# A comparison between HEC-RAS 6.0 and FLO-2D as tools used in tailings dam breach analyses

**A. Scholtz and S. Chetty**

SRK Consulting, South Africa

Tailings Storage Facility (TSF) failures are critical, and can potentially result in loss of life. In August 2020, the Global Industry Standards on Tailings Management (GISTM) prescribed tailings dam breach analyses (TDBAs) of TSFs as a requirement. In this paper two programs are compared, HEC-RAS and FLO-2D, in terms of their use as tools for TDBAs. To facilitate this, a mock TSF was created in an arbitrary location, and a hypothetical breach of the TSF was simulated using each program. These simulations resulted in differing inundation extents where the HEC-RAS model breach flow covered a larger extent than the FLO-2D model. It was also seen that the maximum flow depths were greater in the downstream inundation extent in the HEC-RAS model, and greater just after the breach in the FLO-2D model. Also investigated were the different equation sets available in HEC-RAS which did not show substantial variations in results.

## INTRODUCTION

Tailings Storage Facilities (TSFs) are a major component of mining infrastructure, where the waste product of the mining process (tailings) is stored. A breach of such a facility would result in destructive, oftentimes toxic, tailings flows over a substantial distance downstream of the TSF. More than 63 major tailings dam failures were recorded worldwide in the last 50 years, thereby establishing a failure rate which is several times higher than that of water-retaining dams. Understanding and predicting the tailings flow path should a TSF failure occur is crucial to the design process of a safe TSF. A hypothetical analysis of these flows is referred to as a Tailings Dam Breach Analysis (TDBA). These analyses typically follow guidelines set out for water-retaining dams with some adaptations to account for the critical non-Newtonian properties of a tailings flow. Following the tragic failure of the TSF at Feijão mine in Brazil, and as of August 2020, conducting a TDBA has become a requirement of the Global Industry Standards for Tailings Management (GISTM) for all TSFs.

A commonly used software for modelling a non-Newtonian breach flood is FLO-2D. FLO-2D is a flood-routing model created in 1986 for the purpose of predicting mudflow hydraulics and is supported by the US Federal Emergency Management Agency. The software allows for the geotechnical properties of a tailings flow (rheology and sediment concentration) to be modelled.

In the most recent release of the popular water flow modelling software, Hydrologic Engineering Center's River Analysis System (HEC-RAS), the software's capabilities have been extended to include non-Newtonian flow modelling. This allows the flood-routing model to be used as a TDBA tool. HEC-RAS was designed by the US Army Corps of Engineers, and is universally available at no cost to the user. The software has been widely used to perform one-dimensional steady flow and one and two-dimensional unsteady flow simulations involving hydraulic structures.

*Global Tailings Standards and Opportunities 2021*
*Online via Zoom, 15, 17, 19, 22, 24, 25 November 2021*
*The Southern African Institute of Mining and Metallurgy*

In this paper we assess the suitability of both HEC-RAS version 6.0 and FLO-2D Pro as tools used in tailings dam breach analyses. We compared both programs based on the complexity of their setup procedures, simulation run-times, and the appropriateness of their results. To facilitate this, a mock TSF was created in an arbitrary location, and a hypothetical breach of the TSF was simulated using each program. The models were set up using, as far as possible, the same parameters such as the computational grid sizes, tailings characteristics, breach outflow hydrographs, and surface roughness. Since HEC-RAS offers three different equation sets; namely the 2D Diffusion Wave equations, Shallow Water Equations with a Eulerian-Lagrangian approach (SWE-ELM), and the third equation set with a Eulerian approach (SWE-EM); each option was investigated and compared to the Diffusion Wave equation set used in FLO-2D.

The results from each model, including the inundation extent, volume conservation, and flood characteristics at chosen locations, are then presented and this paper concludes by highlighting the benefits, and shortcomings of each flood-routing model in terms of their use as a TDBA tool. The study is limited to only FLO-2D and HEC-RAS, other software also capable to perform a TDBA, such as Muck3D and FLO-3D, are neither discussed nor investigated. It should also be noted that this study assumes a failure of the TSF and does not consider nor comment on the probability of such a failure occurring.

## INVESTIGATION

This section comprises the set-up procedures followed for each program. This includes a summary of the parameters used in the models as well as brief explanations of how each program interprets these parameters. This section then briefly describes the simulation processes followed by each program and concludes by presenting the results of the models as displayed in their respective programs.

### Setting Up the Models

For non-Newtonian fluids, unsteady flow equations incorporate rheology in the momentum equations. The capabilities of FLO-2D are restricted to the 2D diffusion wave equation that only solves the volume and momentum conservation equations. With HEC-RAS, the depth-averaged Shallow Water Equations (SWE) include the temporal and spatial acceleration with horizontal mixing. Solving advection, two approaches can be followed in HEC-RAS namely a Eulerian-Lagrangian approach (SWE-ELM) and a Eulerian approach (SWE-EM).

Considering the various capabilities of both programs, four models were chosen for comparison. These are summarised in Table 1. It should be noted that the FLO-2D model was set up using a plugin created for QGIS which is an open-source, desktop GIS application.

