selecting this option has very little effect on the computation time for any one realization, it will slightly add to the computer's computational burden and can lengthen an overall McBreach simulation (especially when running a large amount of realizations). It is suggested to select this option when doing some preliminary small batch tests, but not for the full run of thousands of realizations.

Show Breach Hydrograph While Computing. This option displays a graph during the McBreach simulation of an ensemble of all the computed breach hydrographs. Selecting this option takes a large amount of computational effort and memory and will progressively slow the McBreach simulation considerably. It may not be noticeably slower at the beginning of the McBreach simulation, but over time it will increase each realization's split time substantially. Only select this option for testing a relatively small amount of realizations. This option is useful for obtaining a graphical image of the range of breach outflow hydrographs that are computed during the McBreach simulation (Figure 7).

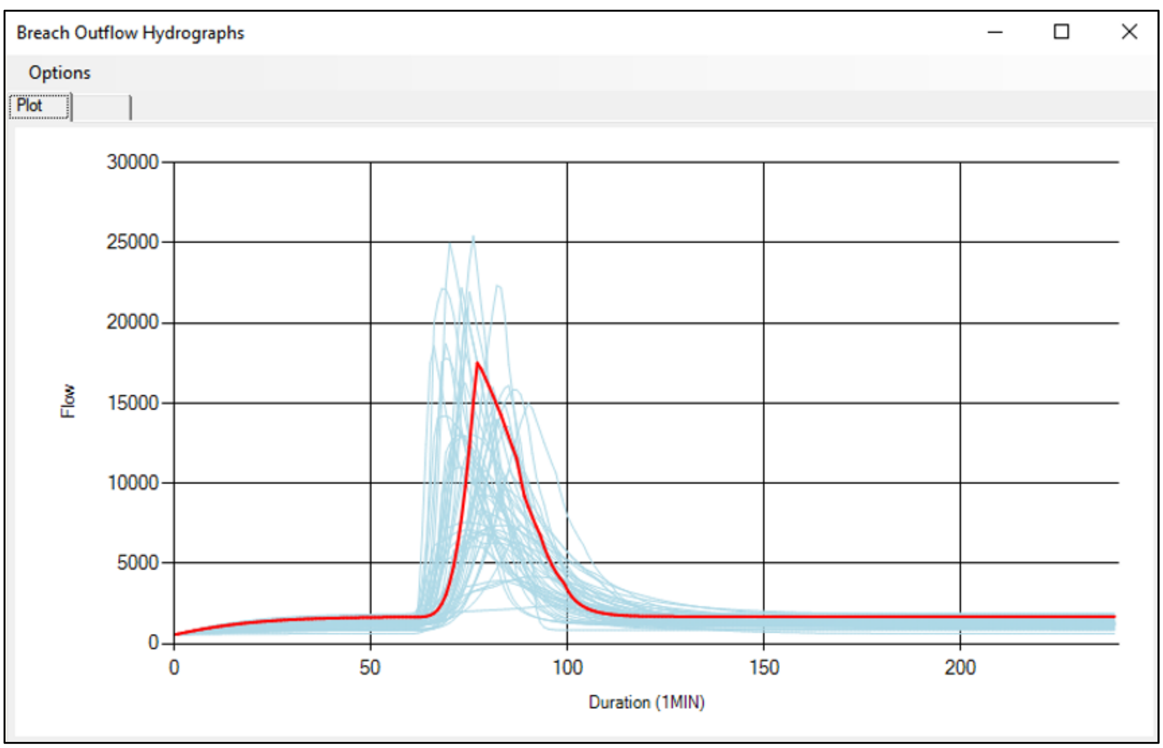


Figure 7. Computed Breach Hydrographs

Show Inflow Hydrograph While Computing. This option displays a graph during the McBreach simulation of an ensemble of all the sampled inflow hydrographs (refer to inflow hydrograph discussion). Selecting this option takes a large amount of computational effort and memory and will progressively slow the McBreach simulation considerably. It may not be noticeably slower at the beginning of the McBreach simulation, but over time it will increase each realization's split time substantially. Only select this option for testing a relatively small amount of realizations. This option is useful for obtaining a graphical image of the range of sampled inflow hydrographs during the McBreach simulation. Figure 8 illustrates an example of an ensemble of inflow hydrographs.

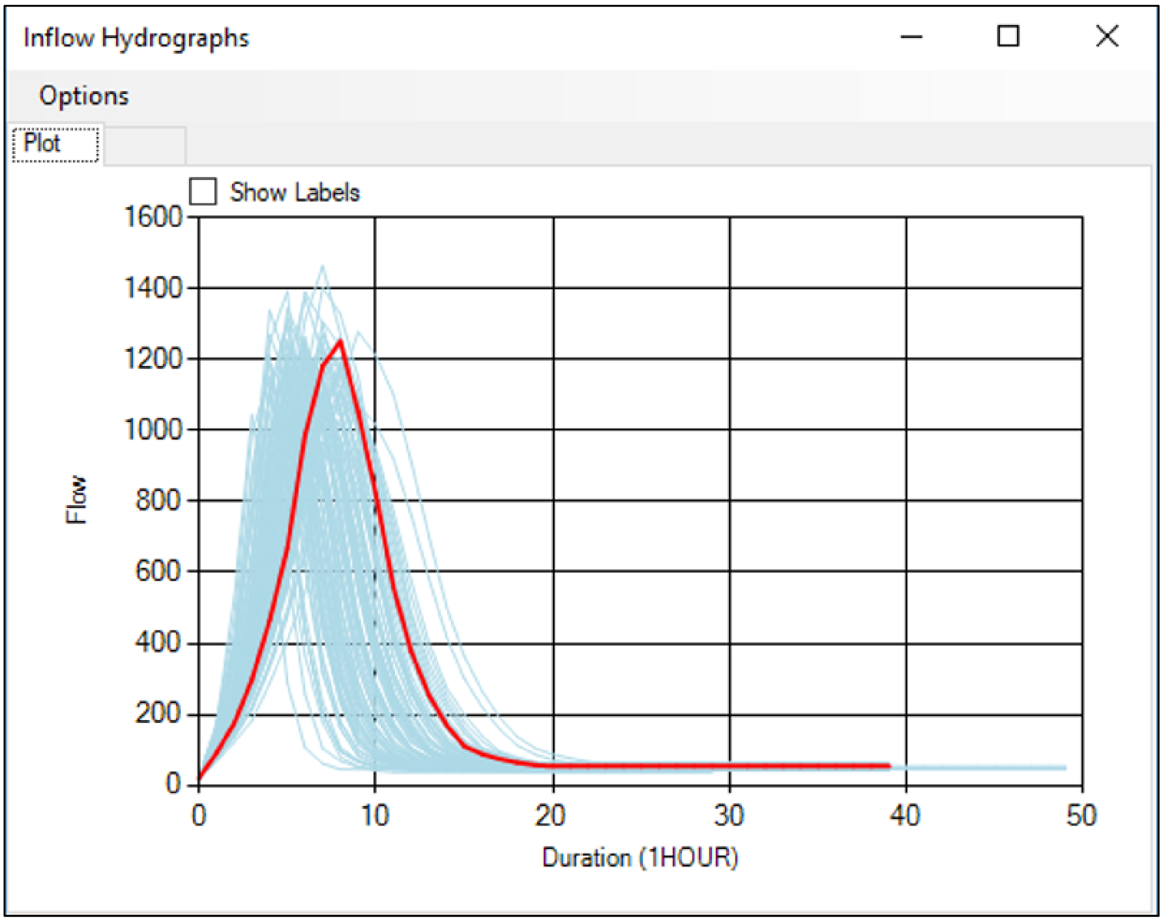


Figure 8. Ensemble of Inflow Hydrographs

Compute Sample Only. Select this option to ONLY compute the sample set of breach parameters and inflow hydrograph multipliers for the entire sample size. HEC-RAS computations will not be performed. This option is useful to preview the sampled breach and inflow parameters and can also be used to evaluate the erosion rate/headwater depth (ER/Hw) relationship. When this option is selected, McBreach creates the sample set and writes it to a sample file. The results of the sampling can be viewed in the computation window and is also available to evaluate in the ER/Hw plot.

Inflow Hydrograph. Select this option to open the Inflow Hydrograph sampling window. This option allows the user to treat the inflow hydrograph as an uncertain input parameter. The inflow hydrograph will be sampled for each realization of the McBreach simulation by applying a flow multiplier and a duration multiplier. Both multipliers are randomly sampled for each realization based on their statistical distributions as determined by the user. Select the mode and distribution and fill in the required input parameters. Uniform, triangular and normal distributions are available for McBreach Version 5.0.7. Figure 9 illustrates the inflow hydrograph input window.

Once the inflow hydrograph inputs are entered, the user can plot the inflow hydrograph distribution by clicking the Plot button (Figure 10). During the McBreach simulation, the user can track the sampling of inflow hydrographs by selecting the option "Show Inflow Hydrograph while Computing", found in the Options menu of the main McBreach window.

