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# Non-Newtonian Rain-on-Grid Tailings Dam Breach

2020 UFSMA Virtual Conference



# Who We Are

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# Presentation Outline

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1. Tailings Dam Breach History
2. Modeling Tailings Dam Breaches
3. Rain-on Grid
4. Non-Newtonian Dam Breach Analysis
5. Extreme Rainfall Hydrology
6. Dam Breach Inundation and Rain-on-Grid Surface Development
7. Non-Newtonian Tailings Dam Breach Development
8. Tailings Dam Breach Validation
9. Final Results and Inundation Mapping



# Tailings Dam Breach History

# Tailings Dam Breach History

What is a Tailings Dam?



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A tailings dam is typically an earth-fill embankment dam used to store byproducts of mining operations after separating the ore from the gangue. Tailings can be liquid, solid, or a slurry of fine particles, and are usually highly toxic and potentially radioactive.



# Tailings Dam Breach History

## Dam Breach Failures



- Barahona Dam, Chile 1928 (54 killed)
- Dos Estrellas Dam, Mexico 1937 (70 killed)
- El Cobre Dam, Chile 1965 (200 killed)
- Sgurigrad Dam, Bulgaria 1966 (488 killed)
- Aberfan Dam, Wales 1966 (144 killed)
- Stava Dam, Italy 1985 (268 killed)
- Merriespruit Dam, South Africa 1994 (17 killed)
- Mariana Dam, Brazil 2015 (19 killed)
- Brumadinho Dam, Brazil 2019 (259 killed)



By Ibama from Brasil - Brumadinho, Minas Gerais,  
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# Tailings Dam Breach History

## Water Dams vs. Tailings Dam



	Water Dams	Tailings Dams
Ownership	State, Public Utility, Water Resources Authority	Private Mining Company
Environmental Impact	Minimal Impact, Footprint, Little to no Contamination	Store contaminants, potential impact on surface and groundwater, air
Lifespan	Finite	Forever?, operation closure and post-closure phases
Failure Rate	~0.01%	~0.1%
Worst Failures	South Fork Dam, Pennsylvania 1889 (2209 killed)	Sgurigrad Dam, Bulgaria 1966 (488 killed)



# Tailings Dam Breach History

## Modeling Tailings Dam Breaches...Why?



- Emergency Action Plan
  - Required for all High and most Significant hazard dams
  - Generally follows provisions of FEMA 64
    - Dam breach analysis necessary for development of inundation mapping, flood arrival time, etc.
- Closure Permitting



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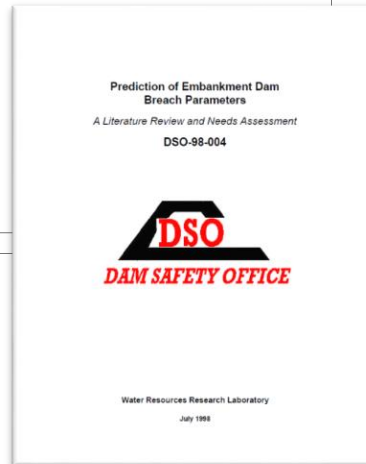
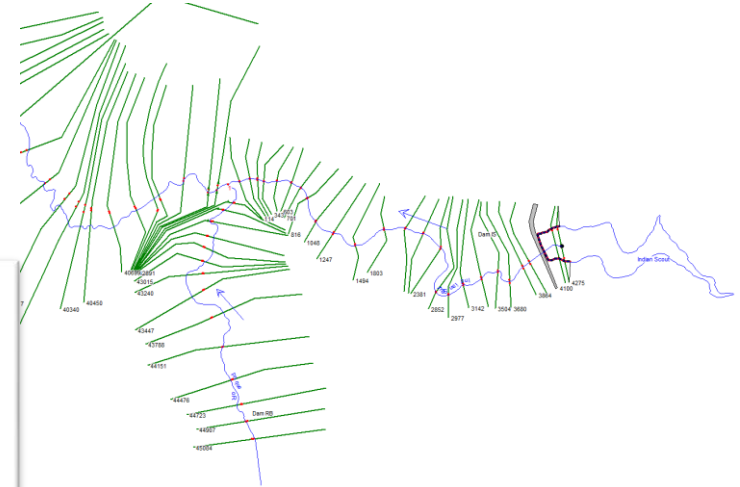
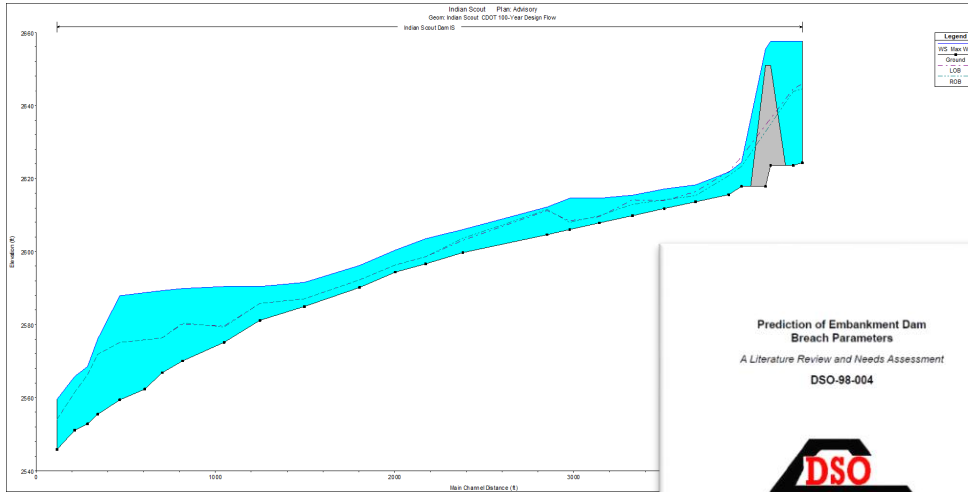
# Modeling Tailings Dam Breaches

# Modeling Tailings Dam Breaches

1D



- Treat it like a Water Dam...HEC-RAS?



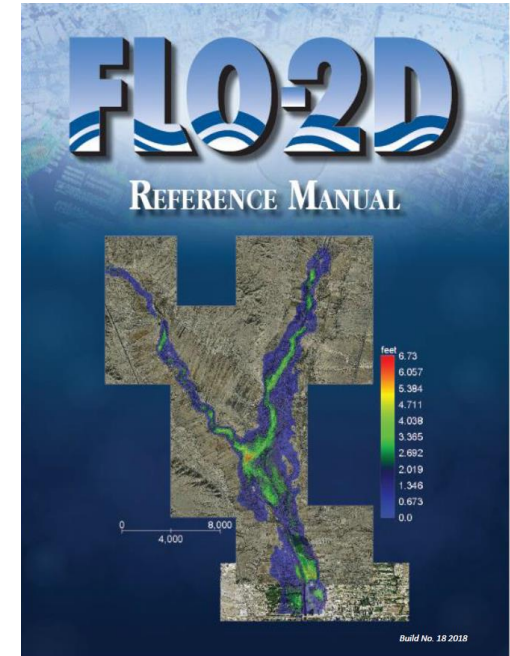
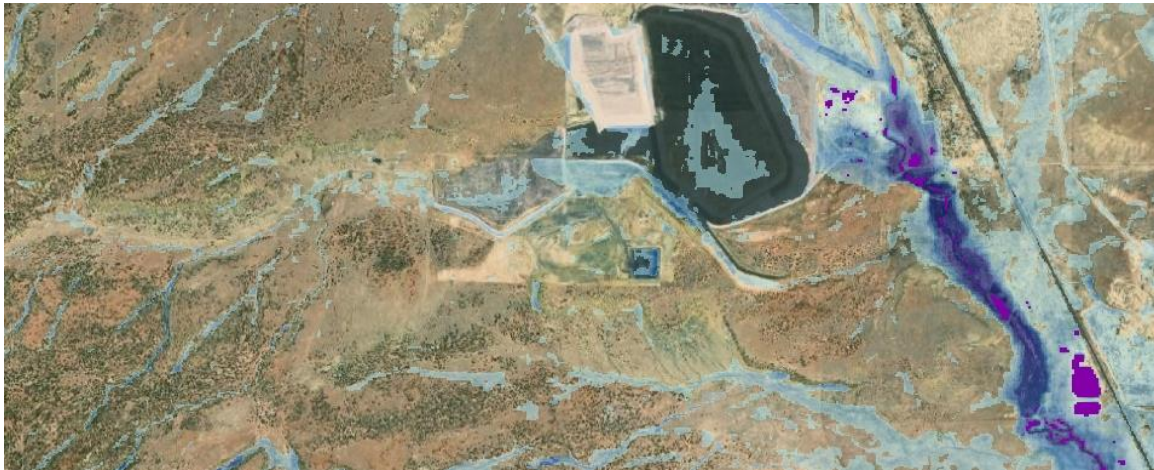
# Modeling Tailings Dam Breaches