*Table 1. Summary of models run*

| Model | Program | Description |
|---|---|---|
| A | FLO-2D | 2D Diffusion wave equation |
| B | HEC-RAS | 2D Diffusion wave equation |
| C | HEC-RAS | Shallow Water Equation with a Eulerian-Lagrangian approach (SWE-ELM) |
| D | HEC-RAS | Shallow Water Equations with a Eulerian approach (SWE-EM) |

#### *Breach Hydrograph*

A breach hydrograph is used to define the material discharge rate over time as the breach develops. This is dependent on breach parameters such as the outer wall height, angle of friction of the wall material, tailings density, free water, and the expected sediment concentration of the outflow from the TSF. For this study, these parameters were chosen based on precedent, and the breach hydrograph shown in Figure 1 for an overtopping scenario due to a large storm event was created.

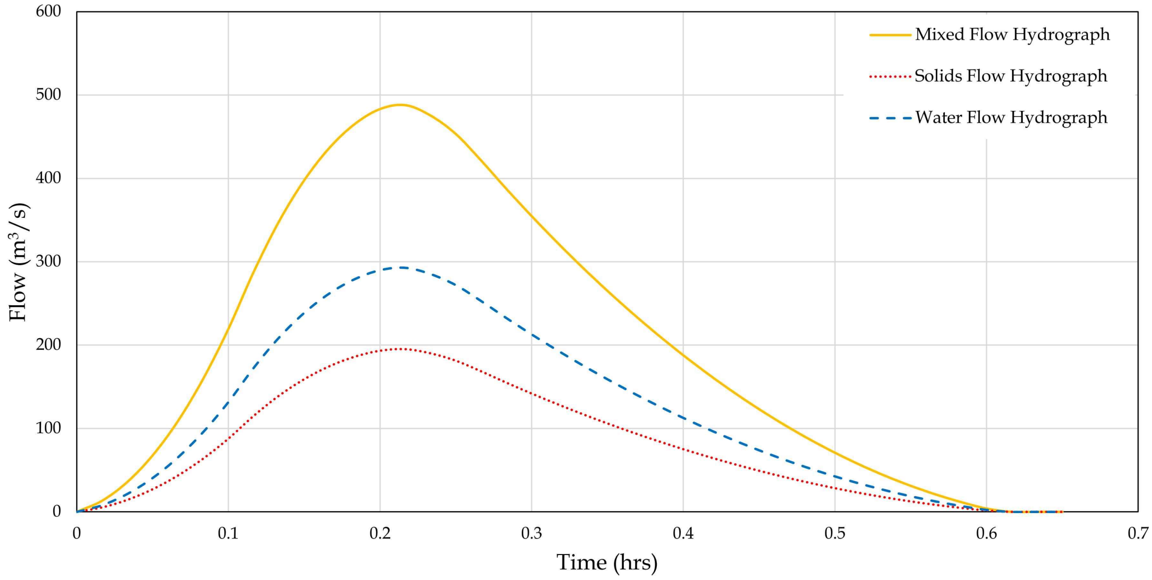


*Figure 1. Breach hydrograph.*

***Sediment Concentration***

Both programs require the proportion of sediment in the outflow material to be defined. FLO-2D uses concentration by volume ($C_v$) as the input, and allows for the values to be varied over time while HEC-RAS is able to convert between different units of concentration but uses a constant value for the duration of the breach. Outflow from a breached TSF usually contains a lower sediment concentration at the start of the breach and increases towards the end. This is because the initial flow from a breach contains most of the interstitial water in the TSF. Therefore, a model using varied sediment concentrations can be more realistic than one using a constant value. For this study, however, a constant value of 40% was used in all the models as HEC-RAS does not have the capability to vary the $C_v$ value. FLO-2D also requires the specific gravity of the tailings material to be specified, for which a value of 3 was used.

***Surface Roughness***

To define the surface roughness of the computational area, both programs require the Manning's coefficients for all areas to be specified. In this study, a default Manning's value of 0.04 was used throughout the computational area for all models. Both programs however have the capability to assign different Manning's n-values to different regions with similar land cover roughness.

***Rheological Parameters***

Rheology refers to the study of the deformation and flow behaviour of materials. Parameters that define this include the dynamic viscosity and yield stress of the material. According to Jeyapalan *et al.*, (1983), Seddon (2010), and Kulesza (2011); tailings material follows the behaviour of a Bingham plastic fluid as opposed to water which follows Newtonian fluid behaviour. Other non-Newtonian models in HEC-RAS include the O'Brien equations, Clastic Grain-Flow, and the generalised Herschel-Bulkley method. FLO-2D, however, uses only the Bingham equation. Thus, the Bingham equations for Bingham yield stress and plastic viscosity as calibrated using lab test results, and stated in Table 2 were used to define the rheology of the tailings.

*Table 2. Rheological parameters*

| Tailings characteristic | Parameters |
|---|---|
| Specific gravity (Sg) | 3.0 |
| Sediment concentration by volume ($C_v$) | 0.40 |
| Bingham yield stress ($\tau_y$) (Pa) | 9.012 |
| Plastic viscosity ($\eta$) (Pa.s) | 0.028 |

***Computational Area and Grid Size***

For consistency, the same computational area and computational grid sizes of 10 m, computing to 242 106 cells, were used for all models. This was optimised using the inundation extents from trial simulations to reduce the computational area to allow for smaller, more detailed grid sizes to be used. FLO-2D was the limiting program in this regard; however this was due to the limitations of the computing system and not the program itself. FLO-2D also limits this study to constant-sized square computational grids, whereas HEC-RAS can adjust the grid sizes and shapes in localised areas of concern (e.g. residential areas) for more detailed results. HEC-RAS also has the ability to enforce break-lines to ensure an accurate capture of more abrupt changes in the ground elevation. These break-lines are used as refinement regions to align the grids to accurately represent, for example, a levee or berm.