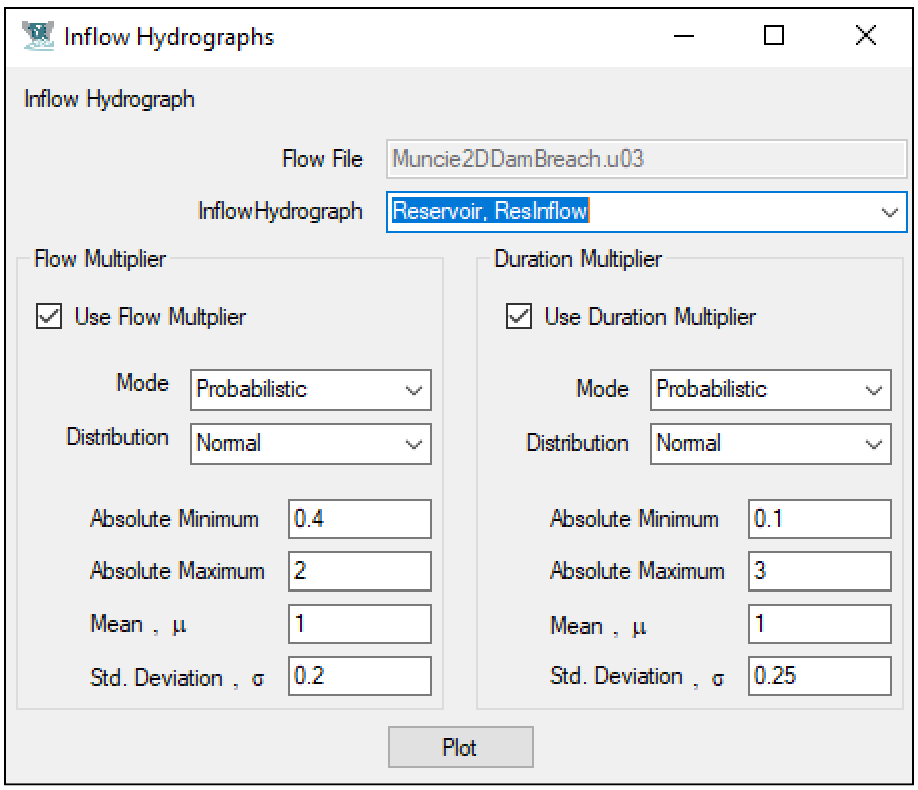


Figure 9. Inflow Hydrograph Window

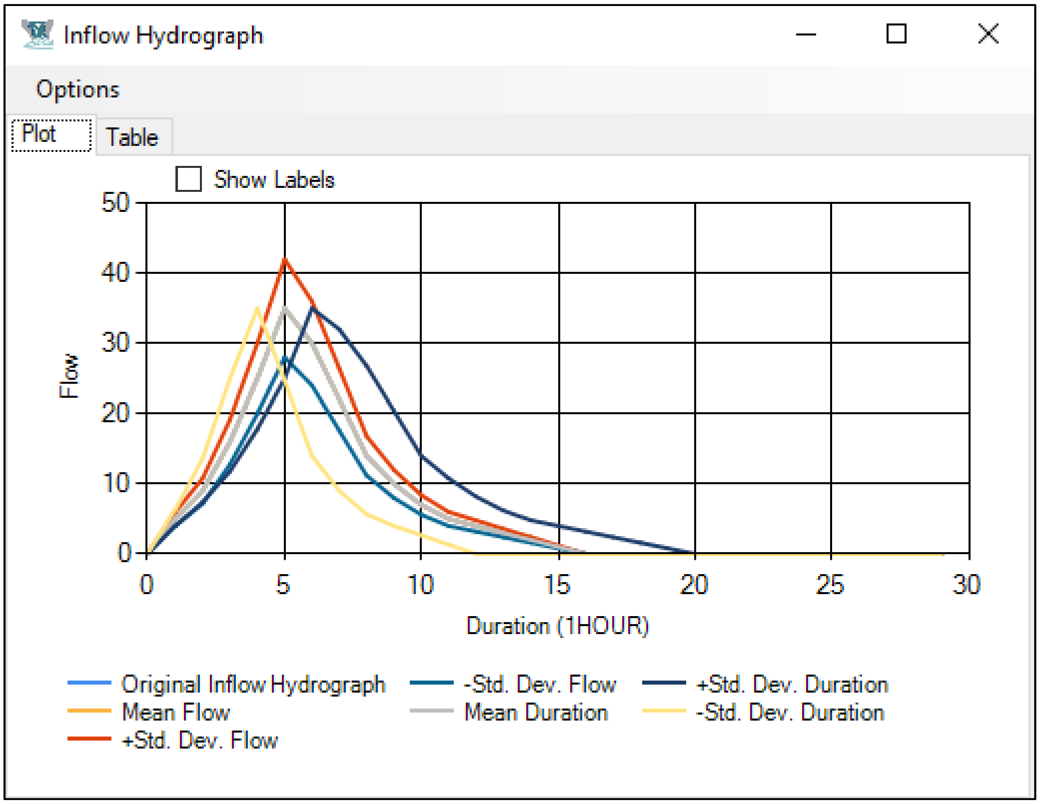


Figure 10. Inflow Hydrograph Distribution

Output Menu

The Output menu contains four plots and one table for evaluating output (Figure 11). The plot window contains a Table tab for viewing tabular data. The values in the table can be selected by clicking and dragging over a range of values. Once highlighted, the selected values can be copied by pressing the Ctrl and the C keys simultaneously on the keyboard (Ctrl+C), which stores them in the Windows™ Clipboard. They can then be pasted into another software application (i.e. spreadsheet program) by pressing the Ctrl and V keys simultaneously (Ctrl + V).

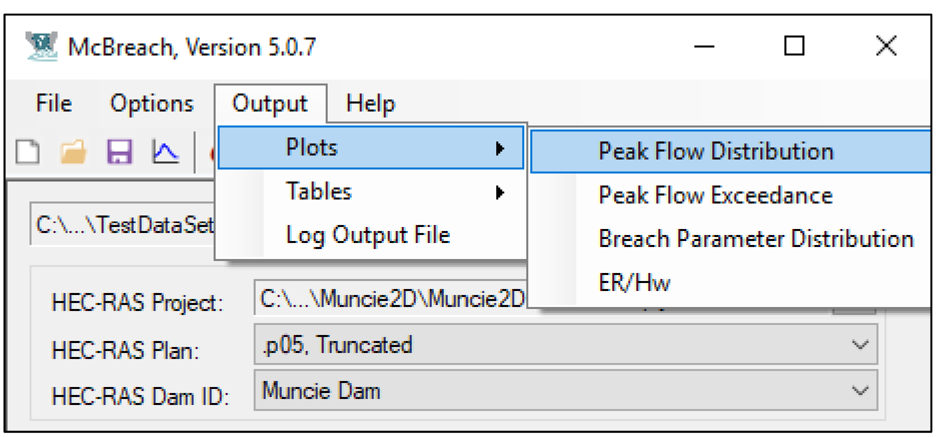


Figure 11. The Output Options

Peak Flow Distribution Plot. Peak Flow Distribution produces a histogram plot grouping peak flow discharges as shown in Figure 12. The values are read directly from the *.mcb.outQ file located in the same directory as the McBreach project file. Should the *mcb.outQ file not exist, the user must run McBreach to produce the file.

Ideally, with enough realizations and a small enough bin interval, the Peak Flow Distribution plot should resemble a normal distribution and is typically slightly skewed to the right. There will usually be some extreme peak flows returned on the right side of the plot. The values labeled on the x-axis represent the smallest value in that bin. Under the Options menu on the Peak Flow Distribution plot, the user has some control over the look of the histogram plot by changing the bin interval. The bin interval sets the size of each class represented by individual histogram bars. The more realizations that have been run, the smaller the bin interval can be selected and still provide a useful plot. Also provided under the Options menu is the ability to copy the plot to the Windows™ clipboard. There it can be pasted into many different software applications (i.e. word processors, spreadsheets, presentation software).

The Table tab on the upper left of the window provides all of the peak flows numerically in a table format.

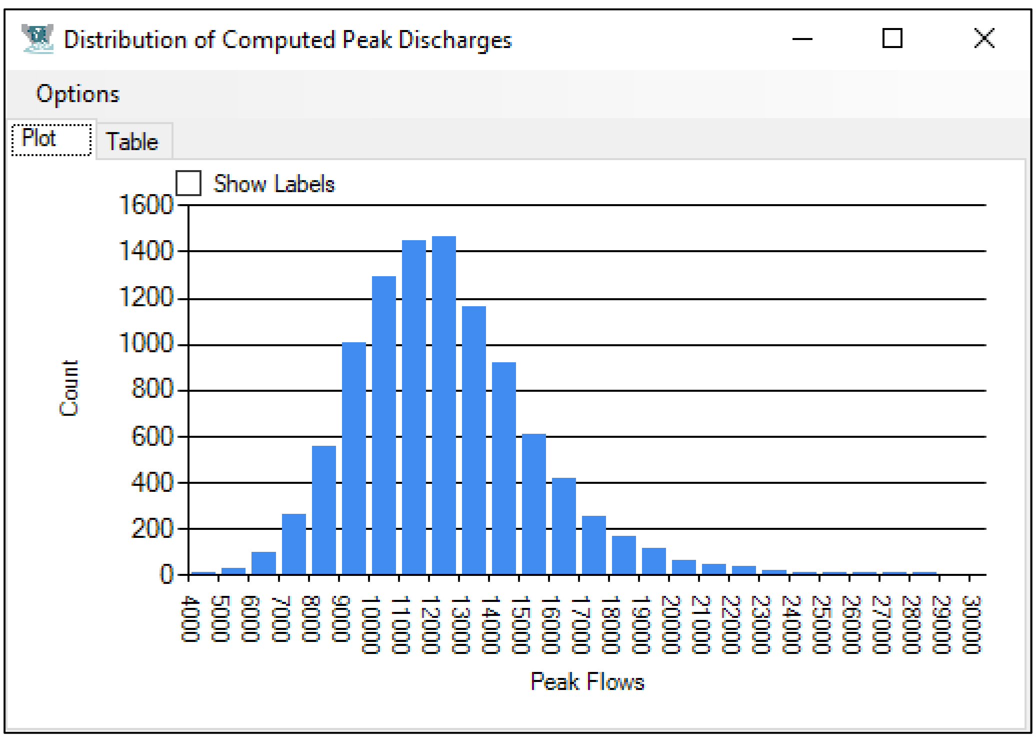


Figure 12. Peak Flow Distribution Plot

Peak Flow Exceedance Plot. Peak Flow Exceedance provides a plot of exceedance probability versus peak flow (Figure 13). The values are read directly from the *.mcb.outQ file located in the same directory as the McBreach project file. Should the *mcb.outQ file not exist, run McBreach to produce it. The Table tab displays a table of selected exceedance probabilities and their respective peak flows.

