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Advances in estimating dam breach parameters

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May 2024

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Through our specialist expertise, we're challenging boundaries to deliver advanced infrastructure solutions.

Agenda

- Background
  - ✓ Main breaching components
  - ✓ Methods to estimate breaching parameters
- Recently developed empirical equations and modeling package
  - ✓ Data-Fusion based approach (Azmi & Thomson 2024 - Natural Hazards)
    Azmi, M., Thomson, K. (2024) Dam breach parameters: from data-driven-based estimates to 2-dimensional modeling. Nat Hazards 120, 4423–4461
  - ✓ BREACHER modeling package (ForwardHydro)
    https://forwardhydro.com.au/breach-hydro-product-1
- Conclusion and recommendations

Background

Estimating dam breach parameters: currently a challenging exercise due to

- limited reliable recorded information/databases and
- complex relationships between different elements of a dam breach event;
- high uncertainties (±0.5 to ±1 order of magnitude)
- Public service is not sure about outcomes

Models	Complexity	Accuracy	User friendly	Need of details	Technical support	Modelling length	Purchase & licence	Other maters
Physical & Laboratory								Replicating topography and material Highest costs amongst methods
Computational Fluid Dynamics								Required plenty of reliable information (Geotech, structure and hydraulic) for calibration/validation
Machine Learning								Monte Carlo (e.g. software package McBreach) Artificial Neural Networks, Gene Expression Programming
Empirical Equations (EEs)								Based on statistical and curve fitting methods Lowest accuracy amongst methods

Poor		NA		Excellent

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Background

- Main breaching parameters
  - Failure time in hr (T_f), "breach formation time", time from the onset of formation to the full completion stage
  - Final breach average width (B_{ave}): final breach top and bottom widths along the dam crest
  - Breaching peak outflow ($Q_{br\ out}$): the peak of discharge from breached section
- Empirical Equations (EEs) challenges & shortcomings:
  - Limited data for calibration-validation stages, (from 40 to 180 cases depending on the study)
  - Recorded data used mostly for small dams with height <15m,
  - Failure mode (overtopping or piping)
  - Dam types (rock fill, core wall, homogenous ...)
  - Geotechnical characteristics (i.e. erodibility, additional safety components)
  - High uncertainties in estimations

Motivation behind a new approach

- Low complexity & low uncertainty: Accuracy of machine learning with simplicity of empirical equations
- "Objective" framework: Regardless of experience, practitioners would be able to easily follow steps (at least for initial assessments)

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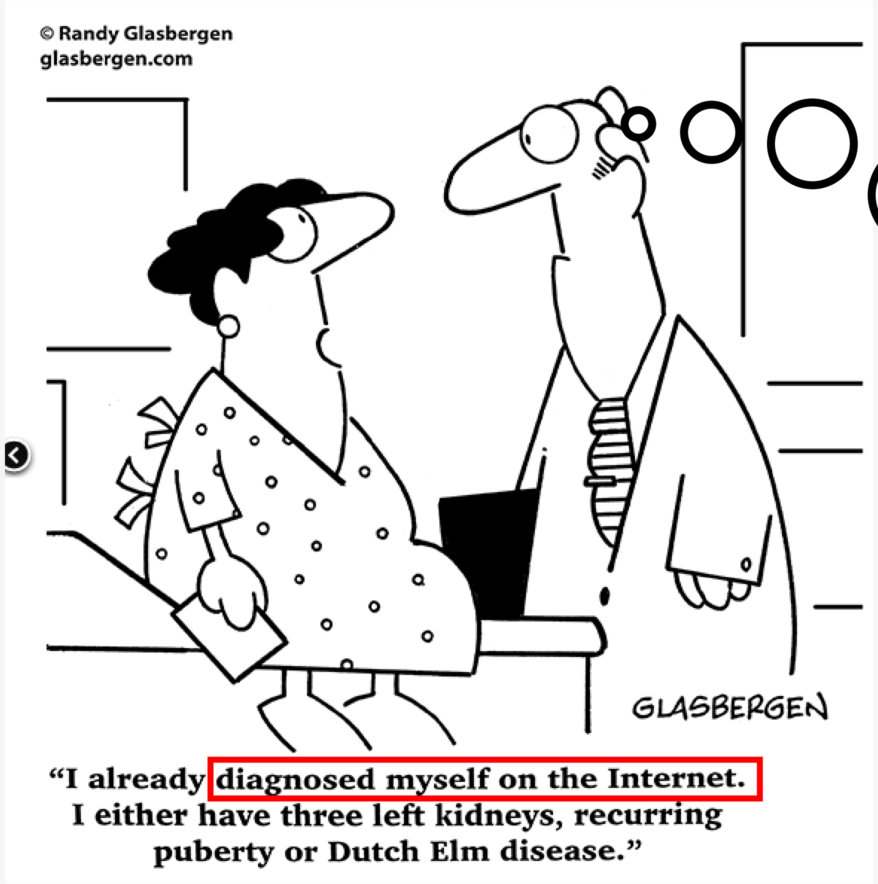
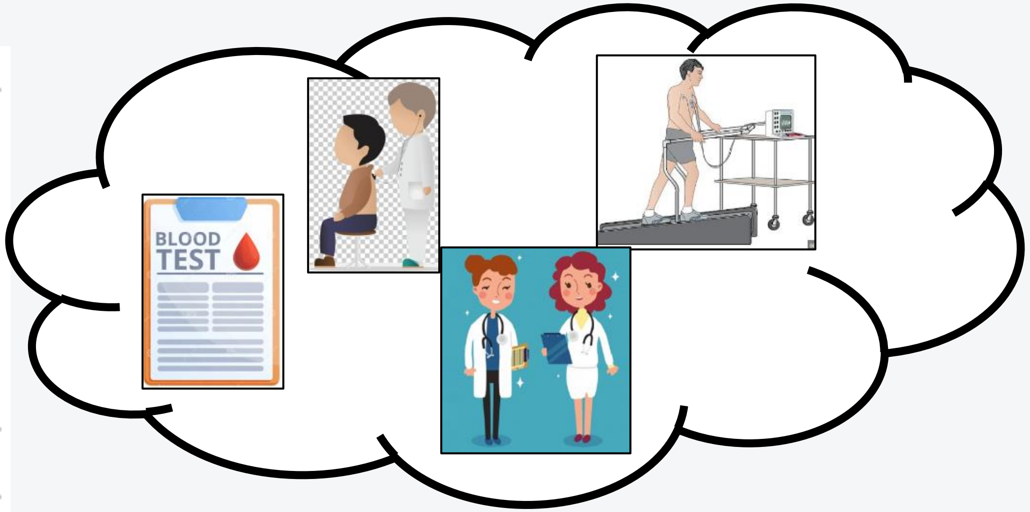
Data Fusion Approach

If a situation or phenomenon is either complex or multiple aspects are directly or indirectly impacting it, attempt to understand it by a single element or method, would highly likely lead to insufficient or incorrect comprehension.





