DRA-15. HYDROLOGICAL MODELING

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Establish the flow system of the final conceptual model based on the GHN rock pile.

1. STATEMENT OF PROBLEM:

What are the long-term pore-water pressures within the rock pile in both the upper and lower regions? What are worst-case scenarios for pore-water pressures given extreme climatic events in the next 100 years? Will there be ponding in any particular portion of the waste rock pile? What is the length of residence time of various types of pore-water in the system? What are the percent water saturation levels in the system? The influence of annual climate on the overall flow regime must be established. The distribution of pore-water pressures is needed for the slope stability modeling program.

2. PREVIOUS WORK:

Previous related work in this area of the project includes the Phase I hydrological modeling activities. A summary of this work is shown in the following paragraphs.

Comprehensive numerical modeling has been completed to provide insight into the possible/probable flow scenarios for the rock piles of the Questa mine. The 1D, 2D, and 3D numerical models all provided contributing pieces to the allow reasonable conclusions to be drawn. The most important conclusions from the hydrologic numerical modeling program are the following:

1D MODELING

A large focus of the numerical modeling was to i) determine the sensitivity of various input parameters to the conceptual results as well as ii) to quantify the expected infiltration, and iii) the calibration of results to soil suctions and water contents measured near the surface by New Mexico Tech (NMT) and Golder Associates. The following results were observed.

- The relative influence of input variables on the minimum soil suction at a depth greater than 1 meter (m) can be tabulated in the order shown below. This listing of relative importance should be used to guide future field and laboratory efforts since they control soil suction in the SHALLOW failure zone. The hydraulic properties near the soil surface as well as the assumed values for osmotic suction and the climatic events establish the soil suction profile. For the gravel soil the influence of dry density is of primary importance. Dry density becomes of importance because it is an indicator of the porosity of the soil.
    1. Slope of the unsaturated hydraulic conductivity curve (K_{unsat} slope),
    2. Osmotic suction,
    3. Climate / Meteorological influences,
    4. Saturated hydraulic conductivity (K_{sat}),
    5. Air Entry Value (AEV),
    6. Residual soil suction (ψ_r),
    7. Dry density (γ_d) and

8. Residual water content (θ_r).

- Amounts of infiltrations for the 5-year simulation for the base case, osmotic suction + SD (i.e., standard deviation) and Osmotic suction – SD are 41%, 78% and 4.8%, respectively. Comparing these results with the water content and soil suction field data presented in Golder's report (2005) shows that the average osmotic suction value that used in the sensitivity analysis appears to be reasonable. The average annual surface infiltration rate appears to be **41%** (Sand) or **37%** (Gravel) of precipitation. The average infiltration passing a depth of 10m is **30%** (Sand) or **35%** (Gravel) of precipitation. The primary influences on these values are the assumed osmotic suction and the slope of the unsaturated hydraulic conductivity curve near the surface.
- For 15 cases of variation with all soil properties the reasonable depth of influence of extreme drying events appears to be 2m for the finer sand and 5m for the coarser gravel material. It appears unlikely that a soil suction greater than 250 kPa would be achieved at a depth between 2m – 10m. These model results are not calibrated to any field data as suction measurements were not taken at this depth.
- For 15 cases of variation with all soil properties the reasonable depth of influence of storm events appears to be approximately 10m. It remains unlikely that a suction less than 10 kPa (Sand) or 2 kPa (Gravel) would be achieved at a depth between 2m-10m.
- Runoff for most numerical models remained negligible. This is not to say that localized runoff will not occur during extreme storm events in the field. While there will be localized runoff, site-wide runoff is unlikely in the context of the soil properties adopted for this study. Calculation of runoff is highly sensitive to the soil properties adopted at the surface of the numerical model. It is noted that the calculation of negligible runoff is consistent with the lack of gullies on the original GoatHill North rock pile surface. Gullies were noted in field observations on the front rock piles which would indicate possible runoff conditions are being reached in certain storm situations. Detailed hydrological data was not available at the time of numerical modeling for the front rock piles. The current hydrological numerical modeling should therefore not be considered to apply to the front rock piles. Evaluating the runoff for the front rock piles is to be considered a separate effort.