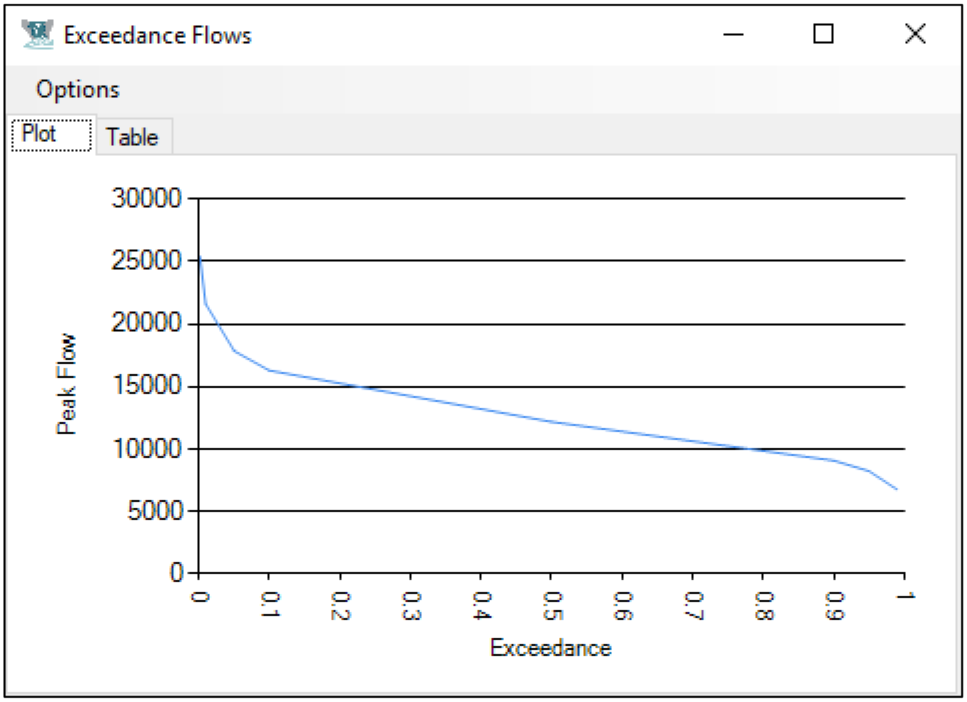


Figure 13. Exceedance Flows

Breach Parameter Distribution Plot. Opens a plot that displays the distribution of all sampled breach parameters. The dropdown box on the right allows the user to view each of the breach parameters. With enough realizations, the distribution plot should follow the same shape as the selected distribution.   If the distribution plot does not follow the shape of the selected input distribution, that is a good indication that more realizations is needed. Figure 14 demonstrates a distribution plot of breach bottom widths, using a lognormal distribution.

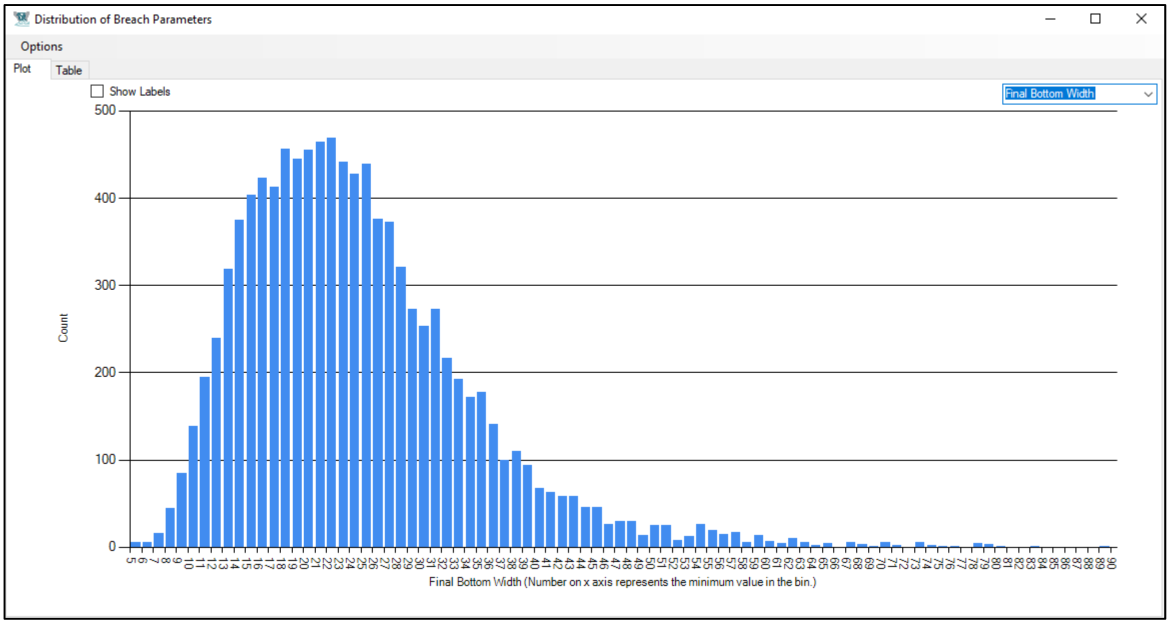


Figure 14. Breach Parameter Distribution Plot

ER/Hw Plot. Opens a plot that shows the relationship between erosion rate (ER) and the Headwater (HW) for every realization. The erosion rate is defined by Von Thun and Gillette (1990) as the average breach width divided by the breach formation time (B_{avg}/Tf). Expanding upon Von Thun and Gillette, the State of Colorado Guidelines for Dam Breach Modeling (Colorado 2010) suggests a minimum ER/Hw of 1.6. If ER/Hw is less than 1.6, then either the failure time or the breach width should be adjusted until ER/Hw is greater than 1.6. McBreach provides a warning if more than 5 percent of the sampled breach parameters produce an ER/Hw relationship less than 1.6. Colorado (2010) also suggests a maximum ER/Hw of 21. If the ER/Hw is greater than 21 then the user should reconsider the selected breach parameters. McBreach provides a warning if more than 5 percent of the sampled breach parameters produce an ER/Hw greater than 21. Figure 15 provides an example ER/HW plot. Notice that more than 5 percent of the ER/HW samples are less than 1.6. In this case, ER should be increased by either increasing breach width (B) or decreasing the formation time (Tf).

This plot requires the use of the “starting WS elevation for failure initiation” breach parameter (Init). If the user selects formation time to be computed from sample erosion rates, McBreach will use the sampled erosion rate for this plot.

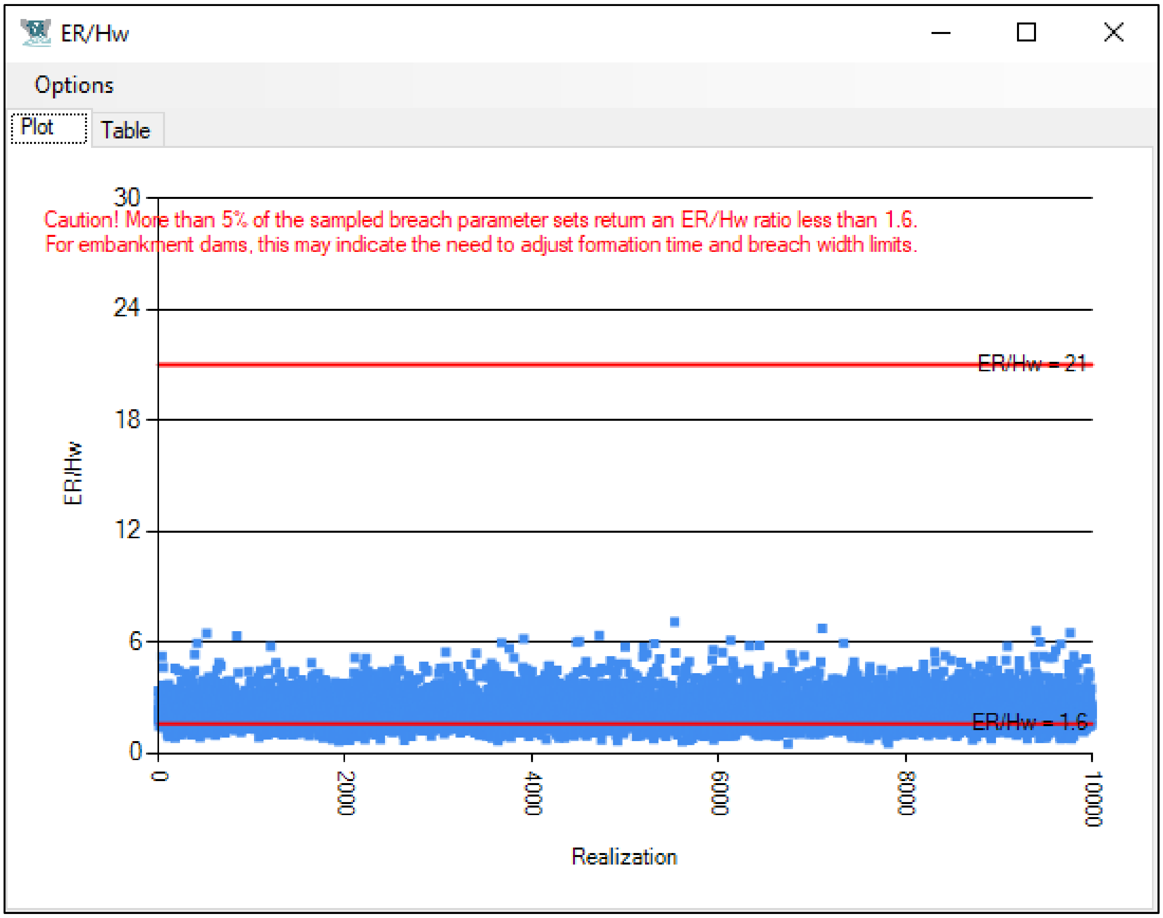


Figure 15. Erosion Rate to Headwater Depth (ER/Hw) Ratio

This method should only be considered for earthen embankment dams. Every dam is different, and it is up to the user to determine if the ER/Hw evaluation as presented by State of Colorado (Colorado 2010) is appropriate to use.