2D



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- Treat it like a Tailings Dam?
  - FLO-2D Pro w/Dam Breach and Mud Flow

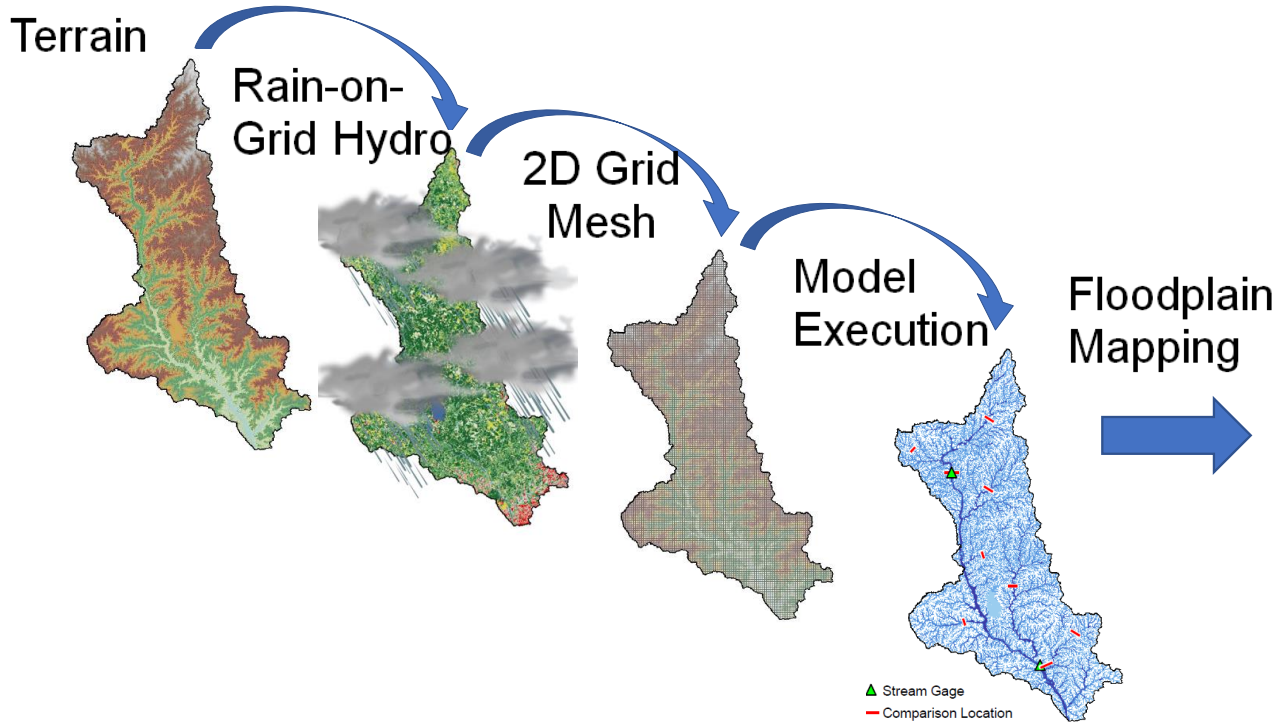


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Rain-on-Grid

# 2D Rain-On-Grid

## Model Development Overview



# Rain-on Grid Best Practices Initiative

2D



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- In addition to the Colorado 2D Consortium 2D Floodway Recommendations, we tackled ROG Best Practices
- Consistency among contractors and teams
- Improved product, methodology, & reviews
- Resources/info for training and reference (internal & external)
- Recommendations to FEMA for revised SIDs and refined guidance
- *12-meeting series from Dec 2019 – Aug 2020*  
*26 individuals from 7 states (CO, KS, KY, NJ, NY, UT, VA)*  
*~350 hrs*

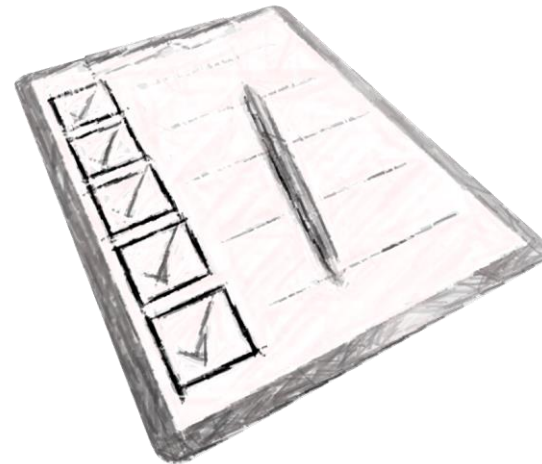
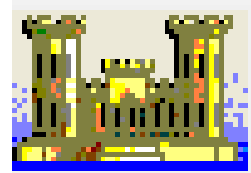


# Rain-on Grid Best Practices Initiative



2D

1. Model Setup & Basin Delineation
2. Hydrology (Development & Application)
3. Model Detail & Refinements
4. Stormwater & Development Applications
5. Model Settings & Tolerances
6. Model Calibration & Validation
7. 2D Mapping & Rendering
8. Unsteady 2D Floodway
9. Updates to FEMA SIDs



# Non-Newtonian Dam Breach Analysis

# Newtonian vs Non-Newtonian Fluids



## Definitions

- Viscosity – A fluid's resistance to flow
- Newtonian fluids have predictable viscosity
- Examples:
  - Water
  - Gasoline
  - Mineral Oil

An aerial photograph of a large, dark green reservoir in a rural, agricultural landscape. The reservoir is surrounded by fields and some buildings. The text "Ish Reservoir (Irrigation Water)" is overlaid on the reservoir in white.

Ish Reservoir  
(Irrigation Water)



# Newtonian vs Non-Newtonian Flow

## Non-Newtonian Fluids



- Variable Viscosity
- Bingham Plastics
  - Weak Solid Structure
  - Mudflow Characteristics
- Examples
  - Gravy
  - Ketchup
  - Mayonnaise
  - Mine Tailings



# Newtonian vs Non-Newtonian Flow

## Definitions



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$$\tau = \mu \frac{du}{dy}$$

- $\tau$  is the shear stress,
- $\mu$  is the viscosity, and
- $du/dy$  is the shear rate.

### Newtonian Viscosity

$$\tau = \tau_y + \mu_B \frac{du}{dy}$$

- $\tau$  is the shear stress,
- $\tau_y$  is the yield stress,
- $\mu_B$  is the Bingham viscosity, and
- $du/dy$  is the shear rate.