2D MODELING

A 2-D seepage model was developed to take into account the effect of the geometry of the slope and the bedrock layer. Results from a 2-D model at different locations along the slope provide an insight into hydrological flow along with the soil suction distribution in the rock pile profile; and therefore, provide a better insight into slope stability analyses.

From the 2D analysis the following points can be noted:

- Approximately 5 years of numerical modeling was required to approach steady-state conditions. Ponding is possible at the bedrock interface on the lower portions of the slope. The development of ponding is largely controlled by slight depressions in the geometry.

- The average (base case) model indicates an infiltration rate of **57%** of precipitation.
- In the numerical model the upper heights of the GHN site see flow in the rock pile between 80-95% of total flow. Inversely flow in the rubble zone in the upper heights is between 5-20%.
- At approximately halfway down the slope the total water flow within the rock pile layers between the rubble zone and the waste rock are approximately equal.
- At the toe of the model between 93-99% of the flow is through the rubble zone.
- The current flow into the weathered bedrock is approximately 8% but this rate is highly variable depending on the conceptual model used for representing bedrock flow. Therefore in the phase II numerical model the bottom boundary was assumed to be a no-flow boundary and an 8% flow was assumed. An overview of the determined hydrological processes for the entire rock pile pile may be seen in Figure 1.

3D MODELING

The 3D hydrological model provides an understanding of the issues related to lateral flow in the GHN system. It is possible through this model to provide an understanding of how prevalent the funneling of flow can be due to original topography at the base of the waste rock.

A steady-state 3D model was set up and it can be seen that funneling of flow is prevalent at the base of the waste rock. The valleys at the top of the bedrock lead to the development of saturated zones under average applied flow conditions. The location of these saturated zones in the numerical model is heavily influenced by slope geometry at the base of the rock pile. It should be noted that these saturated zones in the numerical model were only noted once at the bedrock interface by NMT during the rock pile destruction.

3. TECHNICAL APPROACH

Use toe seepage, climate data, and tensiometer/water content readings to calibrate the model to field conditions at GHN. The calibrated model may then be used in the future to run predictive models of what scenarios may be reasonable at 100 or 1000 years. The pore-water pressures from the calibrated model will then be used in the slope stability model in order to effectively model the stress state.

The system will be modeled using the SVFlux finite element modeling package which is based on the classic Richards equation for saturated/unsaturated flow in a porous medium.

Of particular importance is the quantification of the top boundary in the model. This top boundary controls the interface with the climate and has been shown to develop a crust-like consistency. It is this top boundary which primarily controls the flow into and out of the rock pile. This statement is further justified by the findings outlined (SRK, 2007) which found that i) the water table is deep, and ii) the fissures in the bedrock at the base of GoatHill North are filled with clay and unlikely to be a source of spring flow.

4. CONCEPTUAL MODEL
PHASE I – 8-REGION CONCEPTUAL MODEL

The Phase I conceptual model is based on the results of analysis performed in Phase I of the project. It utilizes a simple 8-region conceptual model in which the representation of the waste rock is largely homogeneous (SoilVision, 2006).

The soil-water characteristic curves predicted from the grain-size distribution curve using SoilVision V4.13 (SoilVision Systems Ltd., 2006) are comparable to the data measured using UBC Pressure Plate Cell. The statistical analysis provides mean and standard deviation for various soil properties of the soils at the Questa mine. The soil datasets used in the numerical modeling covered a wide range of possible soil properties and also covered most of the range of soil properties established by other consulting companies such as Golder Associates and Norwest.

The upper boundary condition was represented by an osmotic salt crust mechanism which restricted evaporation. Both 1-D and 2-D simulations with the new crust formation provided reasonable results for the water balance computations. The soil suction distribution obtained from the model is comparable with that measured from the field.