***Digital Elevation Model***

Terrain data with a 1 m by 1 m resolution obtained from a LiDAR (light detection and ranging) survey was used for all the models. Both programs interpolate the data for each grid cell as discussed in their manuals. In FLO-2D, the user defines the minimum number of data points, and the maximum radius around a grid node that the program should consider when interpolating an elevation for a grid cell. Additional settings are also available in HEC-RAS to specify the tolerances used to define the number of points extracted from the terrain. The difference in terrain data interpolated from HEC-RAS and FLO-2D is shown in Figure 2. HEC-RAS is shown to follow the original elevation while FLO-2D deviates, especially at peaks.

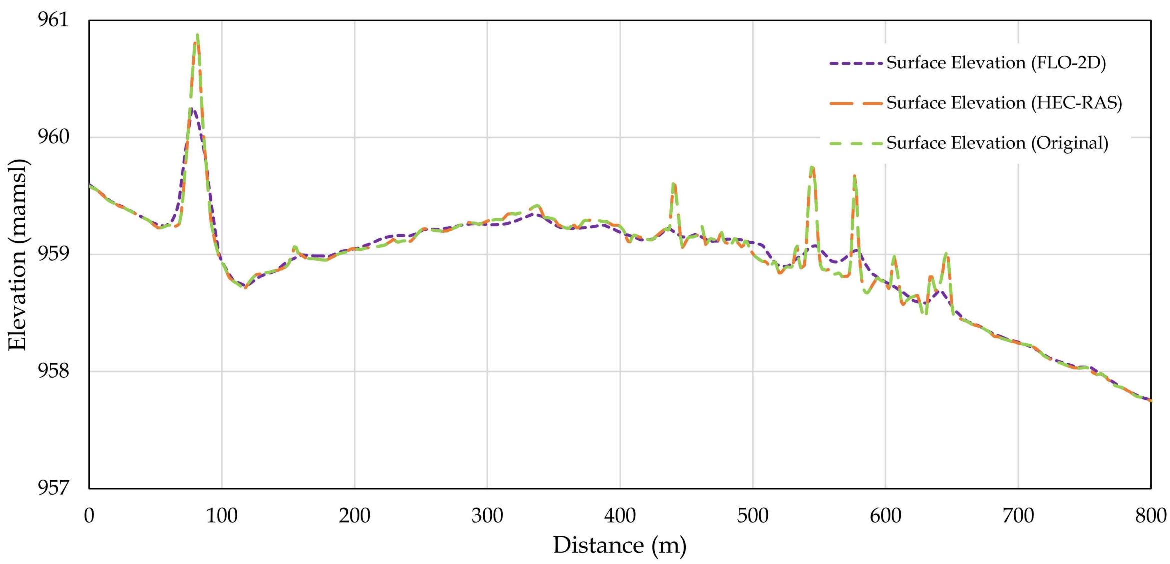


*Figure 2. Terrain comparison.*

**Running the Models**

All models were set up to simulate 24 hours of breach flow starting from the initial breach. The actual times taken to run each model are summarised in Table 3.

*Table 3. Model run times*

| Model | | Run time (hr) |
|---|---|---|
| FLO-2D | 2D diffusion wave | 0.33 |
| HEC-RAS | 2D diffusion wave | 4.58 |
| HEC-RAS | SWE-ELM | 1.15 |
| HEC-RAS | SWE-EM | 1.85 |

***Courant Numbers***

All unsteady flow simulations are solved in time steps. The Courant number is used to determine the size of the time step required. The Courant number is a dimensionless value that is a measure of numerical accuracy, and to ensure stability throughout the simulation. It represents the relationship between the distance the flood travels in a time-step and the length of a grid cell. The optimal Courant number is equal to 1 which means that if the Courant number exceeds this, particle displacement may be inaccurately represented (HEC-RAS User's Manual). HEC-RAS allows the user to use adaptive time steps with defined Courant number limits to give acceptable resultant Courant numbers and FLO-2D adjusts the Courant number automatically by changing the time-step to ensure model stability (FLO-2D Reference Manual, 2009).

***Model Equations***

The diffusion wave equation - the equation used in FLO-2D - satisfies only volume conservation between grid cells and not energy conservation. This causes the simulated breach flow to be distributed evenly across the terrain, and drainage channels as the wave travels downstream without any significant momentum changes. The shallow water equations, however, implement both volume and energy conservation between grid cells. This means the simulated breach flow moves with a high momentum capable of deviating from drainage courses. The SWE-EM model is more momentum conservative than the SWE-ELM model which means a smaller time-step, and ultimately longer run-times. HEC-RAS suggest that the SWE-EM model is only necessary where a more detailed analysis is desirable at for example hydraulic structures. Since past TSF and water dam breaches have been observed to result in high momentum waves travelling downstream, the shallow water equations are considered to be better suited to this type of modelling (Wang W, Chen W and Huang G, 2020).

**Results**

The results from the models can be viewed within the respective programs immediately after the simulations are complete as shown in Figure 3 for Model A and Figure 4 for Model B. HEC-RAS offers more functionality in this regard as it easily allows the user to compare the results of different HEC-RAS models. FLO-2D, in its result viewing application, Mapper Pro, can only present the results of one model at a time. The results are also saved as shapefiles which can be imported into various geographic information system-based software. In this investigation, Global Mapper was used to present the results used for the comparison between models. It should be noted that FLO-2D can create shapefiles with attribute data for each individual grid cell (e.g. maximum flow depth and maximum velocity at a cell). This allows the user to compare results from different models at sensitive locations.