### Non-Newtonian Viscosity (Bingham Model)



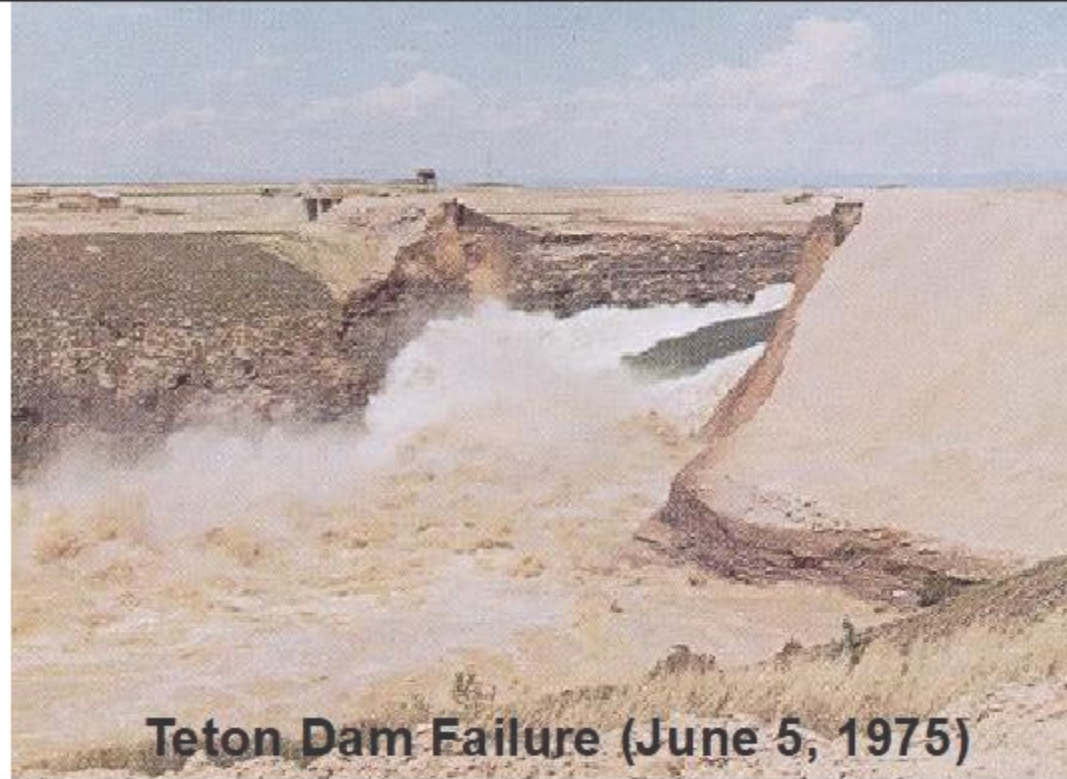
# Non-Newtonian Dam Breach Analysis



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## PMP-Induced Tailings Dam Failure by Overtopping

- Hydrologic Failure
- PMP – Probable Maximum Precipitation
- Dam Breach triggered by overtopping



Teton Dam Failure (June 5, 1975)



# Analysis Overview

## PMP-Induced Tailings Dam Failure by Overtopping



1. Extreme Rainfall Hydrology
2. Rain-on-Grid for Probable Maximum Flood
3. Tailings Dam Breach Development
  - Model Validation
4. Combined Conditions
  - Inundation Mapping



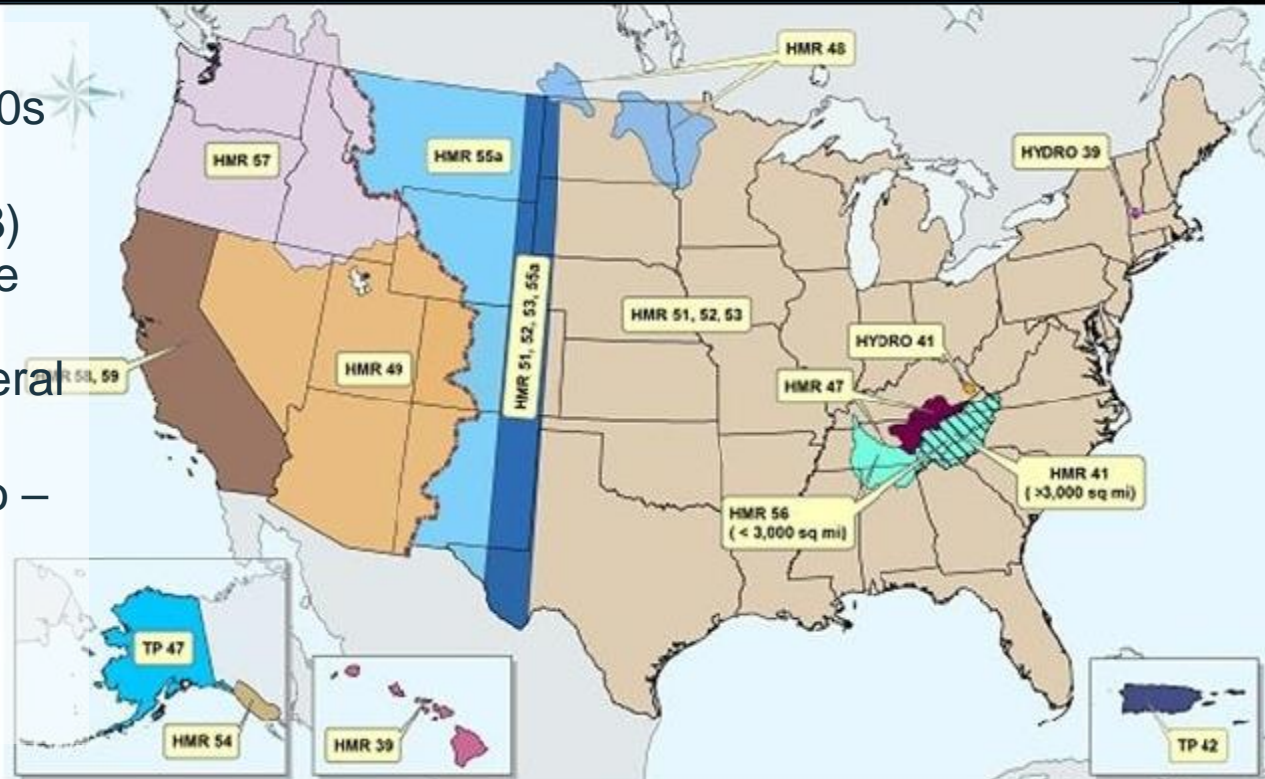
# Extreme Rainfall Hydrology

# Precipitation Data Sources

## Extreme Rainfall Hydrology



- Hydrometeorological Reports (HMR) – 1930s through 1990s
- Utah – HMR 49 (1983) with updated guidance (1995 and 2003) for estimation of the general storm PMP depths.
- Colorado/New Mexico – Regional Extreme Precipitation Study (2018)

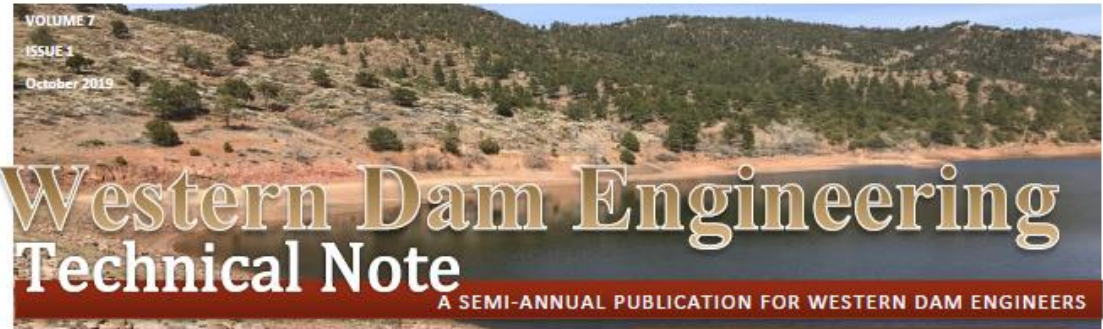


# Precipitation Data Sources

## Extreme Rainfall Analysis



- Summarizes latest PMP studies for Western States
  - Arizona
  - Colorado
  - Montana
  - New Mexico
  - **Utah**
  - Wyoming



In this issue of the *Western Dam Engineering Technical Note*, we present articles on an **alternative method for completing a breach analysis and consequence estimation**, and a **PMP tool discussion**. This newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication focuses on technical articles specific to small and medium dams. It provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

The Western Dam Engineering Technical Note is sponsored by the following agencies:

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This Technical Note was compiled, written, and edited by AECOM in Denver, CO