Dambreak and consequence assessment is a complex exercise, requiring to investigate all available data, information and methods to reach the most reliable outcomes

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Proposed Framework – Parameters Estimates

Data Gathering

Historical data: 175 cases from four documents

Filling Missing data: digging into the sources, similar cases

Initial selection of EEs: breaching parameters

Filtering high uncertain cases: outlier cases based on +50% EEs

Subgrouping Cases
G1 & G2: $Q_{obs\ out;}$ G3: $T_{f\ obs}$ G4: $B_{ave\ obs}$

Best Empirical Equations (EEs) Selection

Dendrogram:
EEs outcomes vs observed data

Factor Analysis:
Scree test, Eigenvalues>1 test (***To sufficiently cover the variation of the database***)

Stepwise regression:
"probability of F test", "collinearity diagnosis" "forward selection & backward elimination algorithm"

Linear & Nonlinear (polynomial) regressions between selected EEs vs breaching observations

Fitting Algorithm:
Levenberg-Marquardt (LM) algorithm (Gavin 2019)

Performance Criteria:
Magnitude: RMSE (extreme) , MAE (average)
Association: NSE (extreme) , R^2 (average) , SR (average)

Cross Validation Approach:
Iterations: +100k
80% training, 20% validation

Avoid Overfitting:
Simple models
Cross validation approach

New Equations are called "Data Fusion Based Models" DFM

Outcomes Assessments (individual selected EEs vs DFMs)
Training & Test stages
Entire group data set

Uncertainties Assessments
Based on entire +100k iteration of test stage
Magnitude based evaluation

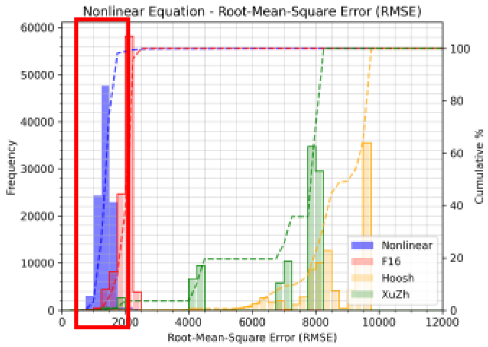
Ultimate Equations for each subgroups (1G to G4)
DFM-L = f (selected EEs)
DFM-NL = g (selected EEs)

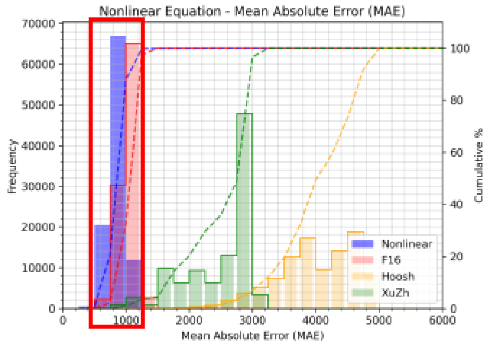
Ultimate DMF Equations

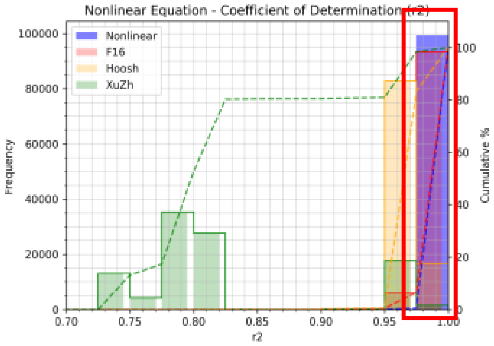
DFM models	Breaching Parameters	Equation *
DFM-L	G1: Q	$Q = 1.23\,F_{16} - 0.84\,H_{14} + 0.26\,XZ_{9}$
	G2: Q	$Q = -1.05\,F_{95} + 2.3\,H_{14} + 0.3\,XZ_{9}$
	G3: FT	$FT = 3.27\,F_{16} - 2.05\,F_{95} + 0.25\,XZ_{9}$
	G4: FBAW	$FBAW = 0.92\,Z_{20} - 0.58\,F_{95} + 1.06\,XZ_{9}$
DFM-NL	G1: Q	$Q = 1.19\,{F_{16}}^{0.97} - 0.81\,{H_{14}}^{0.74} + 1.64\,{XZ_{9}}^{0.8}$
	G2: Q	$Q = -0.81\,{F_{95}}^{0.97} + 1.8\,{H_{14}}^{1.02} + 0.71\,{XZ_{9}}^{0.93}$
	G3: FT	$FT = 3.14\,{F_{16}}^{1.03} - 7.65\,{F_{95}}^{0.35} + 4.8\,{XZ_{9}}^{0.15}$
	G4: FBAW	$FBAW = 0.72\,{Z_{20}}^{1.13} - 0.88\,{F_{95}}^{0.96} + 0.74\,{XZ_{9}}^{1.07}$

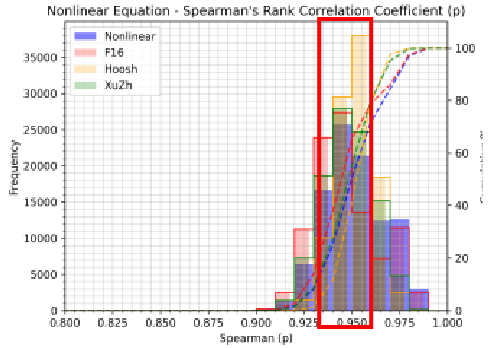
G1: peak outflow for group #1; G2: peak outflow for group #2; G3: FT - failure time; G4: FBAW - final breach average width; DFM: proposed data fusion-based model; F95 and F16 are empirical equations referenced in (Froehlich 1995) and (Froehlich 2016b) respectively; H14 is empirical equation referenced in (Hooshyaripor et al. 2014); XZ9 empirical equation referenced in (Xu and Zhang 2009); Z20 empirical equation referenced in (Zhong et al. 2020).