Soil suctions in the upper 1 m of the waste rock changes significantly in the range from several kPa up to several thousand kPa. Soil suctions from a depth of –1 m or lower in the waste rock are approximately in the range of 20 kPa to 900 kPa (SoilVision Phase II Hydrology report, 2008). The simulations show that the 6 most significant factors that control the minimum soil suction in a soil column are the: i) Slope of unsaturated hydraulic conductivity function; ii) Climate data; iii) Saturated hydraulic conductivity; iv) Dry density and v) Air entry value of the soil.

The 2-D steady state model results show that there are equal amounts of shallow and deep flows near the crest of the Goat Hill North slope. In other words, the volume of water flow near the surface and near the base of the waste rock is similar. However, near the toe of the Goat Hill North, more than 90% of water flow in the waste rock is deep flow (i.e., near the base of the waste rock).

The simulation results show that the amount of water flowing into the bedrock zone is significantly dependent on the soil properties of the bedrock (i.e., ranges from 8.7% to 55.2%). The coarser the material properties for the bedrock, the higher amount of water that will flow into the bedrock. It is expected that approximately 10% of infiltration will go into the bedrock with the selection of reasonable soil properties as presented in the SoilVision phase I numerical modeling (SoilVision, 2006).

In summary it is possible to identify the following approximate flows as outlined in Figure 1. It should be noted that each of these flows represent the average or base case model. These general flows are useful in determining the appropriate setup of future conceptual models.

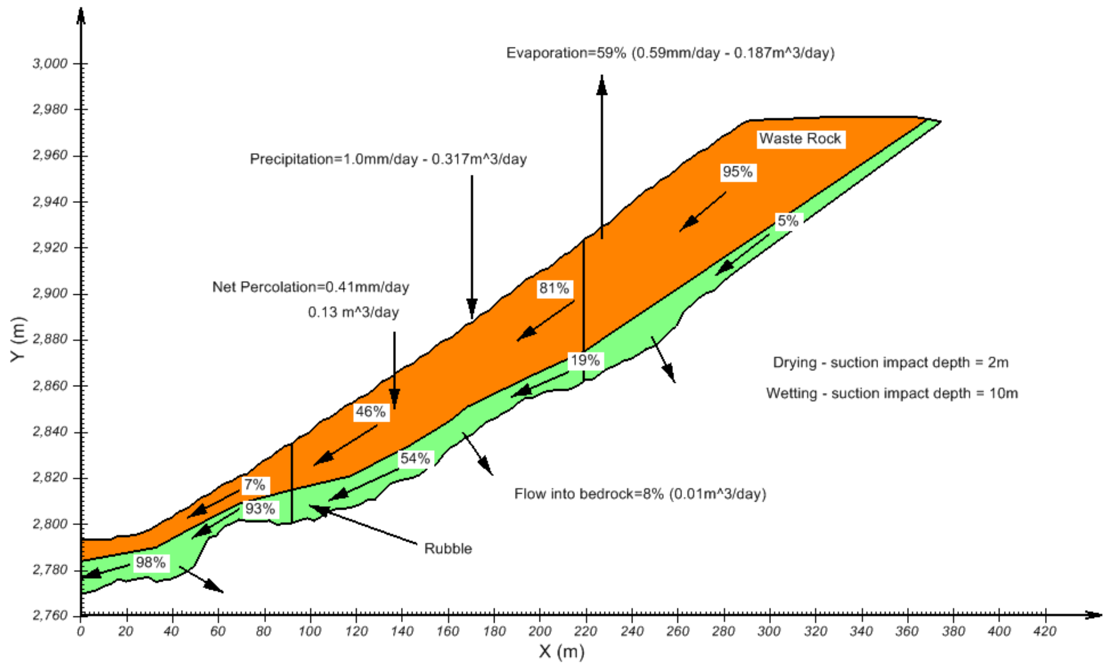


Figure 1 Summary of estimated flows in the waste rock pile as percentages of precipitation or total flow (for the cross-sectional flows)