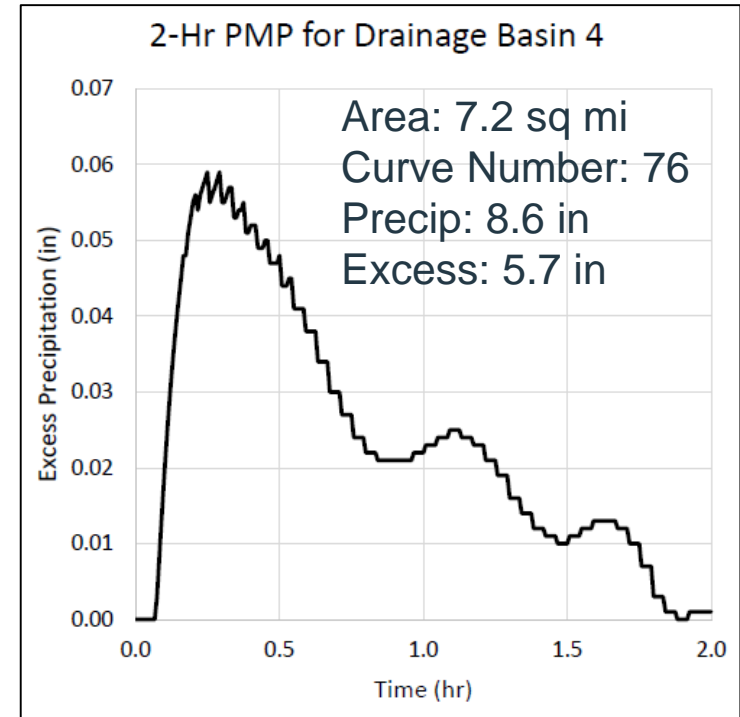


# Excess Hyetographs

## Extreme Rainfall Analysis



- Given a PMP depth, we need to know how much becomes runoff.
- NOAA's Atlas 14 First Quartile Distribution
- Check shorter duration storms for smaller drainage areas



# Dam Breach Inundation Surface and Rain-on-Grid Development

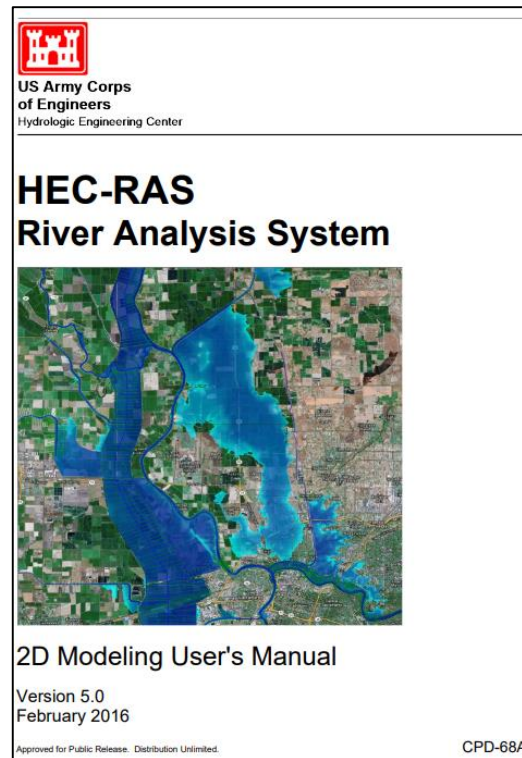
# HEC-RAS 2D

## Rain-on-Grid Modeling



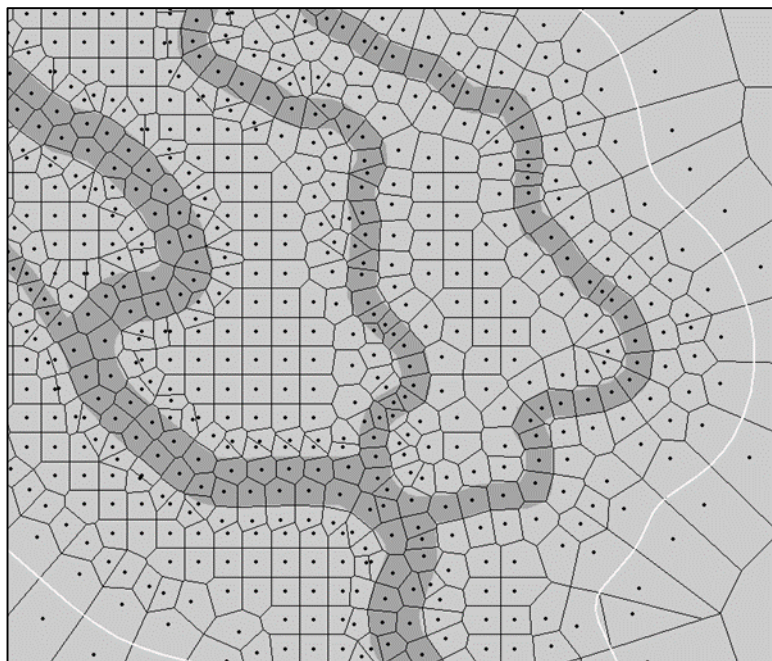
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- HEC-RAS 2D Version 5.0.7
- Clear-Water Flow Only
- Irregular Mesh Generation
  - Allows for more detailed modeling than Cartesian grids
  - Better represent the terrain
- Simple to calibrate