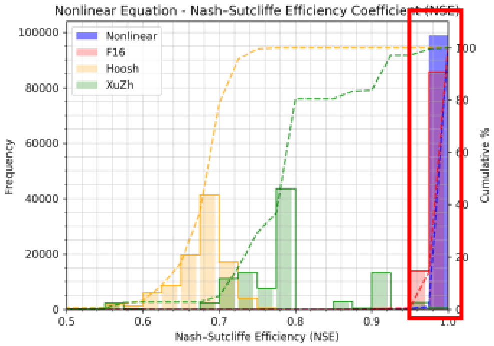
Performance Criteria Histograms for Cross-Validation Approach



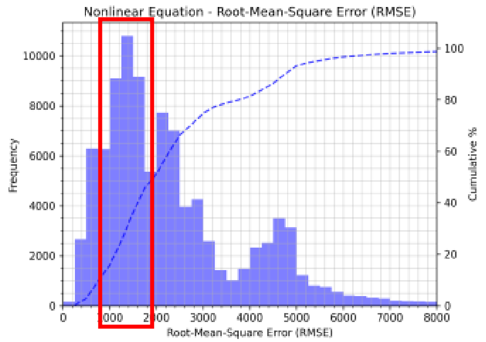


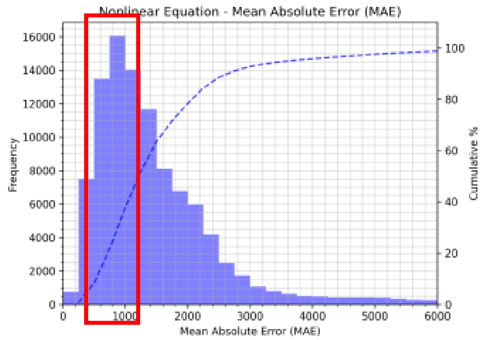


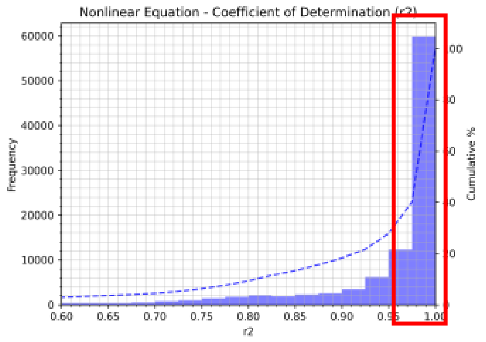


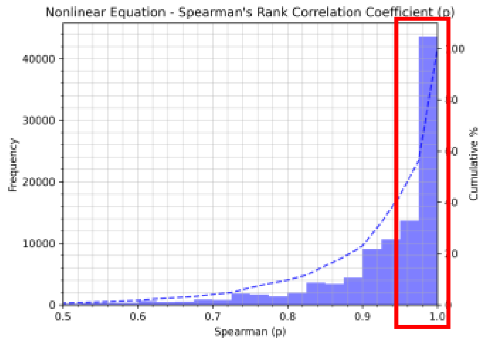


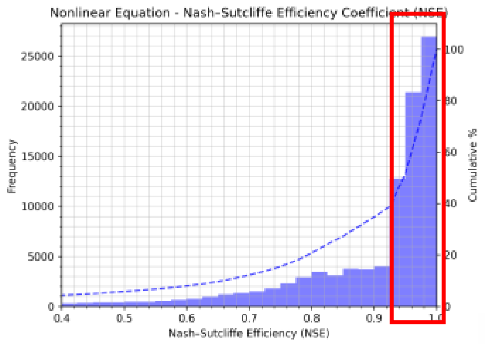
DFM_NL - G1 (Q outflow with Group 1) Training Stage











DFM_NL- G1 (Q outflow with Group 1) Test Stage

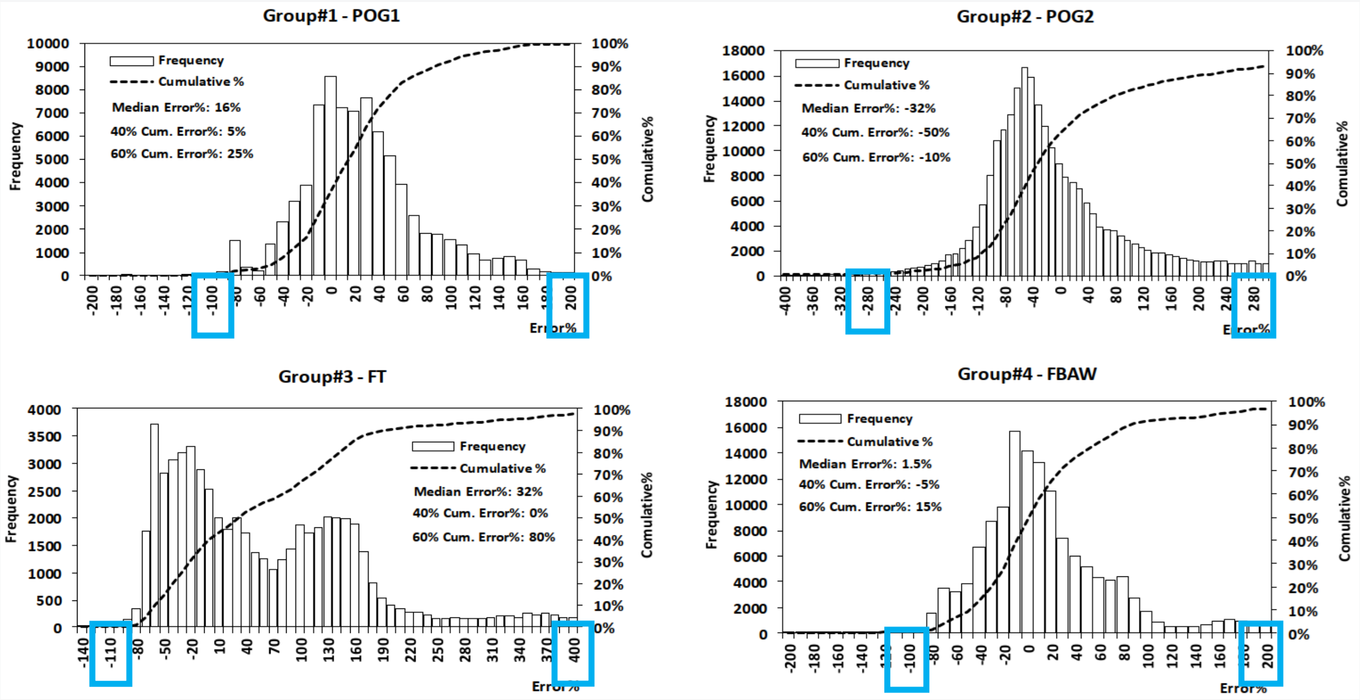
Uncertainties for entire cross-validation 100k iterations