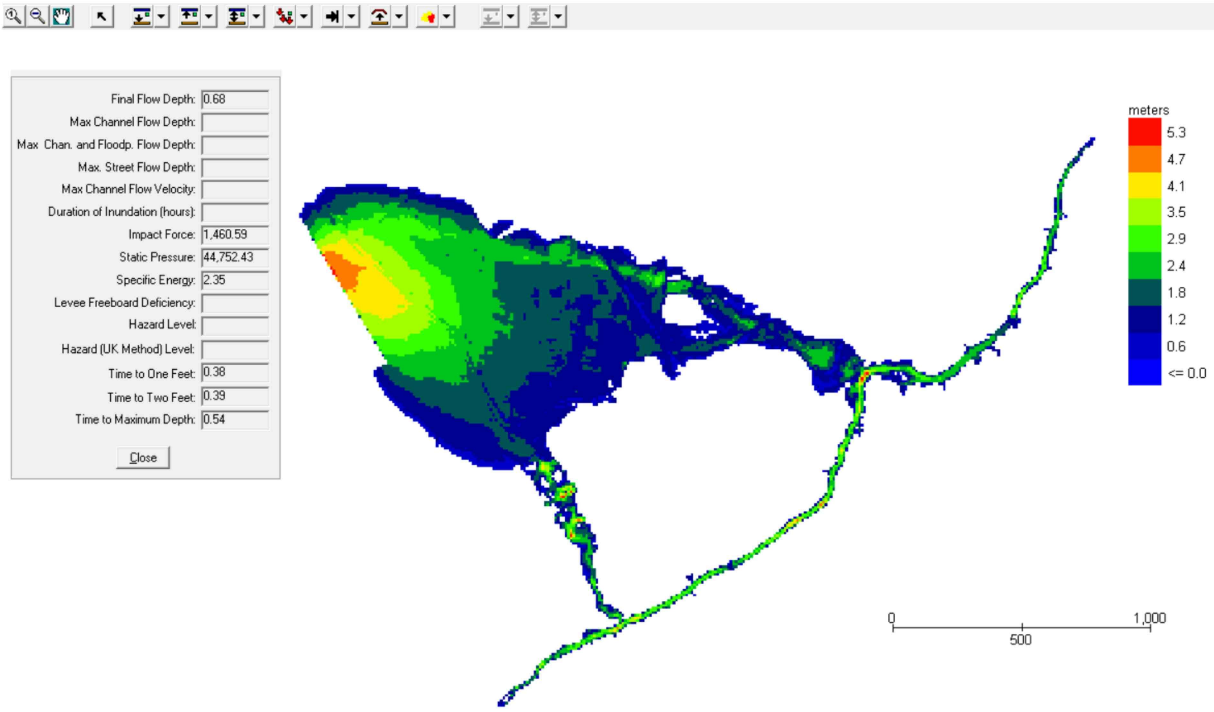


*Figure 3. FLO-2D results in Mapper Pro.*

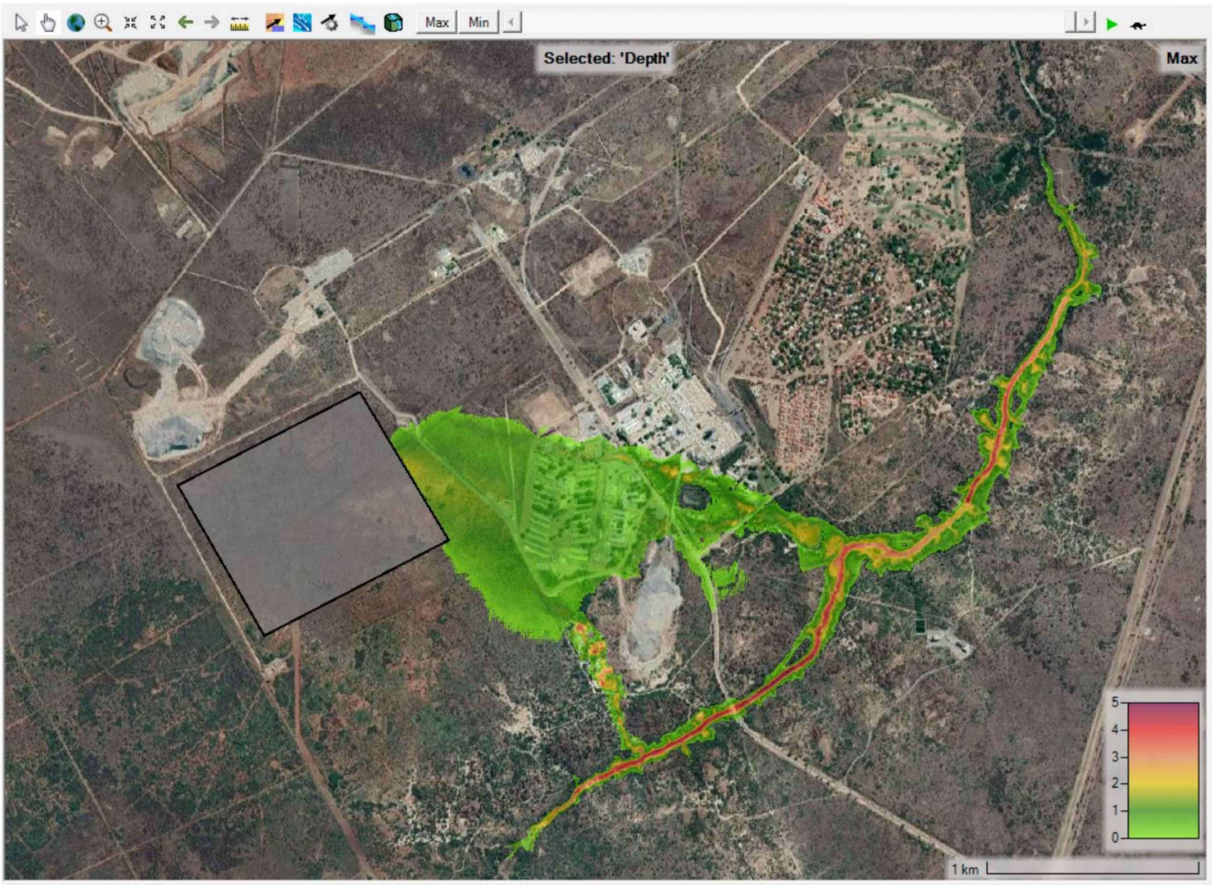


*Figure 4. HEC-RAS results in Ras Mapper.*

## COMPARISON AND DISCUSSION

This section compares the results of the four models which were run. Firstly, it briefly comments on how the programs have compared in terms of their setup and run procedures. Secondly, it compares the results of the models. This section concludes by summarising the comparisons discussed.

### Model Set Up and Run

In terms of setup procedures, both programs were fairly user friendly although a third-party program was used to set up the FLO-2D model. HEC-RAS does include more functionalities than FLO-2D, such as being able to adjust grid sizes, and shapes as well as allowing for more grid cells at critical areas. The FLO-2D simulation took significantly less time to run than the HEC-RAS models.

### Model Results

*Model A (FLO-2D) vs B (HEC-RAS)*