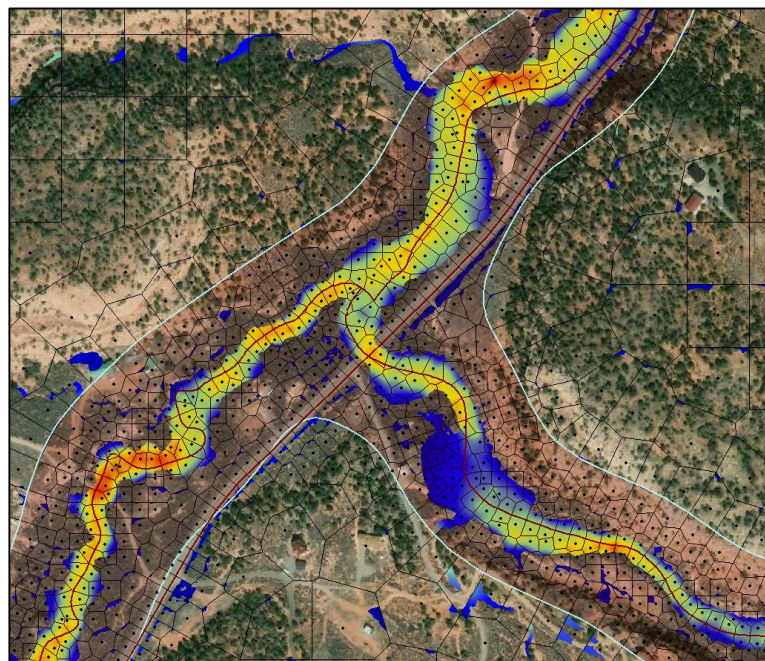


# Refinement Regions

## Rain-on-Grid Modeling



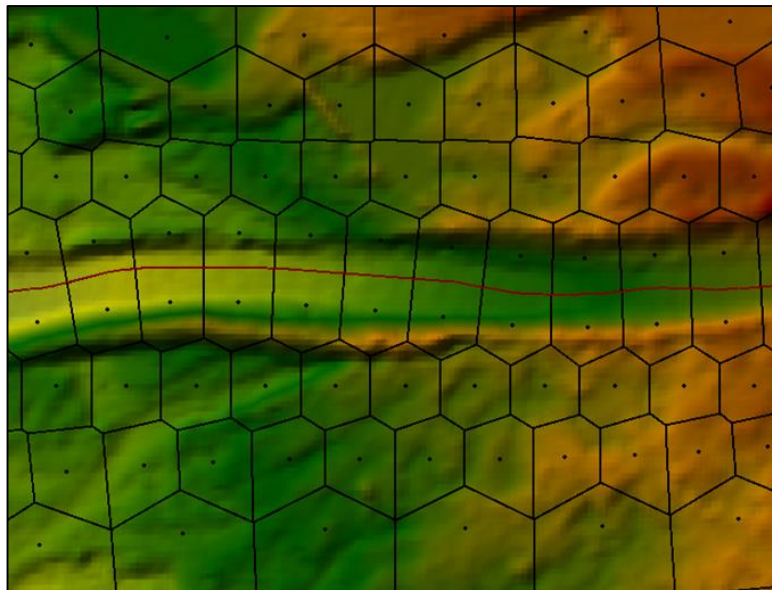
**Channel Refinement Region**



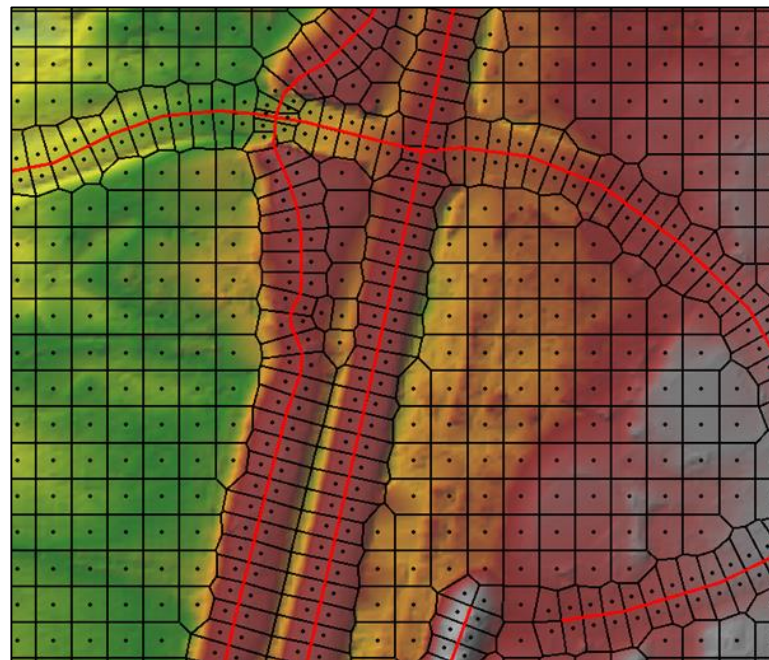
**Floodplain Refinement Region**

# Breaklines

## Rain-on-Grid Modeling



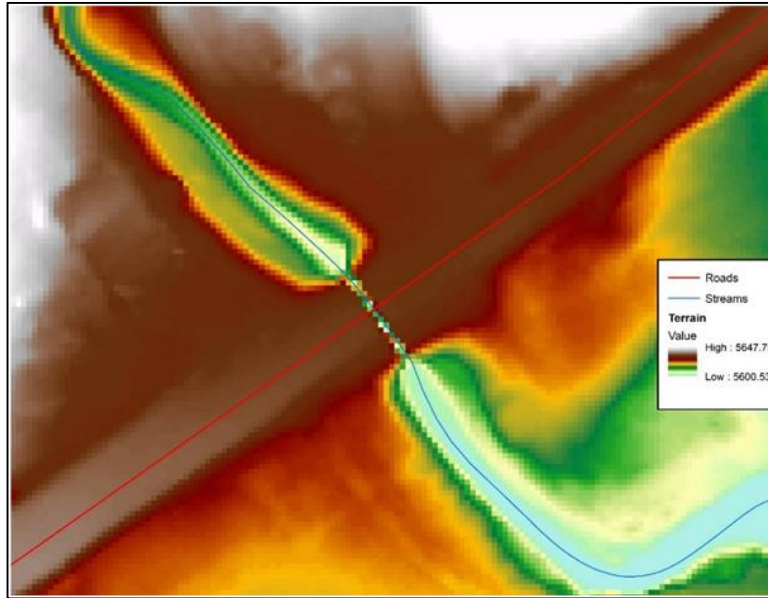
**Channel Breakline**



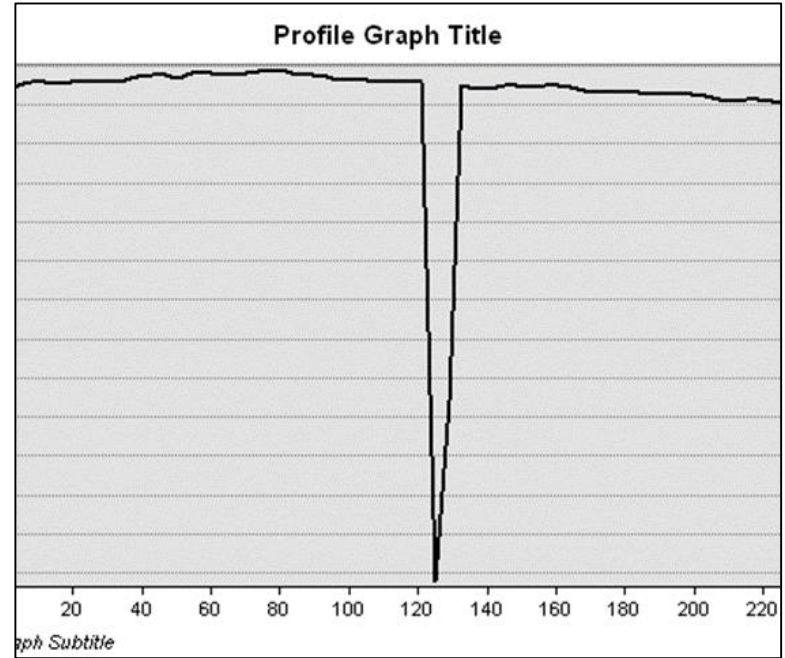
**Floodplain Refinement Region**

# Hydroconnectors

## Rain-on-Grid Modeling



**Hydroconnector**



**Hydroconnector Profile**

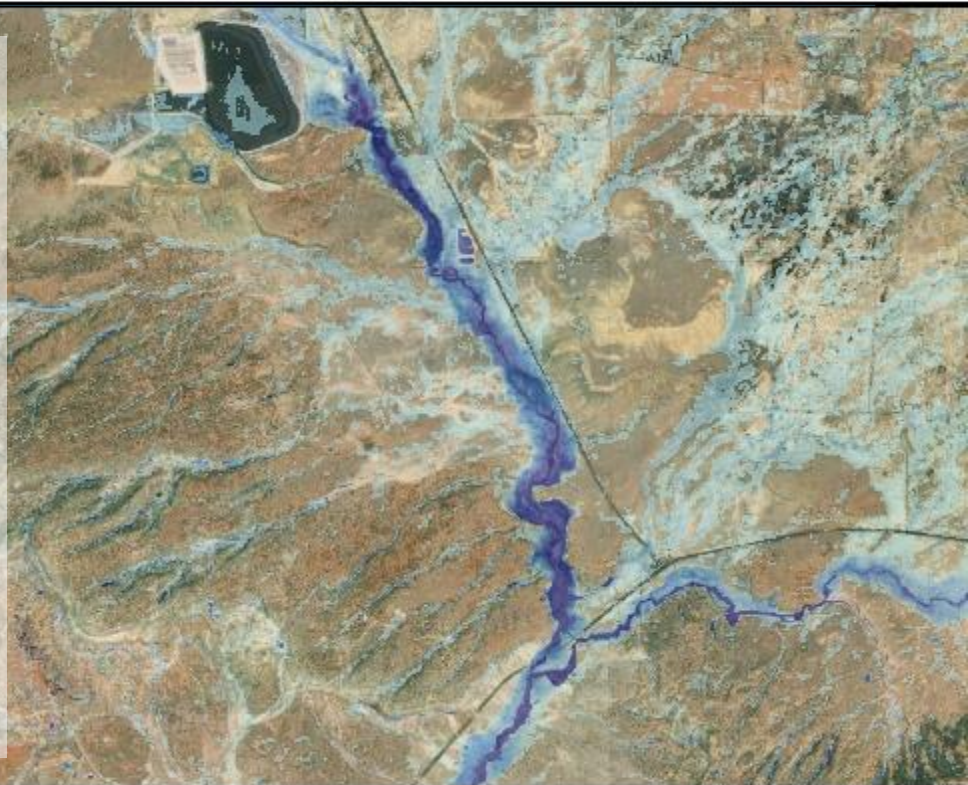


# Model Calibration

## Rain-on-Grid Modeling



- Calibrated to the 100-year event:
  - Roughness Layer
  - Sub-Basin Curve Numbers
- Once calibrated, develop excess PMP hyetographs and run model.