$E\% = 100 \times \frac{X_m - X_O}{X_O}$,
where X_O is observed value and X_m is an estimated value

Positive error percentages show overestimations and negative values present underestimations.

Estimate peak outflow in the worst-case scenario with <0.3 orders of magnitude (±300%), outperforming EEs in literature

DFM for nonlinear equation (DFM_NL)



Uncertainties based on estimates' magnitudes

Breaching Parameters	Categories of Breaching Parameters	Equations	Max range of Error%
G1 Q (m^3/s)	0-1000	$E = 0.00006 \times Q + 0.1494$; (≈15% constant overestimation)	-82% to 134%
	1000-10,000	$E = -0.00003 \times Q + 0.3442$	
	10,000-70,000	$E = -0.0000003 \times Q + 0.0157$; (≈1.6% constant overestimation)	
G2 Q(m^3/s)	0-1000	$E = 0.0004 \times Q + 0.0601$	-99% to 584%
	1000-10,000	$E = 0.000006 \times Q + 0.2435$; (≈24% constant overestimation)	
	10,000-90,000	$E = -0.00004 \times Q + 2.8574$	
G3 FT (hr)	0-1	$E = 0.644 \times FT - 0.5406$	-91% to 110%
	1-8	$E = -0.0302 \times FT - 0.0049$	
G4 FBAW (m)	Entire range (0-350)	$E = 0.0009 \times FBAW + 0.3186$	-76% to 890%

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Framework: from breaching estimates to 2-dimensional model outcomes

i. Estimating Breaching Parameters by DFMs

ii. Calculating Confidence Intervals (magnitude-based uncertainty method – Azmi & Thomson 2024)

iii. Breach weir coefficient (USACE (2014) and HEC-RAS (2016), Lee et al (2019)) (usually between 1.2-1.8)

iv. Determining Breach progression (“Linear” or “Sin Wave”)

v. Breaching side slope of 0 to 1 (USACE 2014)

vi. If no additional geotechnical/hydraulic information, the bottom level of breaching is set as the downstream toe level of the dam (H_d=H_s)

vii. The hydraulic model (e.g. HEC-RAS or TUFLOW) will be run, and the outflow peak will be derived.

viii. Assess breaching <u>outflow peak</u>:

- Within the confidence interval range? Yes, 2-dimensional modeling outcome is acceptable,
- Within the confidence interval range? No, **alterations** on **FBAW**, **FT**, and **weir coefficients** are required

The process of iteration will continue till all breaching parameters including breach weir coefficient are within the desirable range