Figure 5 shows the resulting inundation extent of the two diffusion wave equation models in HEC-RAS and FLO-2D. As can be seen, Model B produced a greater inundation extent than Model A. It is also noted that the inundation extent is greater at the start of the breach for Model A than Model B. As the breach develops downstream, Model A follows the watercourse in a more confined inundation. Model B, while also following the watercourse, resulted in a more widespread inundation extent downstream.

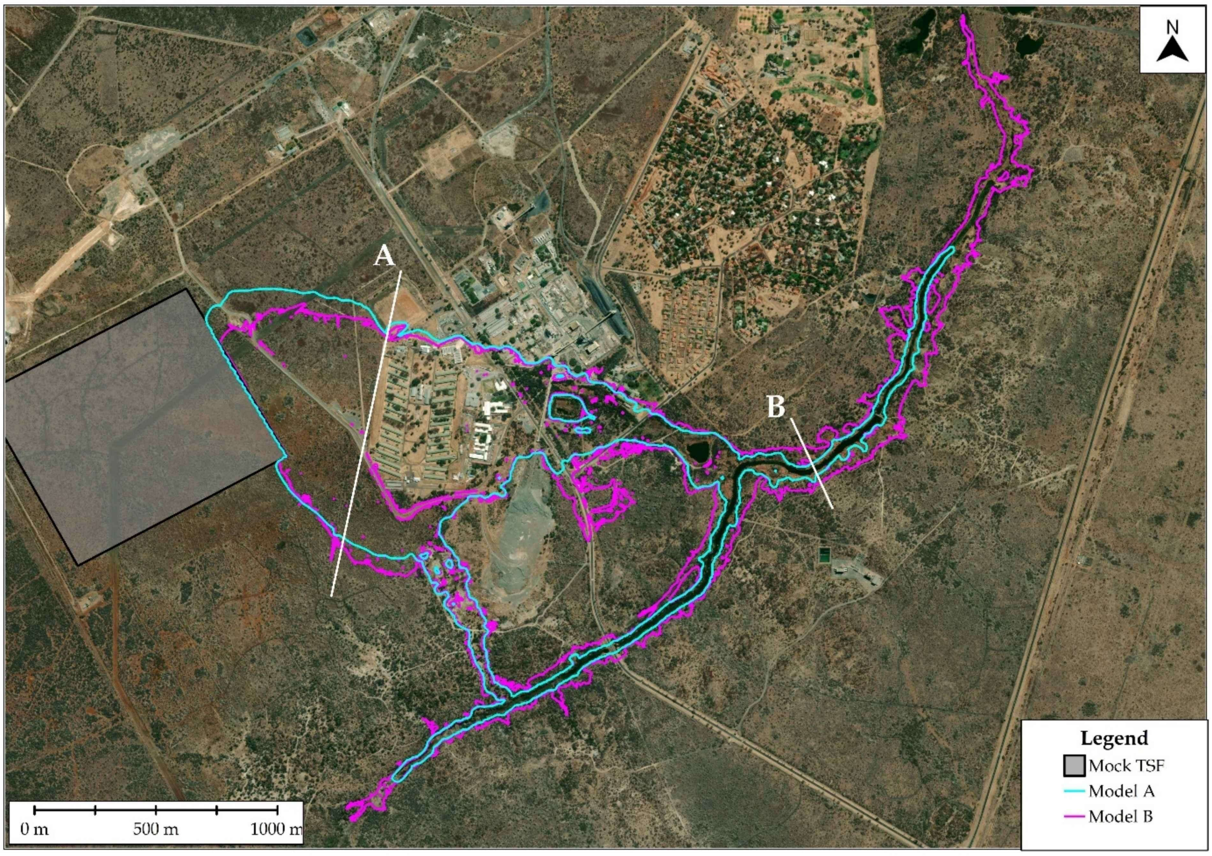


*Figure 5. Inundation extents for Model A and Model B.*

Figure 6 shows the maximum flow depths near the TSF (cross-section A) for Model A and Model B. The maximum flow depth across the cross section in FLO-2D has a significant amount of flow accumulating towards the middle. HEC-RAS showed similar results, except that the flow depth was less. The FLO-2D results also followed the terrain peaks between 600 m and 800 m distance. Figure 7 shows the maximum water surface elevation downstream of the TSF in the watercourse area (cross-section B). At this location, the flow depth from the HEC-RAS model was greater than from the FLO-2D model.