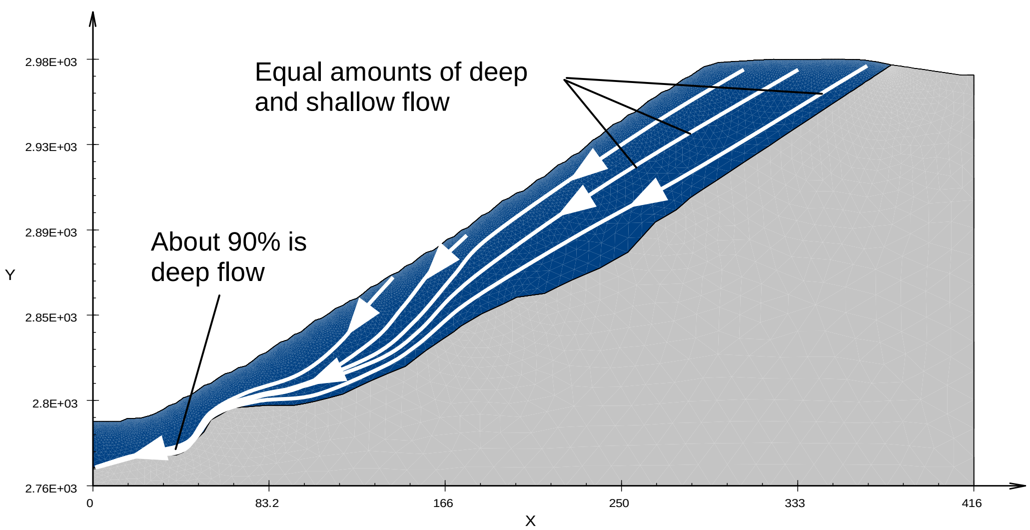


Figure 2 Flowlines for 8-region conceptual model

The 3-D steady state model results show that there is funneling of flow at the base of the waste rock. Analysis also shows that it is possible to achieve saturation levels of approximately 92% at lower portions of the slope. Higher saturation levels are highly dependant on the geometry of the slope and increased saturation levels correspond to naturally occurring depressions. Soil suction distributions in the two 3-D steady state models agree reasonably well with previous 1-D and 2-D modeling results. It should be noted that saturation measurements at the toe zone are not available and therefore it is impossible to benchmark this aspect of the numerical model. It should be noted, however, that these calculated flows agree reasonably with the measured toe flow and therefore there is a certain amount of justification.

PHASE II – COMPLEX CONCEPTUAL MODEL

Phase II will utilize a more advanced 2D conceptual model (Figure 3). In this advanced conceptual model the waste rock layers are divided up into coarse, medium, and fine layers. It was also found in the course of the Phase II testing that the upper boundary condition is not dominated by osmotic conditions. However, the formation of a crust was noted by field observations performed by NMT. Therefore a new boundary condition was coded into the software which allows the representation of a crust boundary condition which started formation immediately upon completion of a precipitation event and finished formation after a continuous 5-day progression of no future precipitation events.

The flow through each respective layer is then examined.