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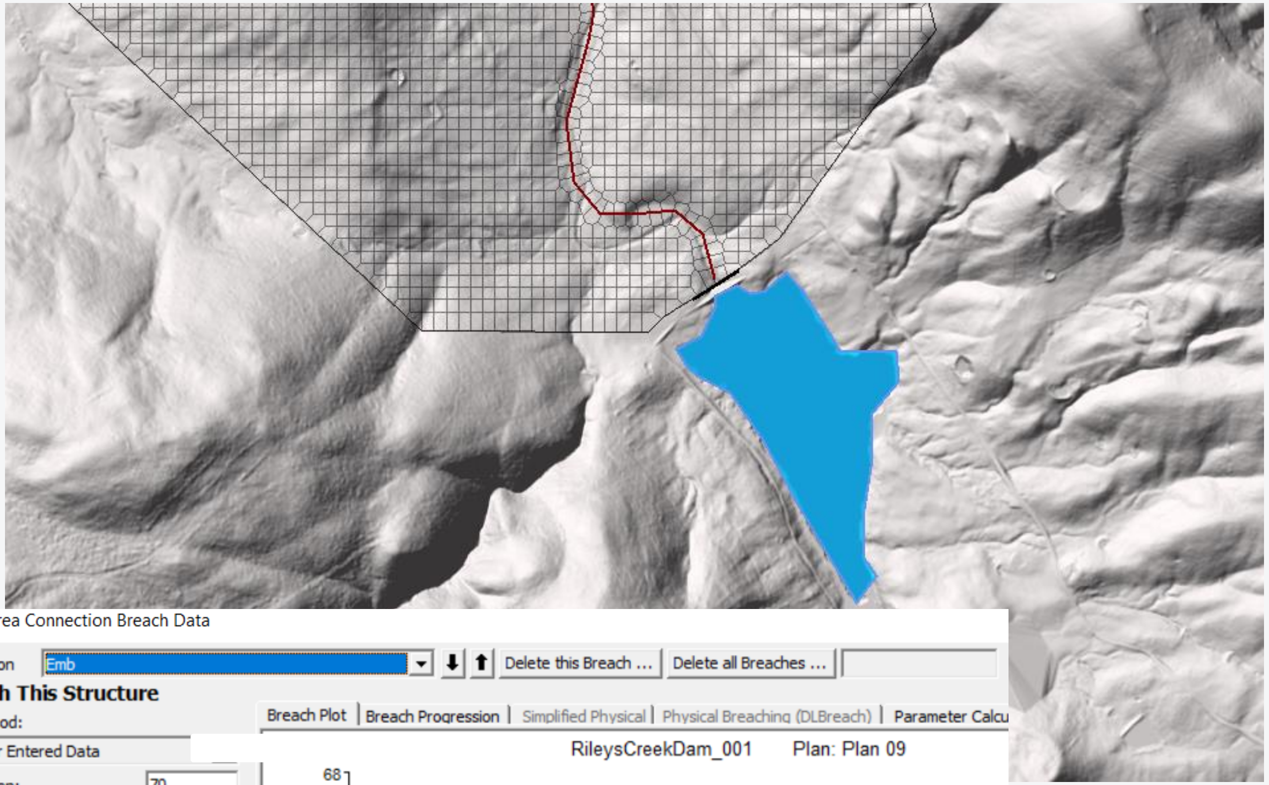
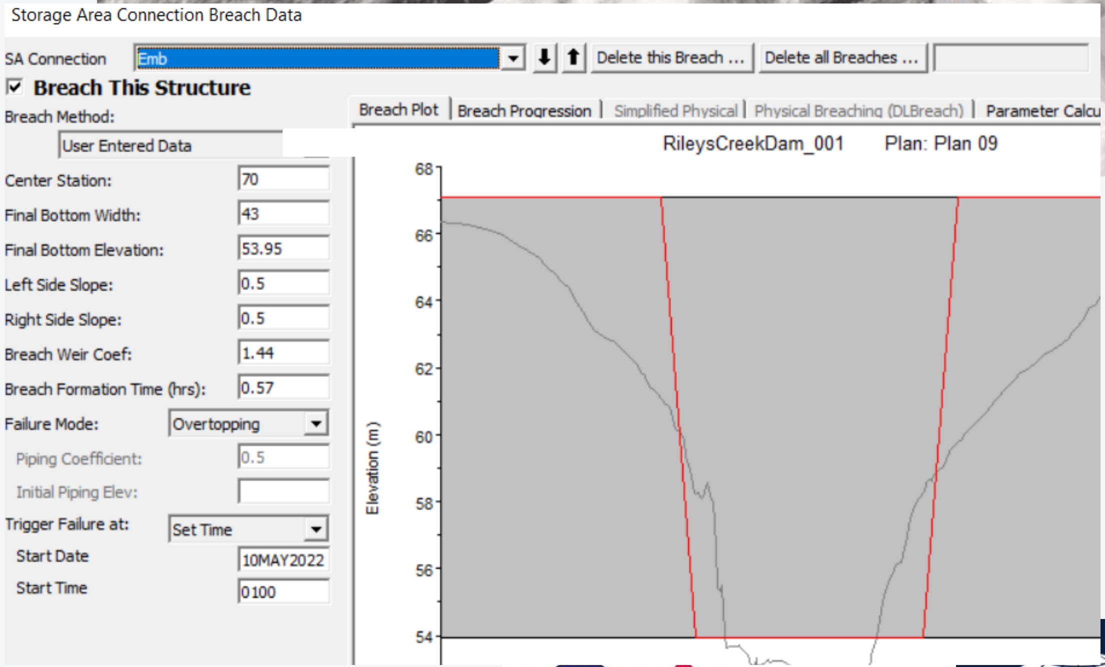
Case Studies

Dam Name	Dam Data in Australia	Breach Parameters Estimates by DFM_NL of G1		
		FT (hr)	FBAW (m)	Outflow (m^3/s)
#1	Zoned earthfill (ZD) Top Embankment=165.65mAHD Embankment Height= 9m DCF volume (ML)=240 Average embankment width=23.47m Top of embankment length=440m	0.66 with 12% underest. 0.66-0.75	28 with 34% overest. 21-28	390 with 17% overest. 333-390
#2	Concrete face rockfill (FD) Top Embankment=67.09mAHD Embankment Height= 13.14m DCF volume (ML)=1660 Average embankment width=19m Top of embankment length=305m	0.57 with 17% underest. 0.57-0.69	49 with 36% overest. 36-49	1793 with 29% overest. 1390-1793
#3	Earthfill (HD) Top Embankment=63.5mAHD Embankment Height= 25.5m DCF volume (ML)=3920 Average embankment width=66.25m Top of embankment length=450m	0.50 with 22% underest. 0.50-0.64	78 with 39% overest. 56-78	4435 with 21% overest. 3666-4435
#4	Earthfill with clay core (CD) Top Embankment=61mAHD Embankment Height= 25m DCF volume (ML)=8000 Average embankment width=77.5m Top of embankment length=348m	0.51 with 21% underest. 0.51-0.65	91 with 40% overest. 65-91	5585 with 18% overest. 4733-5585





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Case Studies

Dam Name	Dam Data in Australia	Breach Parameters Estimates by DFM_NL of G1			Two-dimensional ultimate values			
		FT (hr)	FBAW (m)	Outflow (m^3/s)	FT (hr)	FBAW (m)	Weir coeff	Outflow (m^3/s)
#1	Zoned earthfill (ZD) Top Embankment=165.65mAHD Embankment Height= 9m DCF volume (ML)=240 Average embankment width=23.47m Top of embankment length=440m	0.66 with 12% underest. 0.66-0.75	28 with 34% overest. 21-28	390 with 17% overest. 333-390	0.66	28	1.44	339
#2	Concrete face rockfill (FD) Top Embankment=67.09mAHD Embankment Height= 13.14m DCF volume (ML)=1660 Average embankment width=19m Top of embankment length=305m	0.57 with 17% underest. 0.57-0.69	49 with 36% overest. 36-49	1793 with 29% overest. 1390-1793	0.57	49	1.44	1507
#3	Earthfill (HD) Top Embankment=63.5mAHD Embankment Height= 25.5m DCF volume (ML)=3920 Average embankment width=66.25m Top of embankment length=450m	0.50 with 22% underest. 0.50-0.64	78 with 39% overest. 56-78	4435 with 21% overest. 3666-4435	0.64	56	1.30	4431
#4	Earthfill with clay core (CD) Top Embankment=61mAHD Embankment Height= 25m DCF volume (ML)=8000 Average embankment width=77.5m Top of embankment length=348m	0.51 with 21% underest. 0.51-0.65	91 with 40% overest. 65-91	5585 with 18% overest. 4733-5585	0.65	65	1.40	5520