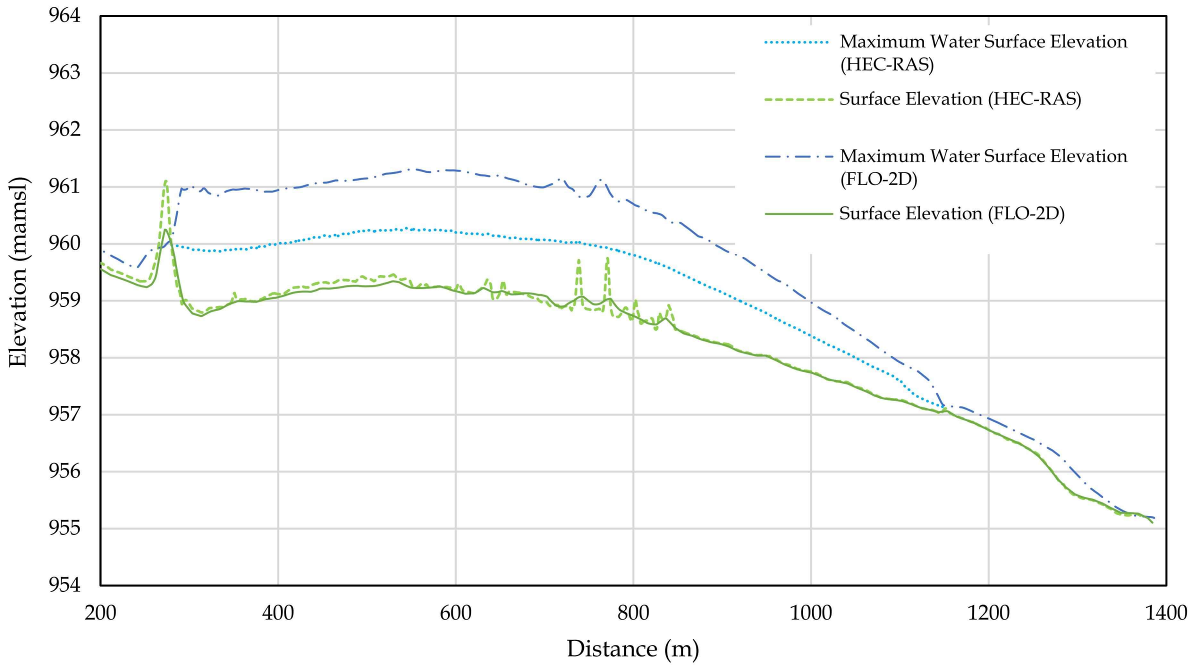


*Figure 6. Maximum water surface elevation with terrain at cross-section A.*

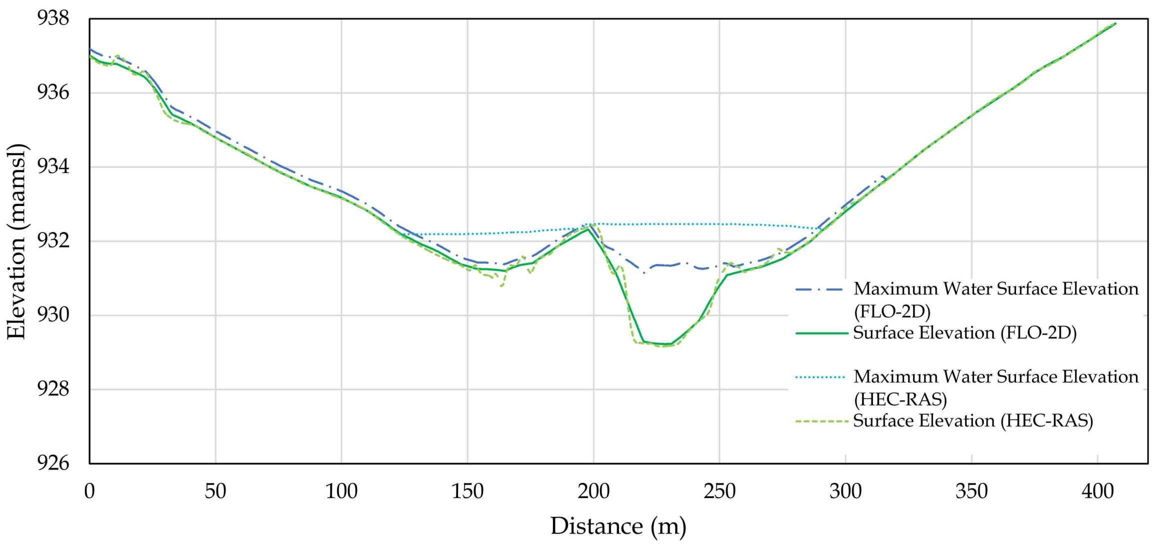


*Figure 7. Maximum water surface elevation with terrain at cross-section B.*

***HEC-RAS: Model B vs Model C vs Model D***

Models B, C, and D used the three different equation sets available in HEC-RAS. Figure 8 shows the inundation extents for the models. Minor discrepancies in the inundation can be seen. Models B and D mobilised the breach material further downstream than Model C. Figure 9 shows the water surface elevation for the three models at cross-section A. The differences in water surface elevations for the three models are minute. However, at areas with steeper terrain slopes where momentum can govern, the water level was higher for models using the SWEs.