EP Breach Parameter Sets Table. The Exceedance Probability (EP) Breach Parameter Sets Table produces a summary table of the EP peak discharges, the realization where that peak discharge occurred, and the breach parameter sets that produced each peak discharge in the Monte Carlo exercise. All data presented in this table is extracted from the McBreach log output file (*.mcbLog.out). This table provides a convenient way to establish plans for specific EP breach simulations, rather than searching the log output file. Figure 16 provides an example EP Breach Parameter Sets Table.

	0.2% User	1%	5%	10%	50%	90%	95%	99%
Realization #	3624	4161	3669	9456	6161	5472	8338	5194
Peak Discharge, m^3/s	149.13	134.17	115.36	106.51	77.33	51.23	45.13	35.64
Invert El., m	286.63	286.61	286.34	286.39	286.66	286.68	287.31	287
Bottom Width, m	71.21	68.49	51.82	55.07	42.77	21.68	44.97	17.93
Left Side Slope, m/m	1.29	1.83	0.71	0.99	1.23	1.02	0.96	1.09
Right Side Slope, m/m	1.13	0.65	0.78	1.37	1.35	1.08	1.13	1.47
Formation Time, hr	0.27	0.25	0.54	0.52	0.55	0.48	0.47	0.45
Initiation, m	288.1	288.1	288.1	288.1	288.1	288.1	288.1	288.1
Discharge Coeff.	1.75	1.53	1.52	1.55	1.31	1.31	1.36	1.5
Progression	Sine	Linear	Sine	Linear	Sine	Linear	Linear	Sine
Failure Mode	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping	Overtopping
Piping Coeff.								
Initial Piping El., m								
Flow Multiplier	0.66	1.2	0.65	0.63	0.73	1.41	0.92	0.96
Flow Duration Multiplier	1.01	1.19	1.28	0.98	0.68	0.88	0.69	1.24
Peak Inflow Value, m^3/s	23	42	23	22	26	50	32	34

Figure 16. EP Breach Parameter Sets

View Log Output File. Selecting this option will open a window displaying the log output file created after a McBreach simulation. The log output file is simply a copy of the computation window output. It is stored in the McBreach project directory and has the extension .mcbLog.out. This file can also be viewed in any text editor.

Help Menu Item

The Help menu includes an About window that presents basic information about the McBreach software. It also provides a convenience link to the User's Manual.

Shortcut Buttons

At the top of the McBreach window, there are several short cut buttons for the more commonly used features. The shortcut buttons are presented in Figure 17.

Figure 17. McBreach Shortcut Buttons

New

New will clear all the input boxes and start a new McBreach project.

Open McBreach

Opens a Windows™ file-open dialog to search for and open an existing McBreach project. Opens files with the *.mcb extension.

Save

Saves the current McBreach project to the *.mcb file.

Inflow Hydrograph Statistics

Opens the optional Inflow Hydrograph Statistics window. This allows the user to randomly sample scaling factors about statistical distributions for both inflow hydrograph magnitude and duration.

Standard Deviation Help

Opens a help window to assist in determining the standard deviations to use for normal distributed breach parameters (Figure 18).

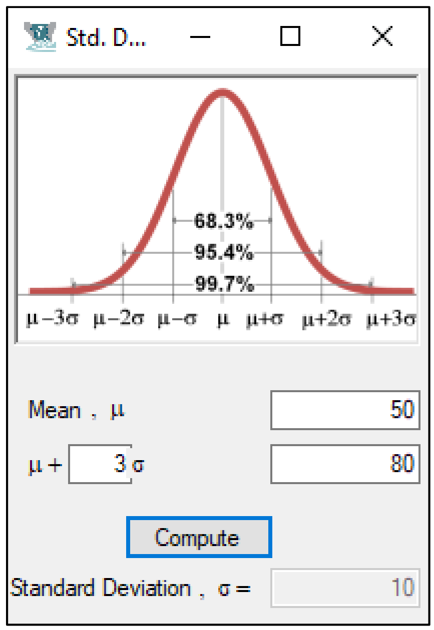


Figure 18. Standard Deviation Help Window

Enter the mean value for the breach parameter. In the μ + __σ input box, enter a value that defines the confidence range of the sample set (typically use a value of 2 or 3). Two standard deviations represent 95.4 percent confidence in the defined range, three standard deviations represent 99.7 percent confidence. Selecting the Compute button returns the standard deviation value to use in the statistical inputs window for the normally distributed breach parameter.

Open the Associated HEC-RAS Project

Opens up the associated HEC-RAS project for viewing and/or editing. Make sure to save and close HEC-RAS before computing McBreach.

VI. Truncated HEC-RAS Model

Running HEC-RAS in a Monte Carlo exercise requires many thousands of realizations to achieve statistical convergence of the mean and standard deviation (and skewness and kurtosis, if desired). McBreach produces plots of computed mean, standard deviation, skewness, and kurtosis of the computed peak discharges to help the user determine if convergence has been met (see Section VII. Theory for more information). Ten thousand realizations are generally a good first start for a typical dam breach model. If the HEC-RAS dam breach model takes one minute to run (this is certainly within a normal range), then a 10,000 realization Monte Carlo analysis would take nearly seven days to complete! To make probabilistic dam breach modeling convenient, the user should target it as an overnight exercise. While this is not always possible for every HEC-RAS dam breach model, most HEC-RAS dam breach models can be truncated to run fast enough to make McBreach an overnight exercise. A good target would be to get an individual realization's run time down to five seconds or less. Five seconds at 10,000 realization is just under 14 hours. That certainly falls within the realm of an overnight exercise. Because McBreach is fully automated, it can be set to run at the end of the day, and it will be finished the next day.

The truncated version of the model is only needed during the McBreach simulation, when it is running thousands of realizations. After McBreach is finished, the user can replicate the breach parameter sets for the EP peak flows, put them in the full model and map the inundation extents for them. This will typically only be five or six breach parameter sets (e.g. 0.2% exceedance probability, 1%, 5%, 10%, 50%).

So how does the user get a HEC-RAS dam breach model that takes minutes or hours to run down to a five second (or less) run time? The following section offers some suggestions for common ways to sufficiently truncate the model:

- Remove the Downstream Reach
  Because McBreach obtains peak flows from the dam that is being breached, there is no need for routing the reach downstream of the dam for the probabilistic runs.

  If the geometry downstream of the dam is a 1D reach, remove all of the cross sections in that reach except for a few just below the dam; enough to provide an accurate tailwater condition. The number of cross sections needed depends on the steepness and conveyance of the reach, the discharge and the height of the dam. A good starting point is to leave enough cross sections to span a length of approximately five main channel widths. To verify if there are enough cross sections, run several dam breach simulations with varying sets of breach parameters with both the truncated and full models. Compare the discharge hydrograph computed with the truncated versus the full model. If they are different, then either adjust the downstream boundary condition or return some cross sections to the truncated model to extend the downstream reach a little more. Figure 19 and Figure 20 show a full and truncated 1D model.

  If the geometry downstream of the dam is a two-dimensional (2D) area, the user has two options for truncating. The first option is to remove most of the 2D area downstream of the dam and leave a small area below the dam to set up a good tailwater condition. The second option would be to replace the downstream 2D area with a 1D reach in the truncated model. Both options require the user to verify the tailwater condition for a wide variety of breaches as previously discussed. Figure 21 and Figure 22 provide a full and truncated 2D model.