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Breach Hydro

A product of **Forward Hydro Pty Ltd**

Closed beta (Version 2024-01-beta.01)

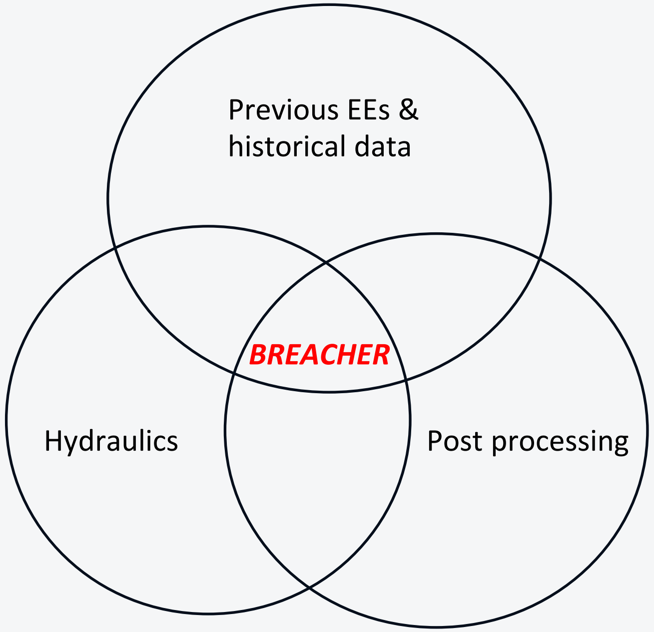
BREACHER is modeling package to:

- Allowing for rapid modelling of thousands of runs in a short duration (~0.05s per run)
- Calculate breaching parameters based on the most common and recently introduced empirical equations
- Investigate through historical database to select the closest cases
- Using water balance to calculate water level at each time step
- Using hydraulic calculation to calculate failure status (width/height of failure)

Operation modes:

- Comprehensive: you will determine plausible ranges for your failure and model will run for all possible combinations leading to probabilistic distribution of outcomes
- Manual: User has reached to a certain values to run model for extracting failure hydrographs

Breach Hydro



Batch file run

Run_Breacher.bat

```
REM Set the below link to the breacher exe
Set Breacher="C:\BREACHER\2024-01-beta.01\breacher.exe"

REM Change the below link to the example breacher control file
set bcf="S:\EXAMPLE_FOLDER\Comprehensive_Example.py"

REM The following line runs breacher with the control file
%Breacher% %bcf%
```

Control commands

Large_Dam_Cressbrook.py

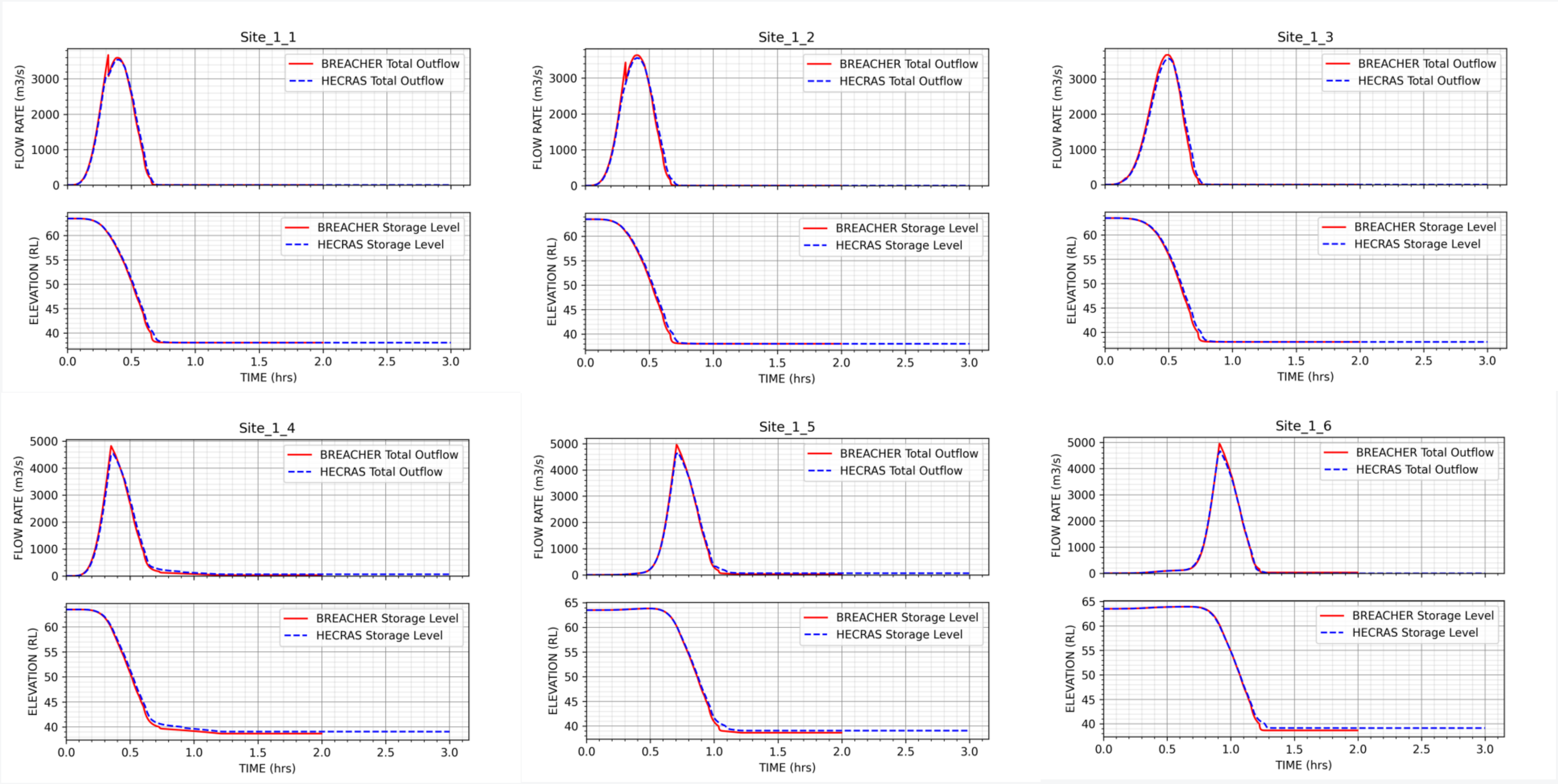
```
# SIMULATION CONTROL COMMANDS
Project_Name = "Cressbrook"
Failure_Type = "SDF"                                    # "SDF" for sunny day failure or "FFS" for flood failure
Timestep = 10                                           # seconds
Start_Time = 0                                          # hours
End_Time = 2                                            # hours
Calc_Precision = 3                                      # decimals solved
Breach_Mode = "Comprehensive"                       # "Comprehensive" to calculate historical dams or literature, "M
Breach_Output = "Summary"                               # "Summary" to only write summary file, "Detailed" output
Total_Simulations = 10000                               # Number of simulations to run, useful for probabilitic m
#
# INPUT BC_DBASE
BC_Inflow = "inflow.csv"                                # dam inflow csv
inflow_name = "Inflow"                                  # inflow column in the dam inflow csv
BC_Elev_Storage = "elev_storage.csv"                    # dam elevation-storage csv, storage is in 10^3 m3
BC_Elev_Outflow = "elev_outflow.csv"                    # dam elevation-outflow (ie spillway rating curve) csv
BC_Breach_Progression = "breach_progression.csv"        # optional custom breach progression curve (ie linear, si
BC_Flow_Tailwater = "None"                              # "flow_tailwater.csv" or "None"
#
# BREACH PARAMETERS
Top_of_dam = 290.26                                     # Top of dam (RL)
Breach_Time = [0.65, 2.96]                              # breach time in hours
Initial_Storage = 280.26                                # initial storage elevation at the dam
Failure_WSL = 280.26                                    # water surface level for failure commencement
Failure_Elev = [276, 277]                               # elevation for failure commencement[231.26, 280.26]
Breach_Base = 231.26                                    # elevation at base of breach  231.26
Side_Slope = 0.4                                        # H:1V
Breach_Bot_Width = [85, 160]                            # breach bottom with in meters [85, 160] 101 replicates zhong
Weir_Cd = [1.1, 1.8]                                    # weir coefficient of discharge for the breach
Orifice_Cd = [0.4, 0.6]                                 # orifice coefficient of discharge for the bre
#
# COMPREHENSIVE PARAMETERS - If "Comprehensive" is turned on in Breach_Mode
Dam_Crest_Width = 7                          # Dam crest width
Z1 = 0.444                                   # Slope of US dam face Z1 (H:V)
Z2 = 0.444                                   # Slope of DS dam face Z2 (H:V)
Dam_Type = "Homogeneous"                     # Options are "Core_wall", "Concrete_Faced", "Zoned_Fill"
Dam_Erodibility = "Medium"                   # Options are "Low", "Medium" or "High"
```