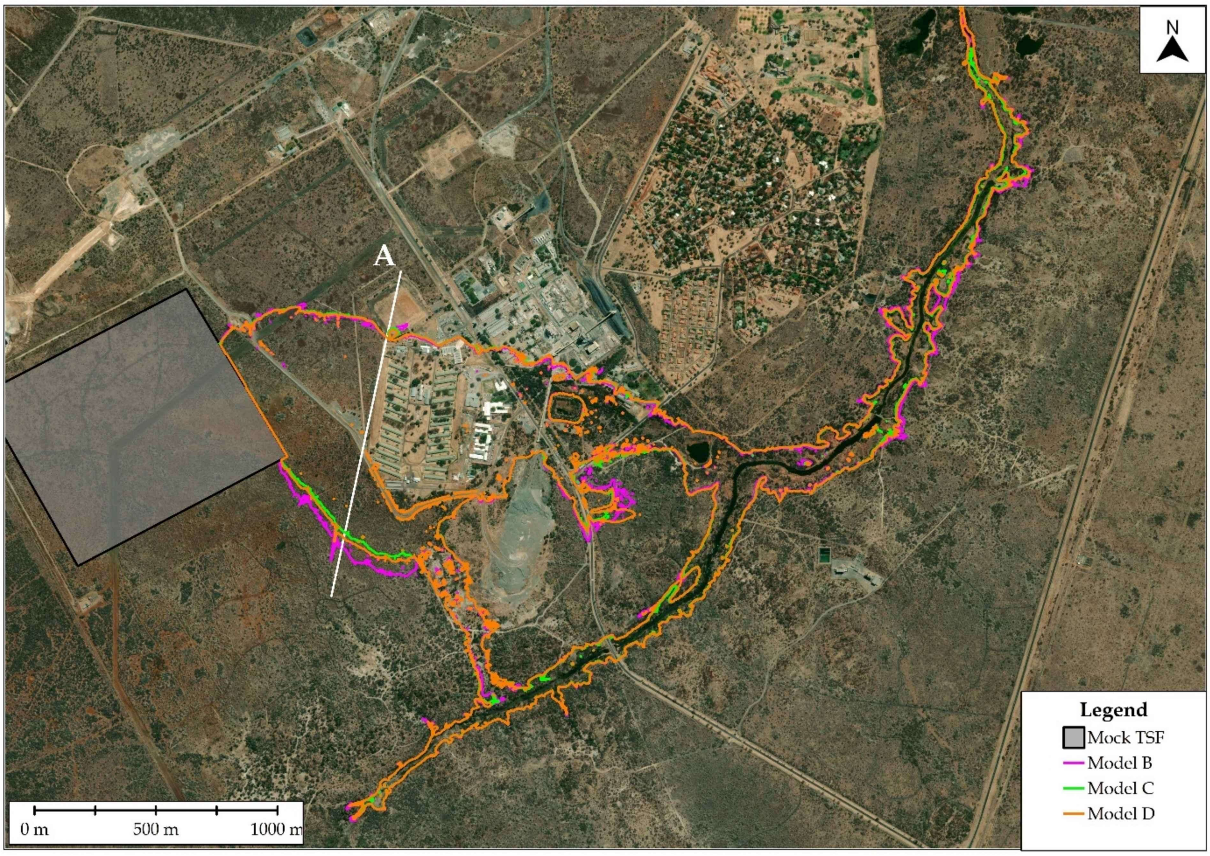


*Figure 8. Inundation extent for Model B, C and D.*

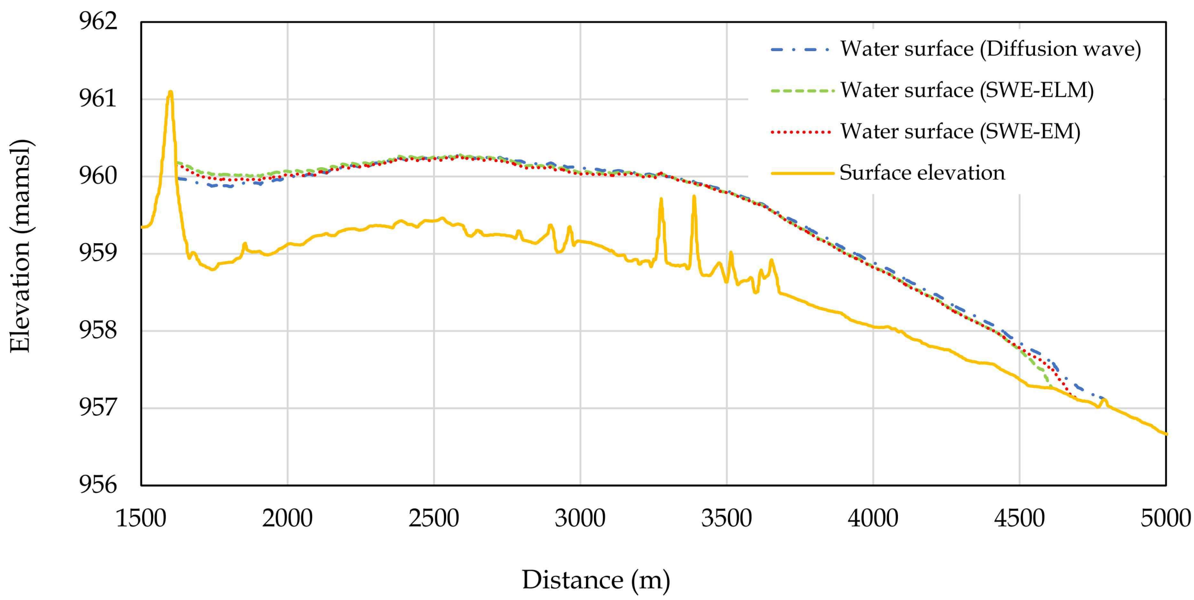


*Figure 9. Results from 2D diffusion wave (B), SWE-ELM (C) and SWE-EM in HEC-RAS (D).*

**Summary**

Table 4 summarises the comparisons discussed in this section as well as other factors that are useful to include. The results showed the following:

- The results of the 2D diffusion wave equation models showed a 30% larger inundation extent for the HEC-RAS model with the same breach parameters as compared to the FLO-2D model. This

may be due to the way HEC-RAS handles certain sediment concentrations or how the program integrates it to the breach hydrograph.
- The FLO-2D model simulated greater flow depths than HEC-RAS near the TSF and lower flow depths further downstream within the watercourse.
- The different SWE sets available in HEC-RAS did not show significant changes in the water depth results.

*Table 4. Model comparison*

| Detail | FLO-2D | HEC-RAS |
|---|---|---|
| Set up procedure | Simple, limited | Simple |
| Mesh | Structured | Unstructured and structured |
| Run time | Short | Lengthy |
| Volume conservation | Good | Good |
| Cost | $995/year | Free |
| Updates | Average improvement | Continuous improvement |
| Support | Included in package | Free with excellent customer support |

**CONCLUSIONS**

A model comparison between HEC-RAS 6.0 and FLO-2D was done to assess the differences in results for a tailings dam breach analysis.

To conclude, both HEC-RAS and FLO-2D can model a TSF breach, and give similar results which would most likely lead to the dam having the same consequence classification. Therefore, the decision to use either program should be based on the intended purpose of the results. If a design of a berm or other structure is required, HEC-RAS will give more detailed flow characteristics than FLO-2D, considering the SWE sets available in HEC-RAS. The capability of HEC-RAS to refine the computational grid around the structure will also benefit this type of analysis. In addition to Table 4, the following should be considered when choosing between HEC-RAS and FLO-2D to conduct a TDBA:

- FLO-2D can model a time varying $C_v$ over the duration of the breach whereas HEC-RAS cannot.
- HEC-RAS can refine the computational grid in areas to, for example, better represent features in the underlying terrain.