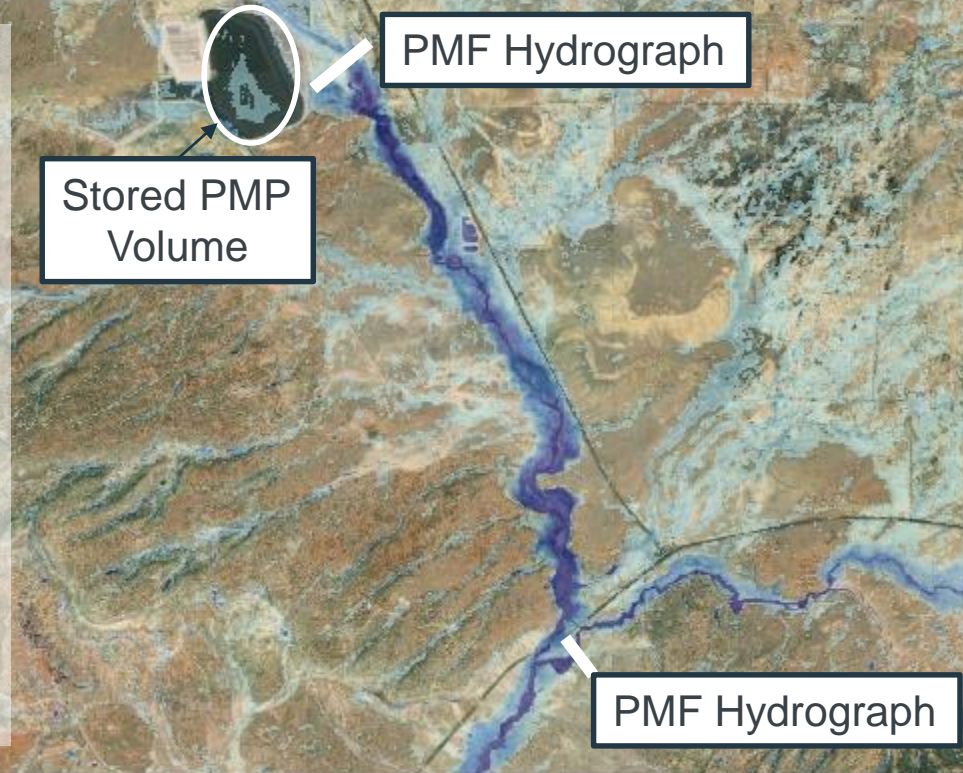


# Probable Maximum Flood Results

## Rain-on-Grid Modeling



- Resulting Inundation Area – PMF
- Model Results
  - Flow Hydrographs at Inflow Points
  - Volume of Precipitation Stored on Top of Impoundment



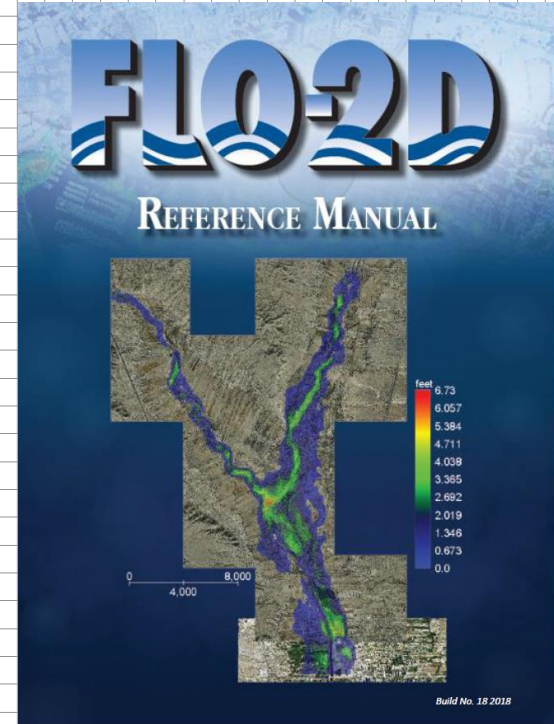
# Flo-2D Pro

## Mudflow Floodplain Model Development



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- FLO-2D Pro
- Cartesian Grid
- Mudflow Capabilities
- Input Layers
  - Inundation Boundaries
  - Hydroconnected Terrain
  - Calibrated Roughness



# Flo-2D Sensitivity to Roughness

## Mudflow Floodplain Model Development



- Check range of roughness values
- Can adjust roughness locally based on model results

2016 NLCD Classification	Minimum	Normal	Maximum
Open Water	0.025	0.03	0.033
Developed, Open Space	0.01	0.013	0.016
Developed, Low Intensity	0.038	0.05	0.063
Developed, Medium Intensity	0.056	0.075	0.094
Developed, High Intensity	0.075	0.1	0.125
Barren Land	0.025	0.03	0.035
Deciduous Forest	0.1	0.12	0.16
Evergreen Forest	0.1	0.12	0.16
Mixed Forest	0.1	0.12	0.16
Scrub/Shrub	0.035	0.05	0.07
Grassland/Herbaceous	0.025	0.03	0.035
Pasture/Hay	0.03	0.04	0.05
Cultivated Crops	0.025	0.035	0.045
Woody Wetlands	0.08	0.1	0.12
Emergent Herbaceous Wetland	0.075	0.1	0.15
Roadway	0.016	0.016	0.02
Buffered Stream Centerline	0.025	0.03	0.033



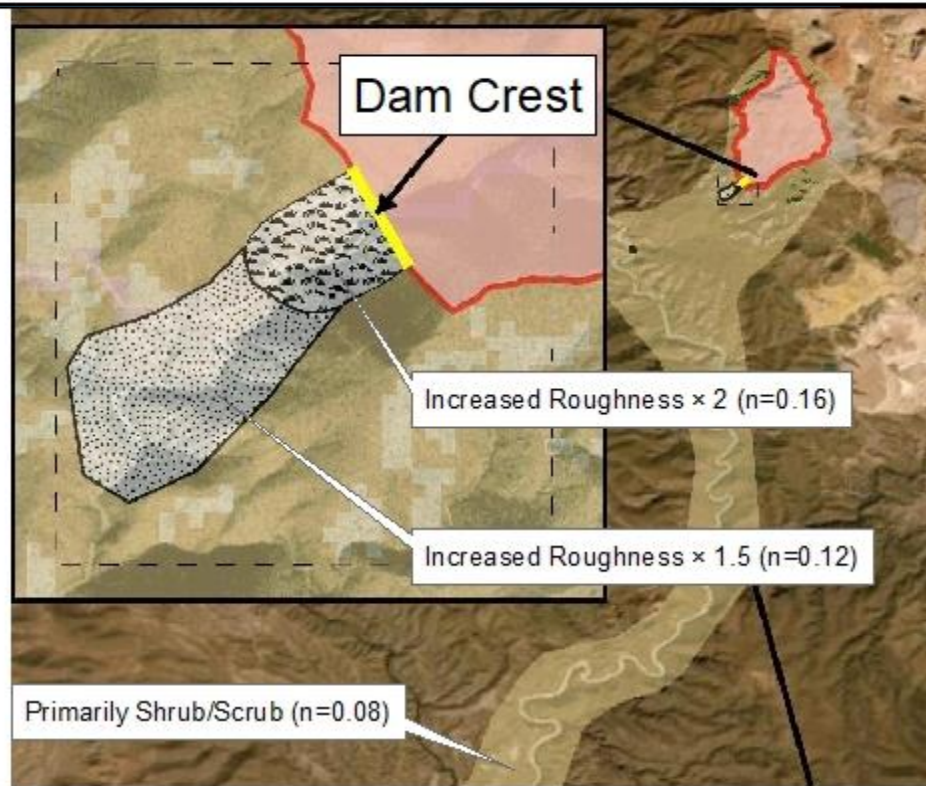
# Flo-2D Roughness Refinement

## Mudflow Floodplain Model Development



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- Can adjust roughness locally based on model results
- Refinement regions to reduce excessively high velocities
- Double roughness values downstream of breach



# Tailings Dam Breach Development

# Rico (2008) Regression Equations

## Dam Breach Calculations



- Rico (2008)
- Regression Equations based on 28 tailings dam failures
- Two Parameters:
  - Height of Impoundment
  - Total Volume of Pond

Parameter	Symbol	Units	Value	Source
<b>Input Data and Assumptions</b>				
Height of Impoundment	H	m	6.401	Detailed contour surface
Total Volume of Cell	$V_{cell}$	$10^6 \times m^3$	2.338	As-Built Drawings
Volume of Cap	$V_{cap}$	$10^6 \times m^3$	1.070	Boring Logs
Volume of Soils (Non-Tailings)	$V_{soil}$	$10^6 \times m^3$	1.120	Boring Logs
Volume of Tailings	$V_T$	$10^6 \times m^3$	0.117	Boring Logs
Volume of Free Water	$V_W$	$10^6 \times m^3$	0.031	$V_{cell} - (V_T + V_{cap} + V_{soil})$
<b>Estimation of Mobilized Tailings and Breach Outflow Volume</b>				
Breach Outflow Volume	$V_{F,Cell2}$	$10^6 \times m^3$	0.835	$V_F = 0.354 \times V_T^{1.01}$
Outflow Run-Out Distance	$D_{MAX}$	km	46.830	$D_{MAX} = 12.46 \times (HV_F)^{0.79}$
Percentage of Total Volume Released	$\%V_{OUT}$	%	35.7%	$\frac{V_F}{V_{CELL}}$