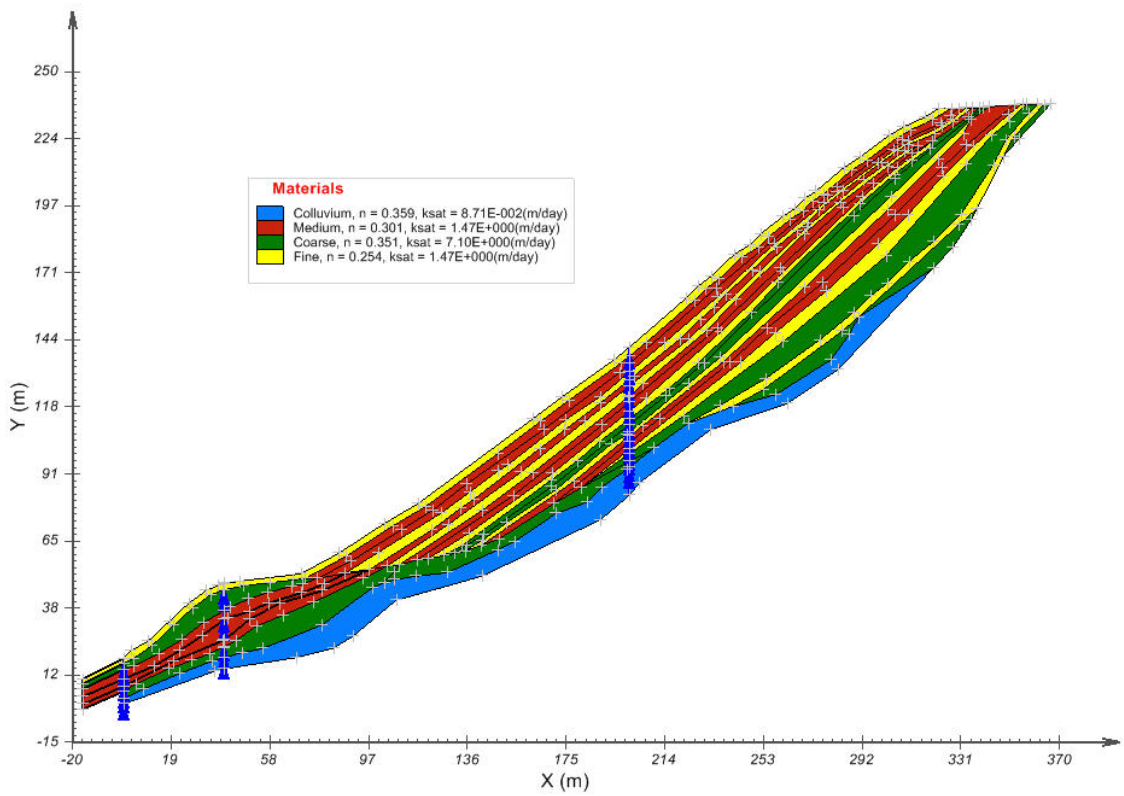


Figure 3 Hydrological Phase II conceptual model

From a steady-state analysis it can be seen that the average particle travel times in the waste rock range between 4000 (11 yrs) days to 7000 days(19 yrs). The particle travel times also give an indication of the reasonable flow paths in the new conceptual model.