- HEC-RAS allows the user to define the tailings behaviour using non-Newtonian models other than the Bingham plastic model.
- FLO-2D can only model a TSF breach using the diffusion wave equation while HEC-RAS also offers the SWE sets which are better suited to dam breach modelling.

**RECOMMENDATIONS**

It is recommended that models with different sediment concentrations be compared to evaluate how HEC-RAS results correlate with FLO-2D results. Other software programs capable of modelling mud flow can also be assessed and evaluated against one another. Experimental modelling of a TDBA can also be used for calibration to evaluate different software and their results.

**ACKNOWLEDGEMENTS**

The authors would like to thank SRK Consulting for their resources that were used to compile the study. Comments from reviewers are appreciated.

**REFERENCES**

FLO-2D Reference Manual (2009). FLO-2D Software Inc., Nutrioso, AZ, 2009.

Jeyapalan, J.K., Duncan J.M. and Seed, H.B. (1983). Analysis of Flow Failures of Mine Tailings Dams. *Journal of Geotechnical Engineering,* 109 (2), 150-171.

Kulesza, R. (2011). Review of Technical Literature on Tailings Dam Failures involving Flow of Tailings. *USSD Workshop on Dam Break Analysis Applied to Tailings Dams*. Denver, Colorado, August 24 -26, 2011.

Seddon, K.D. (2010). Approaches to Estimation of Runout Distances of Liquefied Tailings. *First Int. Seminar on the Reduction of Risk in the Management of Tailings and Mine Waste*. Mine Waste 2010, Perth.

USACE (US Army Corps of Engineers) (2021). HEC-RAS River Analysis System User's Manual Version 6. US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, CA.

Wang W, Chen W and Huang G (2020) Research on Flood Propagation for Different Dam Failure Modes: A Case Study in Shenzhen, China. Front. Earth Sci. 8:527363. doi: 10.3389/feart.2020.527363

**Annelie Scholtz**

Civil Engineer
SRK Consulting

Annelie obtained her degree in Civil Engineering at the University of Pretoria in 2018 whereafter she pursued an honours degree in Water Resources Engineering in 2019. She has one publication in the field of geotechnical engineering. She started her career at SRK Consulting in January 2021 and is part of the tailings dam breach team.

**Simone Chetty**

Civil Engineer
SRK Consulting

Simone obtained her degree in Civil Engineering at the University of Cape Town in 2019. She started her career at SRK Consulting in January 2020 and is part of the tailings dam breach team.