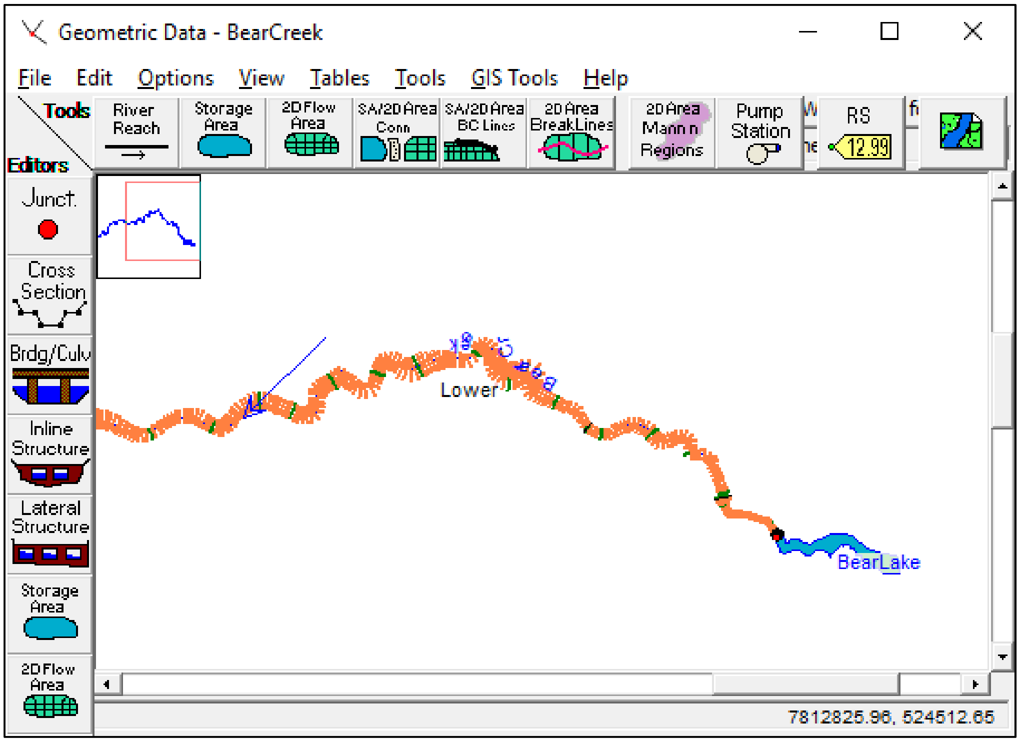


Figure 19. Full Model Geometry for Bear Lake

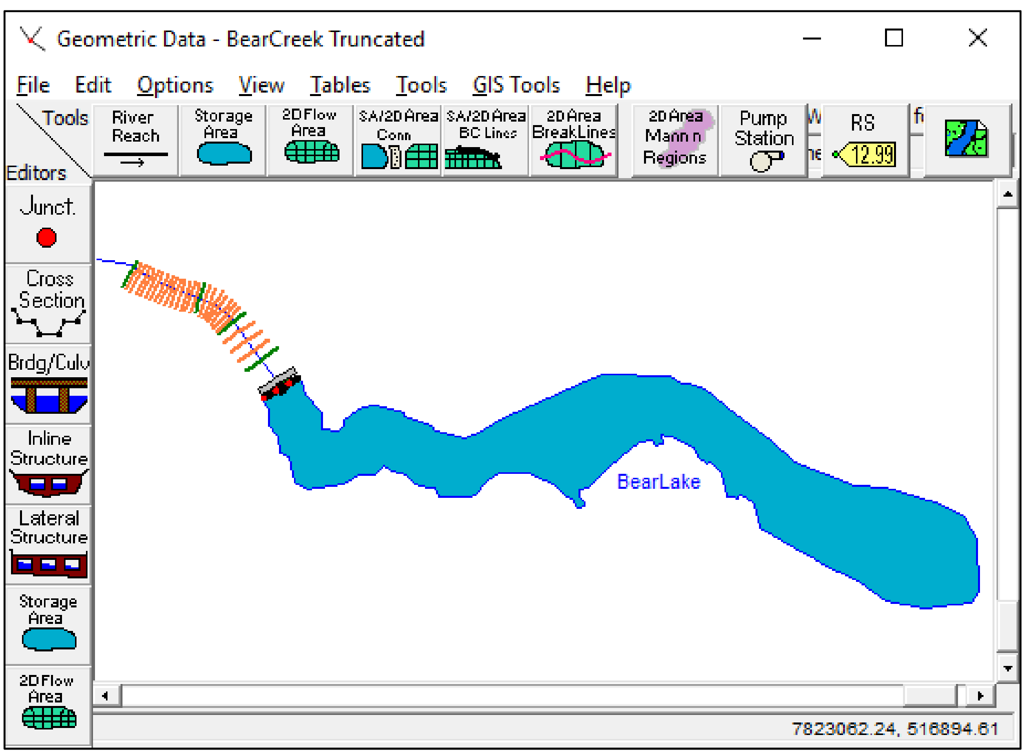


Figure 20. Truncated Model Geometry for Bear Lake

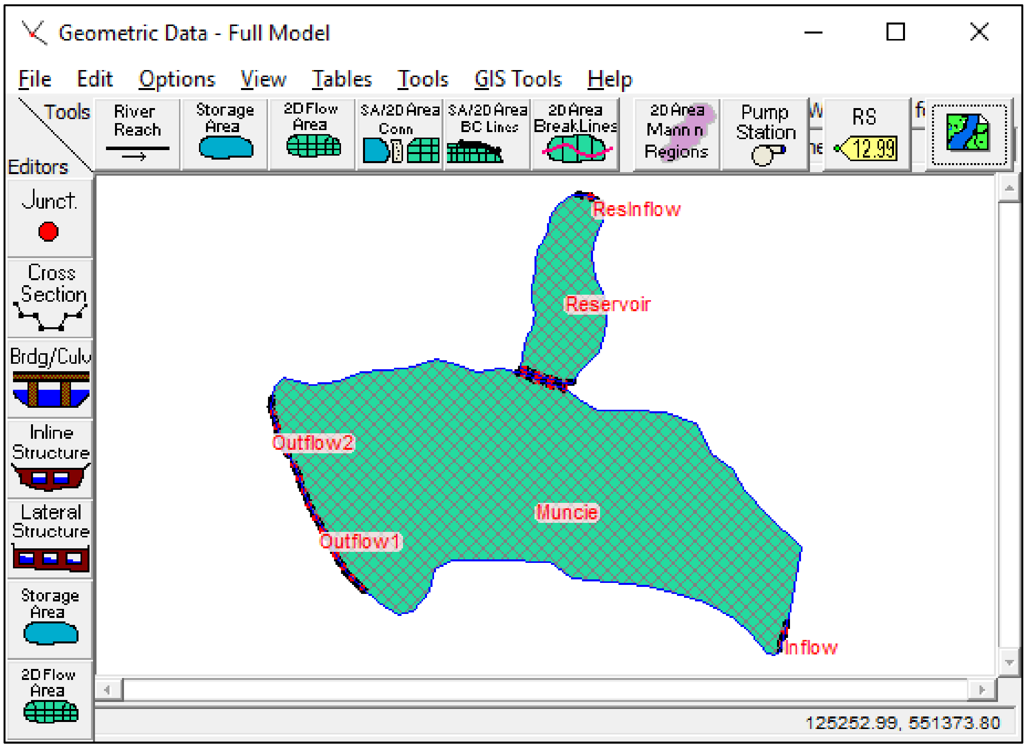


Figure 21. Full Model for Muncie 2D Dam Breach

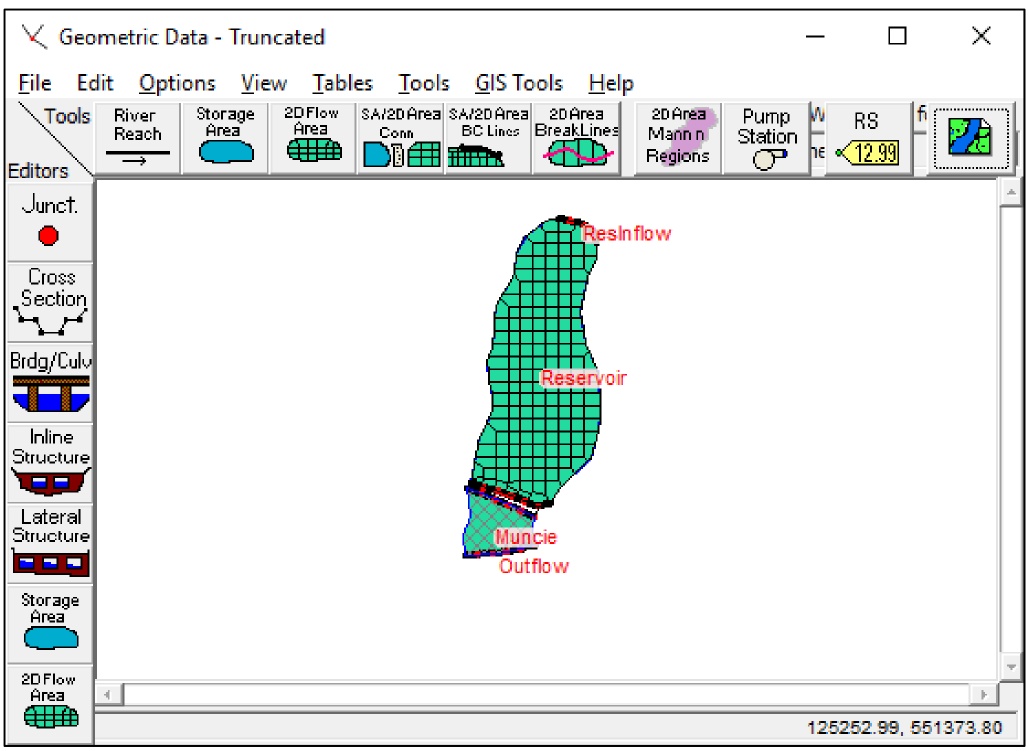


Figure 22. Truncated Model for Muncie 2D Dam Breach

- Uncheck Post-Processing
  McBreach reads peak flows from the plan hdf file, not the output file. The plan hdf file is created after the unsteady flow computations are completed, but before post processing begins. Therefore, it is not necessary to have post processing checked as a program to run, when running the McBreach simulation. This can significantly reduce the overall simulation time of each realization.

- Increase the Computation Interval
  With a large portion of the downstream reach removed, it is likely the user can increase the computation interval and still maintain numerical stability in the truncated model. **Be careful**! Because the model is stable, does not mean it is computing correctly. When increasing the computation interval, it is important to verify that both the truncated and full models produce the same dam breach hydrograph for a variety of breach parameter sets (within reason). If they are different, try reducing the computation interval until the full model and the truncated model produce similar dam breach hydrographs.

- Use Diffusion Wave Equation Set
  If a 2D downstream reach is being used, consider using the Diffusion Wave equation set for the 2D areas of the truncated model. The Diffusion Wave equation set runs much faster and is less prone to generate errors than its Full Momentum counterpart. Make sure that the truncated model still replicates the full model's breach outflow hydrograph for a range of dam breach parameter sets.

- Trim the Simulation Time
  Because McBreach only reads peak discharges from the breach hydrograph at the dam, the simulation only needs to be long enough to capture the peak of the breach hydrograph. The remainder of the simulation can be trimmed to reduce computation time. Make sure to run a simulation in the full model with the highest possible breach formation time that may be sampled during the Monte Carlo process. Examine that breach hydrograph at the dam location to determine t the simulation time can be trimmed. This simulation is demonstrated in Figure 23.