# Fontaine and Martin (2015) Geotechnical Estimates

## Dam Breach Calculations



- Required Tailings Parameters:
  - Average dry density
  - Degree of saturation
  - Mass of tailings solids stored
  - Tailings solids density

Parameter	Symbol	Units	Value	Source
<b>Calculation of Tailings Geotechnical Parameters</b>				
Degree of Saturation of Tailings	$S$	%	85.64	$\frac{SG \times MC_T}{e}$
Tailings Solids Density	$\rho_s$	tons/m <sup>3</sup>	2.94	$SG \times \rho_W$
Mass of Stored Tailings	$M_{s-init}$	Mega-tons	0.191	$\rho_D \times V_T$
Volume of Tailings Solids	$V_S$	10 <sup>6</sup> × m <sup>3</sup>	0.065	$\frac{M_{s-init}}{\rho_s}$
Volume of Tailings Voids	$V_V$	10 <sup>6</sup> × m <sup>3</sup>	0.052	$V_T - V_S$
Porosity	$n$		0.446	$V_V / V_T$
Volume of Mass and Interstitial Water	$V_{IW}$	10 <sup>6</sup> × m <sup>3</sup>	0.045	$S \times V_V$
Mass of Tailings Interstitial Water	$M_{IW}$	%	0.049	$V_{IW} \times \rho_W$
Bulk Density of Tailings	$\rho_{Bulk}$	tons/m <sup>3</sup>	2.05	$\frac{(M_{s-init} + M_{IW})}{V_T}$



# Fontaine and Martin (2015) Geotechnical Estimates

## Dam Breach Calculations



- Fontaine and Martin (2015)
- Geotechnical Relationships
- Determine Maximum Potential Release
- Does not consider failure mode

Parameter	Symbol	Units	Value	Source
<b>Estimation of Mobilized Tailings and Breach Outflow Volume</b>				$\rho_D \times V_T$
Mass of Supernatant Pond Water	$M_W$	Mega-tons	0.033695	$V_W \times \rho_W$
Solids Content	SC	%	50.00	
Mass of Mobilized Tailings Solids	$M_{S-MOB}$	Mega-tons	0.041	$\frac{M_W}{1/SC - 1 - MC_T}$
Mass of Mobilized Interstitial Water	$M_{IW-MOB}$	Mega-tons	0.010	$\left(\frac{M_{S-MOB}}{\rho_D} - \frac{M_{S-MOB}}{\rho_S}\right) S_{PW}$
Volume of Mobilized Tailings	$V_{T-MOB}$	$10^6 \times m^3$	<b>0.025</b>	$\frac{(M_{S-MOB} + M_{IW-MOB})}{\rho_{BULK}}$
Breach Outflow Volume	$V_{OUT}$	$10^6 \times m^3$	<b>0.055</b>	$V_W + V_{T-MOB}$
Percentage of Total Volume Released	$\%V_{OUT}$	%	37.500	$\frac{V_{OUT}}{V_W + V_T}$



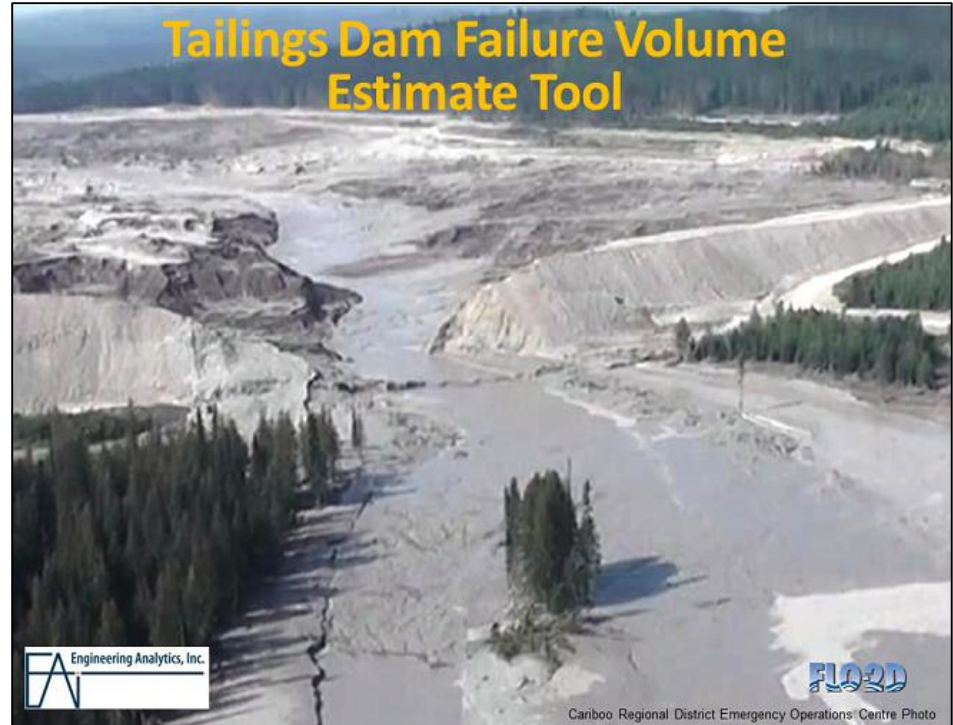
# Flo-2D Tailings Dam Tool (2018)

## Dam Breach Calculations



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- Developed by a team of geotech and tailings dam experts
- Compiled all available tailings dam breach data.
- Multiple linear regression analyses to develop regression equations specific to tailings dam failures

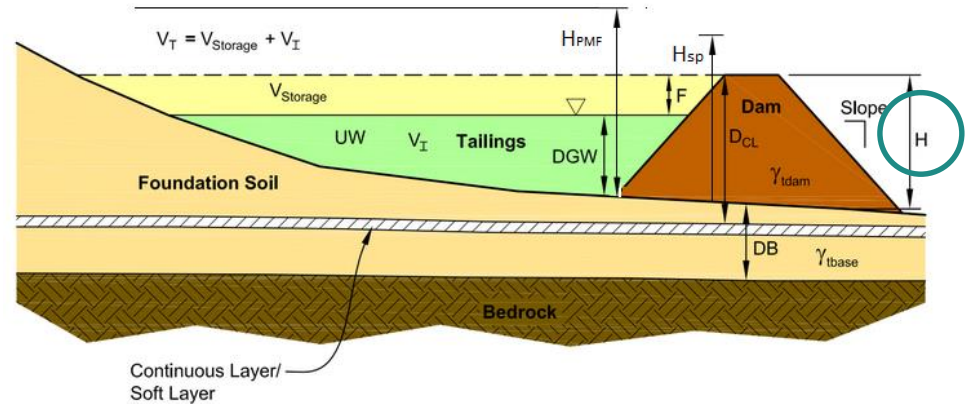


# Flo-2D Tailings Dam Tool (2018)

## Dam Breach Calculations



- Define the Geometry of the Impoundment
  - Total Capacity
  - Impounded Tailings Volume
  - Height
  - Embankment Slope

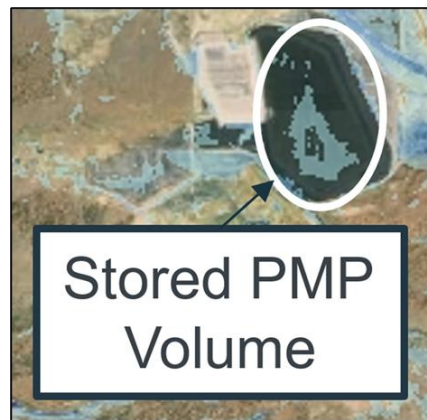


# Flo-2D Tailings Dam Tool (2018)

## Dam Breach Calculations



- Overtopping Volume
- If the input flood event volume is greater than the available capacity, the dam will fail by overtopping.



### Failure Modes

Hydrologic

Static

Available Storage:

920000 cy.

Input Flood Event Volume:

1754000 cy.