C:\WINDOWS\system32\cmd.

```
-> Orifice Coefficient: 0.29559
-> Breach Time:         0.311 hrs
-> Breach Mode:         Manual

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!! WRITING RESULTS !!!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

COMPREHENSIVE OUTPUT TURNED OFF - NOT APPENDING COMPREHENSIVE FILE FOR 000023
WRITING TIME SERIES OUTPUT FOR ITERATION 000023.csv
APPENDING LOG FILE summary.bsf WITH ITERATION 000023

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!! BREACH SOLVER COMPLETE !!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!!!!! RUNNING BREACHER !!!!!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

FAILURE TYPE: Piping (P)
MODE SELECTED: Manual

BREACH PARAMETERS SELECTED:
-> Timestep:            5 s
-> Initial Storage:     18.6 m3
-> Failure WSL:         18.6 RL
-> Failure Elevation:   17.45134 RL
-> Breach Base:         16.5 m
-> Side Slope:          0.5 (H:V)
-> Breach Bottom Width: 2.59313 m
-> Weir Coefficient:    1.25006
-> Orifice Coefficient: 0.3657
-> Breach Time:         0.2798 hrs
-> Breach Mode:         Manual
```

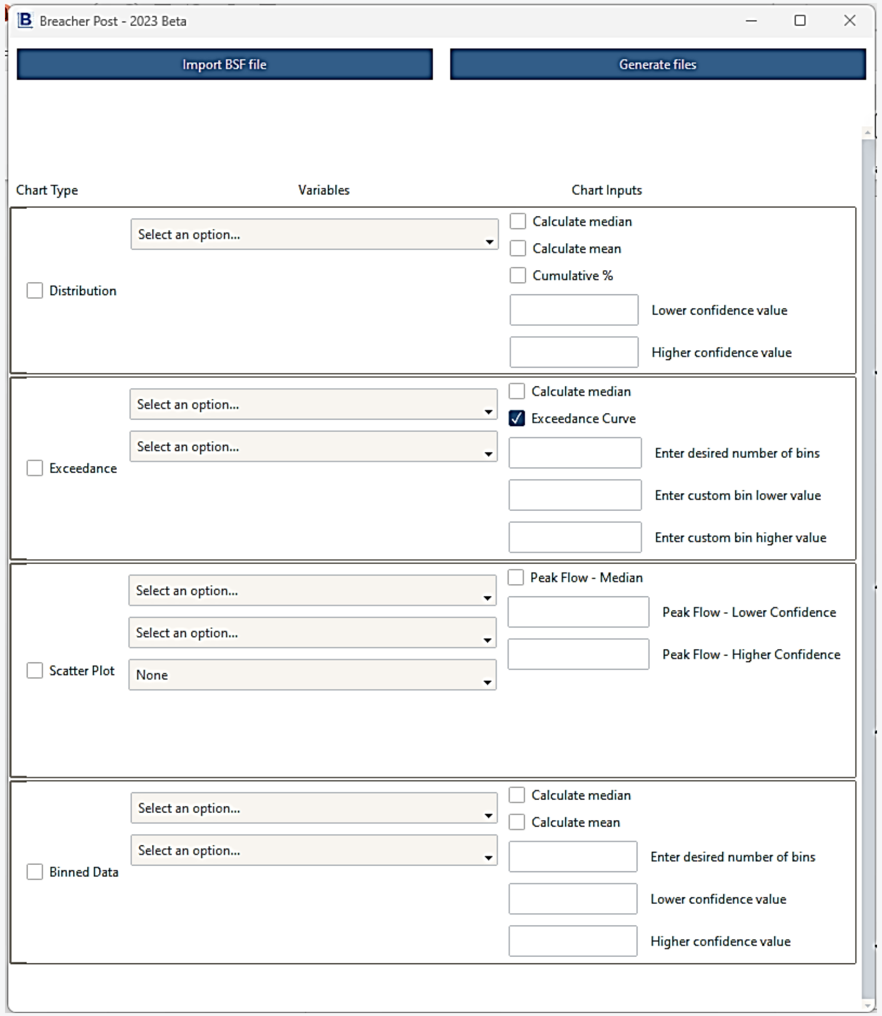
Breach Hydro Validation with HEC-RAS

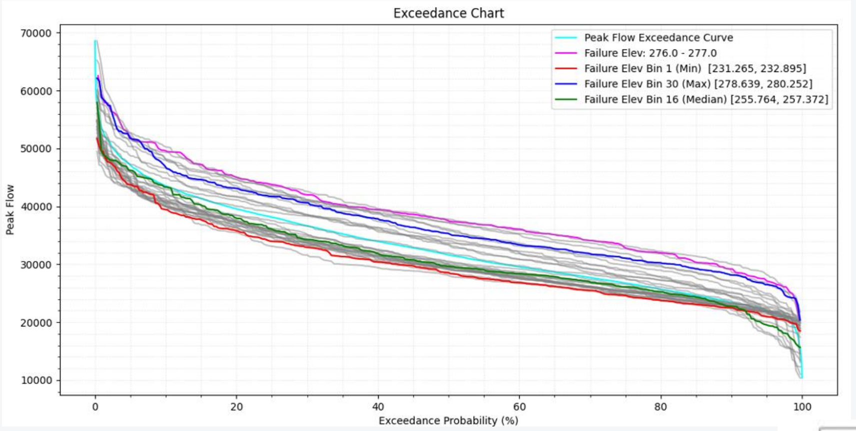
BREACHER has been validated to four HEC-RAS models of real dams, a total of 24 different dam breach scenarios

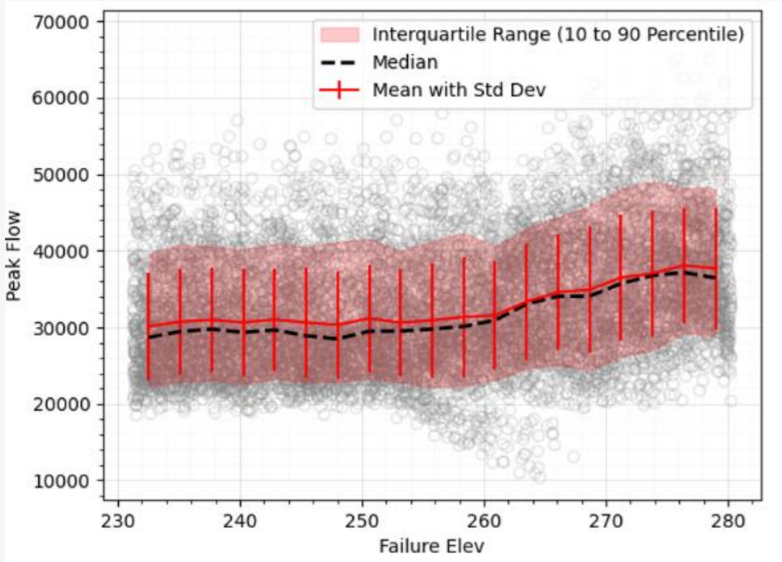


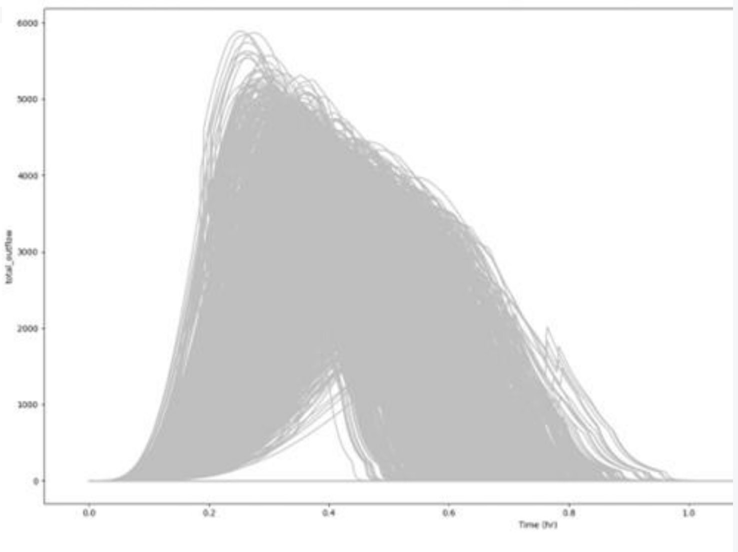
Breach Hydro

Probabilistic Tools (BREACHER-Post): GUI to allow for statistical analyses









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Conclusion

Data Fusion Approach

- This approach was introduced to improve the reliability and accuracy of EE's estimates
- This method presents an objective methodology where proposed EE's can be used to generate peak flows from hydraulic models consistent with the literature and historical dam failure datasets
- Uncertainties still remain within the DFM equations, while a substantial improvement occurred
- DFM equations along with 2d hydraulic modelling have shown substantial improvements

BREACHER

- Breach Hydro (BREACHER) streamlines the EEs (particularly DFMs) and hydraulic modelling
- Hydrodynamic modelling has been replaced by water balance modelling to increase the number of scenarios the practitioner can test

Conclusion

A defensible dam break assessment:

- Understanding a feasible/plausible parameters’ range (safety dams’ components, geotechnical components etc)
- Looking for a referenced historical dam failure of similar characteristics to the site (may not be always available)
- Undertaking a hydraulic (hydrodynamic or water balance) assessment for a range of parameters (breaching and hydraulic) to understand their impacts
- Performing sensitivity (data) analysis on the model outcomes to understand impacts of parameters (probabilistic post processing)

The modelling can never be fully precise, but following these steps are to ultimately reduce uncertainties.