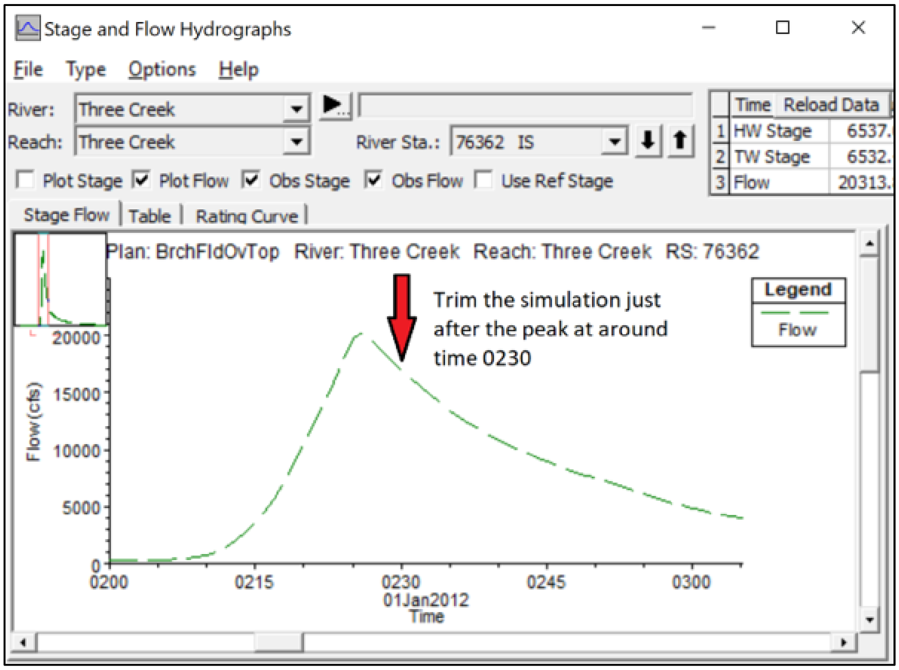


Figure 23. Dam Breach Hydrograph for Full Model.

Note: Simulation time to the right of the red arrow is not necessary for the truncated model.

VII. Theory

Monte Carlo Method

McBreach uses the Monte Carlo Method to determine EP for peak flow rates from dam breach events. The Monte Carlo Method was developed in the 1940s during nuclear weapons research (Goodell 2012). Its applications are far and wide, ranging from economics, to engineering, and to gaming. The Monte Carlo Method works by randomly sampling input values to a mathematical solution and solving for the outcome over and over until the probability of a specific outcome converges on a single value. Each solution in a Monte Carlo Method experiment is called a realization.

The coin flip is perhaps the most basic analog for demonstrating the Monte Carlo Method. It is known that the probability of getting heads or tails when flipping a coin is exactly 50 percent. However, it is also quite plausible that if one were to flip a coin five times, the result may be one-head and four-tails. In that case, the result was 20 percent heads and 80 percent tails. Or maybe two-heads and three-tails. Etc., etc. But the probability of getting either heads or tails is still 50 percent for each and every coin flip. And if the coin was flipped enough times, the result would be exactly 50 percent heads and 50 percent tails. The exercise of flipping enough coins so that the outcomes ultimately define the probability is the theory behind the Monte Carlo Method.

In dam breach modeling, much more input is being used than with a binary coin flip. Except for breach progression, none of the breach parameters are binarily and discretely distributed like a coin, but rather follow a continuous normal distribution, or a uniform distribution; maybe even a triangular or lognormal distribution. Instead of one input parameter (i.e. the coin flip), there are eight breach parameters in McBreach when simulating an overtopping breach event and ten breach parameters when simulating a piping event. Each breach parameter must be randomly sampled about a user-defined statistical distribution. So, while demonstrating statistical convergence for a coin flip may require tens or hundreds of flips (to a fairly precise level), demonstrating statistical convergence for a peak flow from a dam breach event can take thousands or tens of thousands of model simulations.

In most HEC-RAS dam breach models, statistical convergence in a Monte Carlo Method run requires between 5,000 and 10,000 realizations-a realization being a single HEC-RAS simulation. This can be demonstrated with the following plot that shows convergence on the mean and standard deviation of peak dam breach outflow (Figure 24). It is recommended that a McBreach simulation use 10,000 realizations, but that the user would evaluate statistical convergence to ultimately determine the correct number of required realizations. Viewing the statistics during the McBreach run can help determine the required number of realizations.

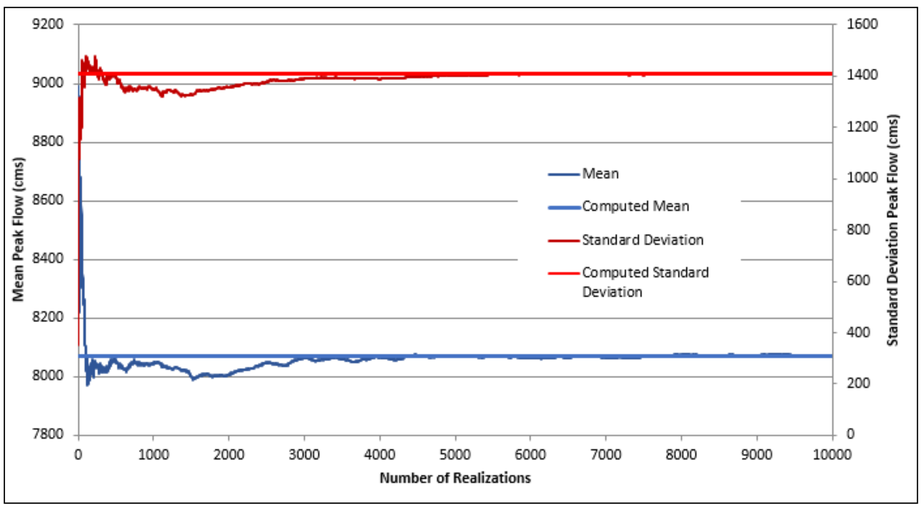


Figure 24. Statistical Convergence of Mean and Standard Deviation of Peak Dam Breach Outflow

Statistical Distributions

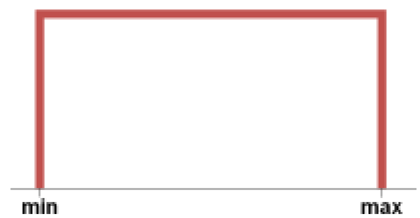
The statistical distributions guide McBreach's random sampling of the breach parameters. The distributions define a parameter's central tendency, its variance, and even its upper and lower bounds. There is very little known about the true statistical distributions of breach parameters. There has been little research here; however, knowledge of site conditions and some common sense can lead to good approximations of the distribution of any breach parameter. Froehlich (2008), Wahl (2001) and Ahmadisharaf et. al. (2016) discuss breach parameter uncertainty.

McBreach Version 5.0.7 has four statistical distributions from which to choose:

Uniform Distribution

The uniform distribution, also called a rectangular distribution because of the shape of its probability density function (pdf), is a symmetrical statistical distribution that assumes within a defined range, all results have an equally probable chance of occurrence. In other words, there is no central tendency. Between a given minimum and maximum value, there is no information to assume any value is more likely to occur than any other.

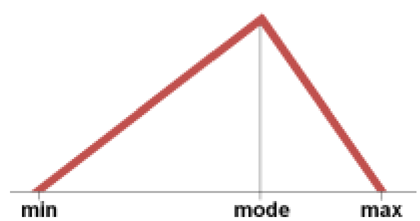
The distribution of the initial piping elevation breach parameter can logically be defined with a uniform distribution. If there is no information on a perceived or known weakness in the dam that could lead to a piping event, then in theory, piping could begin anywhere between the reservoir's water surface elevation and the toe of the dam-and all piping elevations would be equally probable. This represents a uniform distribution.



The uniform distribution in McBreach requires the user input a minimum value and a maximum value to define the range over which values can be sampled.

Triangular Distribution

The triangular distribution is an asymmetric distribution that defines a central tendency. The central tendency (or assumed highest probability value) is defined as the mode of the sample set. The mode is the value that most frequently occurs. An advantage of the triangular distribution is its inherent minimum and maximum values. The tails do not extend to infinity as with a normal distribution. Therefore, if we have information about an absolute minimum or maximum value for a given breach parameter, those values can be directly assigned to the triangular distribution without abrupt truncation. Another advantage is its ability to present a skewed distribution. This can be very important for smaller breaches or faster forming breaches, where the distribution may be positively skewed because of a zero-value limitation (i.e. it is impossible to sample less than zero).



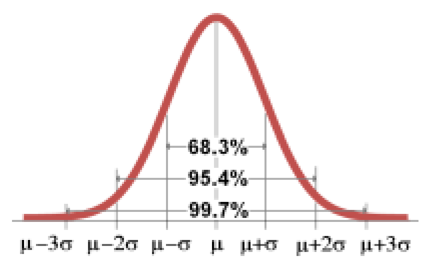
A disadvantage of the triangular distribution is its tendency to oversample towards the extremes of the range and under sample near the central tendency. While triangular distributions are simple to use, they are not typically representative of random sampling with a central tendency.

The triangular distribution in McBreach requires the user to input minimum and maximum values, as well as a mode. The mode might represent an average of all computed breach widths from a range of breach width parametric equations.

Normal Distribution

The normal (or Gaussian or bell-shaped) distribution is a very commonly used symmetric distribution that defines a central tendency. A normal distribution accurately represents an uncertainty distribution for many of the natural phenomena found in science. The central tendency (or assumed highest probability value) is defined as the mean, μ, of the sample set. The range of results is defined by the standard deviation, σ. Any breach parameter that can be assumed symmetric about a central tendency, can be well defined by a normal distribution.