Facility Has Spillway?



Max. Allowable Head (Hsp):

105 ft.

PMF WSE (HPMF):

110 ft.

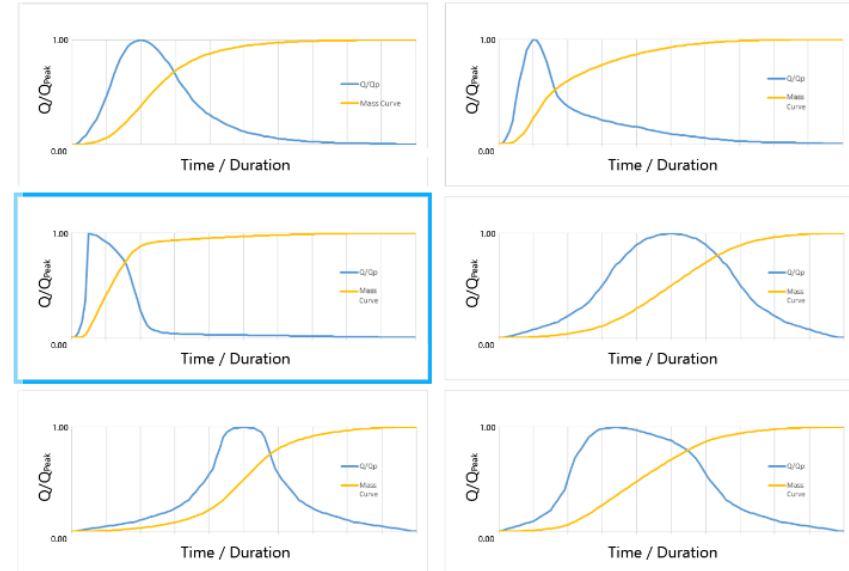


# Flo-2D Tailings Dam Tool (2018)

## Dam Breach Calculations



- Total breach volume ranges from 10 – 35 percent of the impounded tailings volume.
- Breach volume is distributed in a hydrograph shape for a given duration.



# Flo-2D Tailings Dam Tool (2018)

## Dam Breach Calculations



- Porosity - Total sediment volume is adjusted based on user input
- Maximum Sediment Concentration
  - Field Data would be best
  - Mudflow occurs for about 20 to 50 percent sediment concentration

Select Volume (cy)  
Vrmax 3,985,278.92

Grid Cell  
1

Entire Event Time (hr)  
2.00

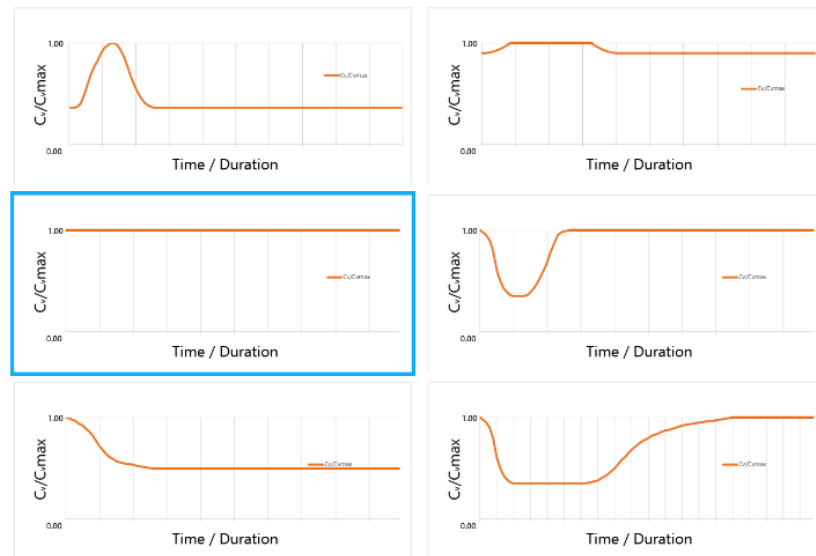
Porosity  
0.45

Maximum Sediment Concentration  
0.50

Sediment Output Format  
Sediment Concentration by Volume

Hydrographs

Sediment Concentration by Volume

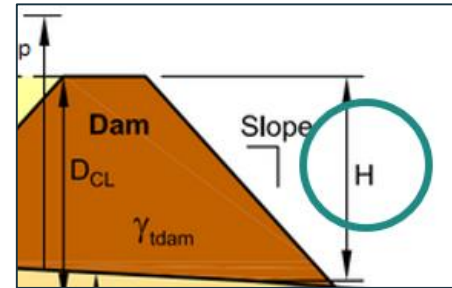
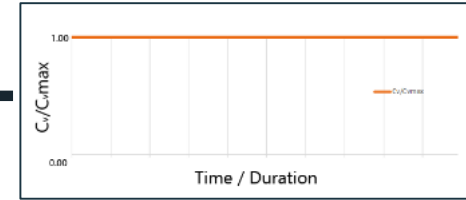
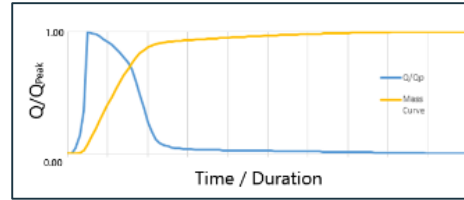


# Flo-2D Tailings Dam Tool (2018)

## Dam Breach Calculations



- Develop pairings of breach hydrographs and sediment distributions.
- Specify breach location (grid cell number)
- Tailings Dam Tool will print an inflow file to represent the tailings breach.



INFLOW.DAT

```
0 765
F 0 765
H      0.000  0.000  0.000
H      0.020  0.000  0.180
H      0.040  128.985  0.187
```



# Flo-2D Mudflow Modeling

## Floodplain Sensitivity to Mudflow Parameters



- Tailings tend to have Bingham Plastic properties (mudflow)
- Dam Breach hydrograph with sediment
- Compare final deposition volumes

Table 12. Yield Stress and Viscosity as a Function of Sediment Concentration				
Source	$\tau_y = \alpha e^{\beta C_v}$ (dynes/cm <sup>2</sup> )		$\eta = \alpha e^{\beta C_v}$ (poises)	
	$\alpha$	$\beta$	$\alpha$	$\beta$
<i>Field Data</i>				
Aspen Pit 1	0.181	25.7	0.0360	22.1
Aspen Pit 2	2.72	10.4	0.0538	14.5
Aspen Natural Soil	0.152	18.7	0.00136	28.4
Aspen Mine Fill	0.0473	21.1	0.128	12.0
Aspen Watershed	0.0383	19.6	0.000495	27.1
Aspen Mine Source Area	0.291	14.3	0.000201	33.1
Glenwood 1	0.0345	20.1	0.00283	23.0
Glenwood 2	0.0765	16.9	0.0648	6.20
Glenwood 3	0.000707	29.8	0.00632	19.9
Glenwood 4	0.00172	29.5	0.000602	33.1



# Tailings Dam Breach Model Validation

# Model Validation

## Floodplain QC



- Inundation Area
  - Signs of unrealistic ponding?
  - Is the outflow distance reasonable (check Rico regression)



# Model Validation

## Flo-2D Model QC



- Check max velocities
- Check for volume conservation (should be within 0.001%)



# Model Validation

## Completion QC



- Check Hydrographs
  - Peak flow passes completely through the model
  - Flow is suspended
  - No numerical instability



# Final Results and Inundation Mapping

# Final Inundation Mapping

Dam Breach plus Natural Flood Conditions



- Consider timing of the peak flows for worst-case scenario
- Add PMF inflow hydrographs to mudflow model
- Mixing occurs in the floodplain

An aerial photograph of a dam and its surrounding floodplains. The dam is a large concrete structure with a reservoir behind it. The floodplains are shown in various shades of blue and purple, indicating different levels of inundation. A white arrow points from a box labeled 'PMF Hydrograph' to a specific area on the floodplain.

PMF Hydrograph



# Conclusion

## Summary of Objectives



- Four major objectives:
  - Extreme Rainfall Analysis
  - Probable Maximum Flood (Rain-on-Grid)
  - Non-Newtonian Dam Breach Analysis
  - Inundation Mapping
    - Natural Flood (PMF)
    - Breach Flow with Dry Tributaries (Flo-2D)
    - Breach Flow plus Natural Flood



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