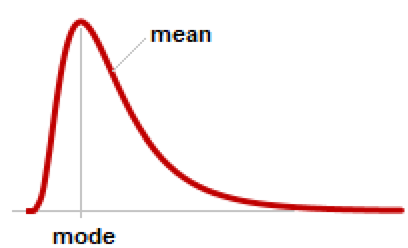
The normal distribution requires the user to enter a mean and standard deviation. The mean may represent an average of all computed breach widths from a range of breach width parametric equations. It may also represent the user's best assumption of the breach weir coefficient. The standard deviation can be backed out from the confidence range. Example: suppose the user has an average breach width of 20 meters and confident to 99 percent that the breach width would not be more or less than 10 meters from the average (i.e. between 10 and 30 meters). Because +-3σ represents 99.7 percent of expected samples, the user could assign 3σ = 10 meters, which results in a σ of 3.33 meters.



The normal distribution can also be truncated with optional absolute minimum and maximum values. These represent the upper and lower bounds of a sampled distribution and allow the user to prevent McBreach from sampling outside of a desired range. For example, a breach width cannot possibly be less than zero. So, while the probability of a breach width equaling zero may be very low, in theory, even a negative value could be sampled. Using an absolute minimum value of zero would prevent this. Same thing on the other end of the distribution. There may be bedrock in the foundation that would limit the breach width growth. This width could be assigned as the absolute maximum.

Lognormal Distribution

The Lognormal distribution is a very commonly used asymmetric distribution that defines a central tendency, but also naturally limits sampling to positive values and can be positively skewed. With a lognormal distribution, the random variable's logarithm is normally distributed. The lognormal distribution is used commonly for defining samples in biology and medicine, economics and hydrology, among many other applications.



The Lognormal distribution has the same skewing advantage of a triangular distribution, but without the disadvantage of under sampling near the central tendency or oversampling near the extremes. A lognormal distribution is typically more representative of natural occurrence than is a triangular distribution.

The Lognormal distribution requires the user to enter a mode and a mean. The mode represents the most likely value, while the mean represents an average of the sampled set. The mean must always be greater than the mode for the lognormal distribution and will affect how skewed the lognormal distribution is. An absolute minimum and maximum value can be used as an option, but if the absolute minimum and/or maximum are too close to the mean value, it is possible to oversample on the extremes. When the absolute minimum or maximum are exceeded, McBreach will use the minimum or maximum value.

VIII. Running McBreach

To run McBreach, the user must first have a working and robust HEC-RAS model. For optimized speed during the McBreach simulation, the user should prepare a truncated model. Before running McBreach, ensure the HEC-RAS model can compute the full range of breach parameter sets that it may encounter during the Monte Carlo exercise without going unstable. To accomplish this, the user should run both a minimum flow set of breach parameters, and a maximum flow set of breach parameters (meaning the set of breach parameters that will produce the lowest and highest peak discharges form the breach). Ensure that both the minimum and maximum HEC-RAS plans produce minimal errors and run fast. From there, the user can optionally create a truncated version of the model as discussed in Section 6. Once the HEC-RAS model is ready, the user can proceed to set up and run McBreach.

Setting up McBreach is a six-step process:

1. Save a new McBreach project.
2. Associate the HEC-RAS model, plan and dam that the user wishes to connect with the new McBreach project. If a truncated plan is created, point to that plan.
3. Choose the sampling method (compute or read a sample file), select overtopping or piping, and then set up the statistical distributions for each of the breach parameter tabs. If an overtopping breach is being simulated, the piping breach parameters are not required.
4. Set the sample size and the optional exceedance probability target and press compute.
5. Once computations are complete, open the Exceedance Probability (EP) Breach Parameters table. Create HEC-RAS plans with the full model by copying the breach parameter sets from each of the exceedance probability results in the table and pasting into each HEC-RAS plan's respective breach parameter editor.
6. Rerun the full model plans to obtain breach output and mapping for each of the EP breach parameter sets.

When Compute is selected, the Computation Window will pop up showing a constant stream of text messages that inform the user of the McBreach simulation progress. The first information displayed in the Computation Window will be the results of the sampled breach parameters (Figure 25). To help ensure statistical convergence, the user should run enough samples so that the input statistics and the computed statistics are close to the same. For example, the computed mean should be the same (or close to it) as the input mean. The same applies for standard deviation. If the input and computed means (or standard deviations) are too far apart, the user should run a larger sample set.

Following the breach parameter sampling results, McBreach will begin displaying the results of each realization, one at a time (Figure 26). While the messages are scrolling through for each realization, the user can review the sampled breach parameters and resulting peak breach discharge and ensure the numbers are logical. If something does not appear correct, press the Quit button at the bottom to stop the McBreach run and review the inputs.

Figure 25. Breach Parameter Sampling Results Shown in Computation Window

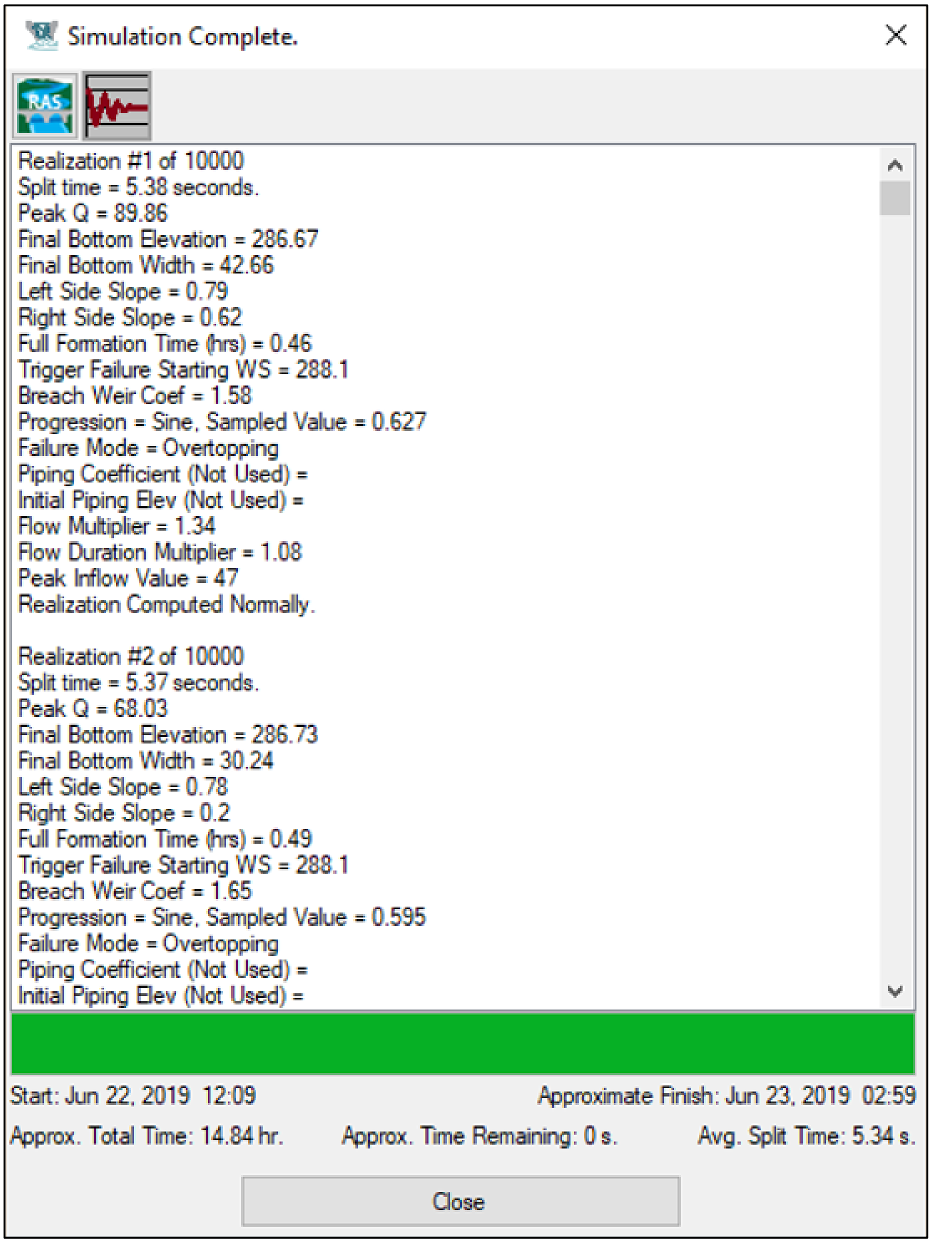
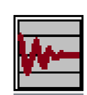


Figure 26. Results of Each Realization Shown in Computation Window



Select the Statistics button (Figure 27) to track the peak outflow statistics (to monitor peak flow convergence). This will allow the user to track the progression of the convergence of the first through fourth statistical moments while McBreach is running. Statistics can be turned on or off anytime during the McBreach simulation.

The four statistical moments are mean, standard deviation, skewness and kurtosis. These four properties define the shape of the resulting distribution of peak flows. Mean will converge first, followed by standard deviation, then skewness and finally kurtosis. The user can view the convergence either by absolute statistics or by percent difference. At the beginning of the simulation, the statistical moments will be bouncing around quite a bit, but after several realizations, the user will see the mean of peak flows begin to settle out at a constant value. Each higher order statistical moment will require more realizations to achieve convergence. Running 10,000 realizations will typically achieve convergence for all four statistical moments.

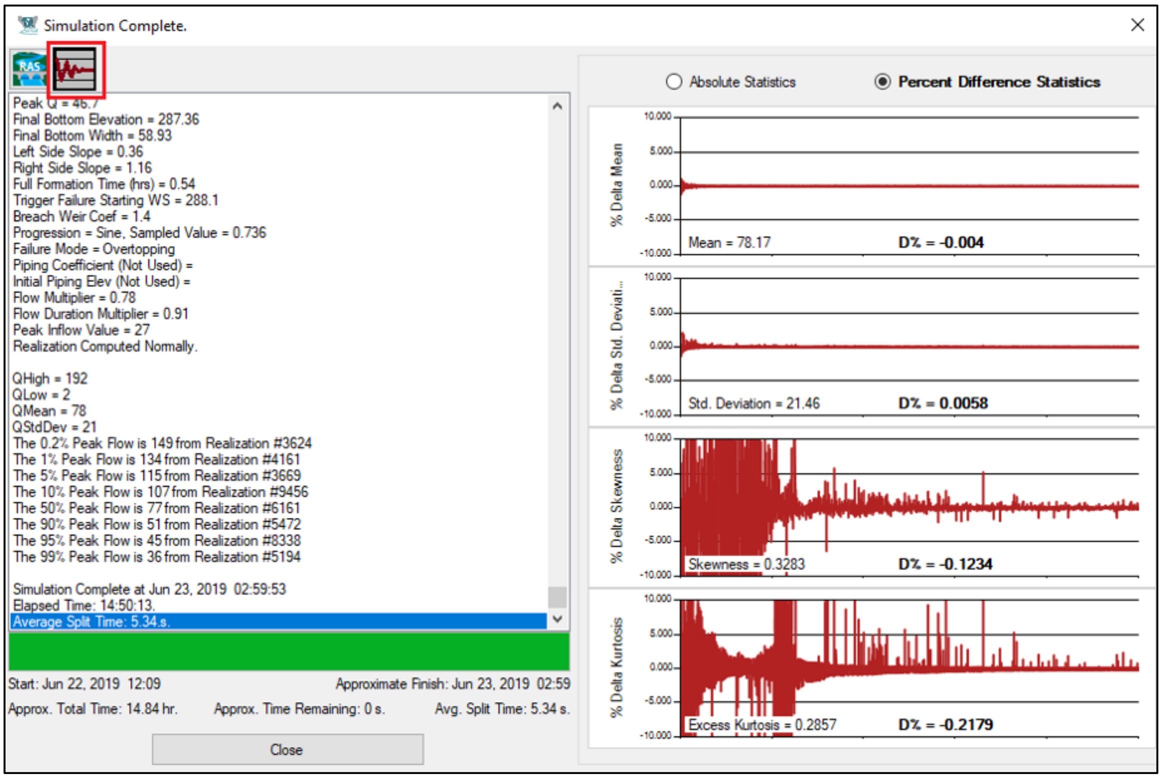


Figure 27. Peak Flow Statistics Monitoring

The HEC-RAS button at the top left of the Computation Window will show HEC-RAS running during each realization. This feature can be turned on or off any time during the McBreach simulation. With it turned on, the user will see HEC-RAS open, run computations and close for each realization. This is a good way to ensure HEC-RAS is computing normally during the McBreach simulation. Click the HEC-RAS button again, and the HEC-RAS computations will resume running in the background. McBreach will run slightly faster with the HEC-RAS computations hidden. It is best to only temporarily view the HEC-RAS computations to verify its computing correctly, then go back to hiding them.

The bottom of the Computation Window will display some information about the timing of the McBreach run. Here the user will view McBreach display the starting date and time of the McBreach run, the approximate date and time of completion, the approximate total time for completion, the approximate time remaining, and the average split time for each realization. These values will be updated after each realization. The more realizations that have been run, the more accurate the timing values will be. After just a few realizations, the user should have a very good idea of how long the McBreach run will take in total.

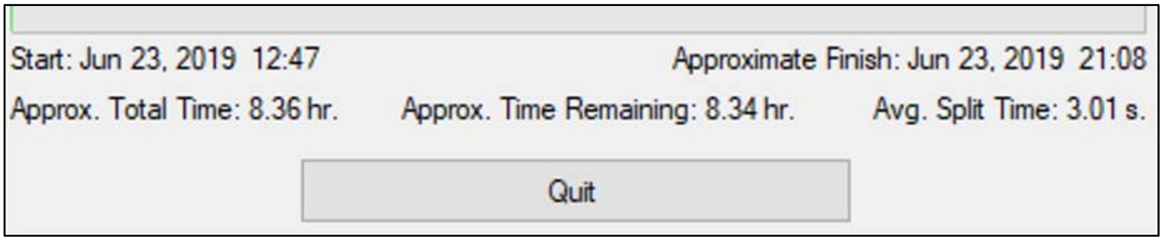


Figure 28. McBreach Simulation Timing

Once the McBreach simulation is complete, the user can close the computation window (it is not necessary). If the computation window is closed and the user would like to view it again, from the main McBreach window, select Output…Log Output File. However, the Log Output File will not show the statistical convergence on peak flow. Therefore, once the user closes the Computation Window the user will not be able to pull up the statistical convergence plots unless the user reruns McBreach.

IX. Troubleshooting

As with any model, if it produces strange results, check the input data. The following are common mistakes that can make McBreach not operate as intended:

- Receive message saying there is already another instance of HEC-RAS open--ensure there are no other HEC-RAS projects open. If it appears that there are none open, then HEC-RAS is running in the background. This typically happens if McBreach abruptly shuts down. The user can remove the other instance of HEC-RAS from your Task Manager. If that does not work, reboot the computer.
- If peak flow results do not change for each realization, it could be that HEC-RAS is producing an error during each run. Try running HEC-RAS on its own. An error message stating that a certain file is inaccessible, means that it is likely open as a zombie in the background of Windows™. A computer reboot will fix this.
- Another reason peak flows might not change in the McBreach output is if the HEC-RAS plan hdf file is open in HDF®View, or otherwise being used external to HEC-RAS during a McBreach run. Make sure the plan hdf file is closed and not being used by another software application while McBreach is running.
- If nothing is seen on an output histogram plot, try changing the bin interval in the Options menu item of the plot.

X. References

<u>NOTE. Not all citations are referenced in the text. However, all of these citations were used in the development of the concepts behind McBreach.</u>

Ahmadisharaf, Ebrahim, Alfred J. Kalyanapu, Brantley A. Thames, Jason Lillywhite (2016). "A probabilistic framework for comparison of dam breach parameters and outflow hydrograph generated by different empirical prediction methods." Environmental Modelling and Software, El Sevier, Ltd. October 18, 2016.

Brunner (2014). "Using HEC-RAS for Dam Break Studies." TD-39, Hydrologic Engineering Center, Davis, CA, August 2014.

Colorado (2010). "Guidelines for Dam Breach Analysis." State of Colorado Division of Water Resources, Dam Safety Branch.

De Lara, P.G.; Goodell, Christopher; Bonumá, Nádia Bernardi (2017). Forecasting of Risk of Flood Cutting Induced by Dams". Proceedings, XXXI National Seminar on Large Dams – SNGB, Brazilian Committee on Dams, Minas Gerais Brazil, May 2017.

Froehlich, D.C. (1987). "Embankment-dam Breach Parameters." Hydraulic Engineering, Proc. 1987 ASCE National Conf. on Hydraulic Engineering, New York, 570-575.

Froehlich, D.C. (1995a). "Embankment Dam Breach Parameters Revisited." Water Resources Engineering, Proc. 1995 ASCE Conf. on Water Resources Engineering, New York, 887-891.

Froehlich, David C. (2008). "Embankment Dam Breach Parameters and Their Uncertainties." American Society of Civil Engineering, Journal of Hydraulic Engineering, Vol. 134, No. 12, December 1, 2008.

Froehlich, David C.; Goodell, Christopher R. (2012), "Breach of Duty (Not): Evaluating the Uncertainty of Dam-Breach Flood Predictions", Proceedings, United States Society on Dams 2012, New Orleans, Louisiana, April 2012.

Gentle, James E. (2010), *Random Number Generation and Monte Carlo Methods*. Second Edition. New York, New York: Spring Science + Business Media, Inc., 2010. Print.

Goodell, C.R. (2012), "A Probabilistic Approach to Dam Breach Modeling", Proceedings of the 2nd European Conference on Flood Risk Management FLOODrisk2012, Rotterdam, The Netherlands, 19-23 November 2012

Goodell, Christopher R. (2013), "Moving Towards Risk-Based Dam Breach Modeling", Proceedings, Dam Safety 2013 Conference, Providence, Rhode Island, September 2013.

Goodell, Christopher (2014), *Breaking the HEC-RAS Code: A User's Guide to Automating HEC-RAS*. First Edition. Portland, Oregon: h2ls Publishing, 2014. Print.

Goodell, Christopher; Raeburn, Roger; Karki, Amit; Johnson, Douglas; Monk, Suzanne; Lee, Aaron (2018). "Probabilistic Dam Breach Modeling using HEC-RAS and McBreach". Proceedings, USSD Annual Conference and Exhibition, Miami Florida, May 2018.

MacDonald, T.C. and Langridge-Monopolis, J. (1984). "Breaching Characteristics of Dam Failures." J. Hyd. Eng., 110(5), 567-586.

U.S. Army Corps of Engineers (2016a). "HEC-RAS Hydraulic Reference Manual, Version 5.0" Hydrologic Engineering Center, Davis, CA

U.S. Army Corps of Engineers (2016b). "HEC-RAS User's Manual, Version 5.0" Hydrologic Engineering Center, Davis, CA

Von Thun, J.L., and Gillette, D. R. (1990). "Guidance on Breach Parameters." Internal Memorandum. U.S. Dept. of the Interior, Bureau of Reclamation, Denver.

Wahl, Tony L. (1998). "Prediction of Embankment Dam Breach Parameters." DSO-98-004, Dam Safety Research Report. U.S. Department of the Interior, Bureau of Reclamation. July 1998.

Wahl, Tony L. (2001). "The Uncertainty of Embankment Dam Breach Parameter Predictions Based on Dam Failure Case Studies." USDA/FEMA Workshop on Issues, Resolutions, and Research Needs Related to Dam Failure Analysis. June 26-28, 2001. Oklahoma City, OK.

Kleinschmidt

June 2019

141 Main Street, Pittsfield, ME 888.224.5942 info@kleinschmidtgroup.com