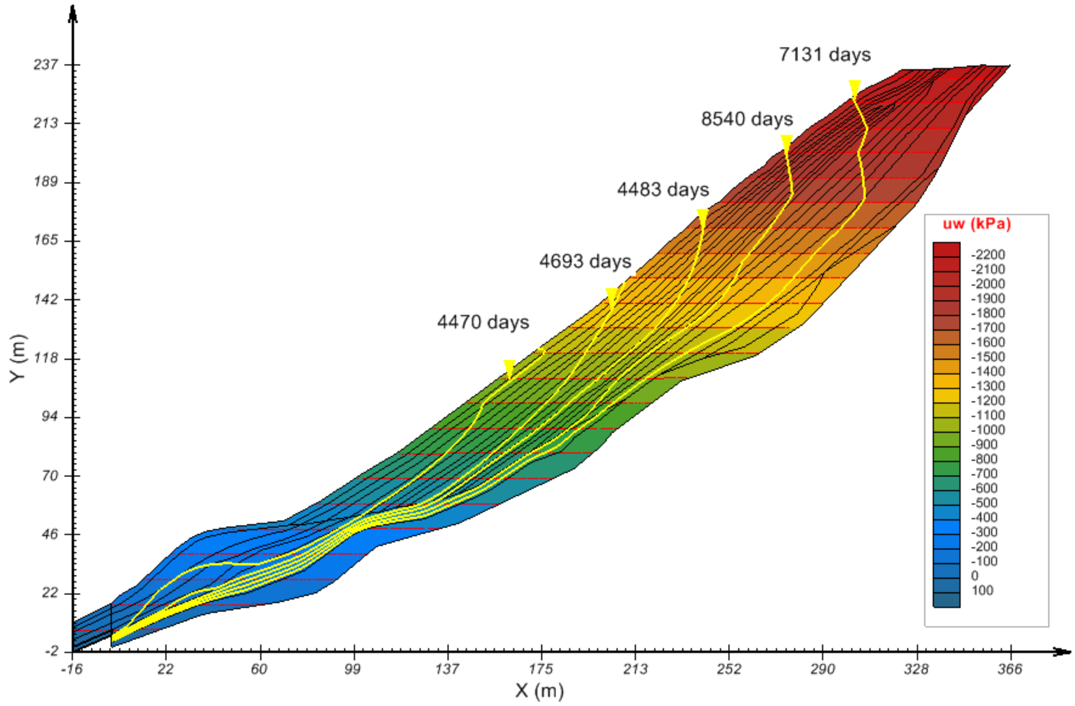


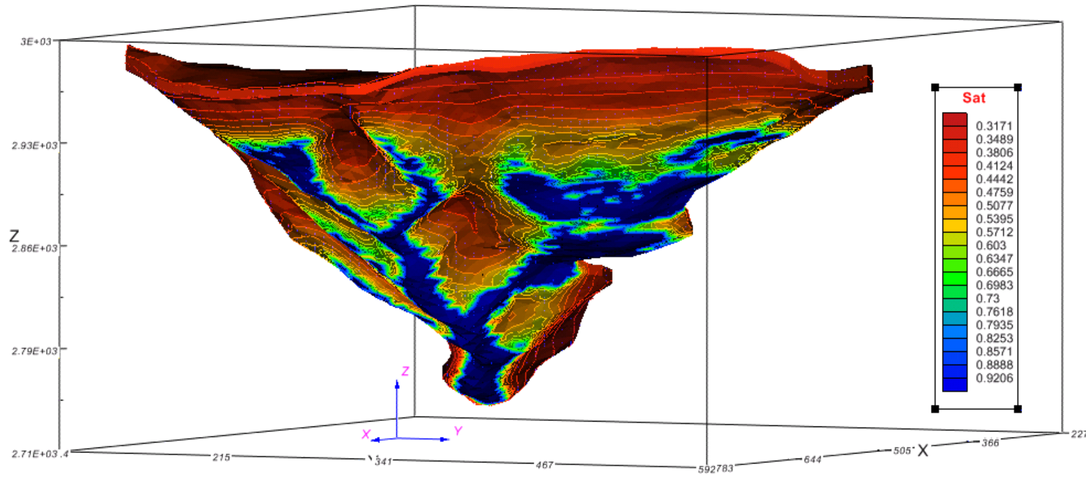
Figure 4 Particle flow times for average particles in the unsaturated system (1mm/day flow application)

A common question related to the numerical modeling is whether or not localized zones of saturation will i) develop in the field, and ii) can be represented in the current numerical model. Local zones of saturation in the upper/mid portion of the rock pile at the bedrock interface have been noted in the field both by SRK and NMT (Virginia McLemore, personal communications, 2008). There has been discussions as to whether these localized zones of saturation occur naturally as a result of pockets of trapped precipitation flow or as a result of springs coming up from the bedrock.

A 3D model was set up in order to determine the reasonable saturation levels. In this model the average fine parameters were used to describe the material. While it is recognized that there is a wide variety of materials the average sand was considered reasonable in order to adequately represent reasonable soil properties for the site.

Localized zones of saturation were noted in the numerical model and were primarily formed i) at the base of the model above the bedrock and ii) were highly influenced by the geometry of the site and lateral flow. The localized zones of saturation are noted in 2D representations of the site but are not as prevalent due to the lack of consideration of lateral flow in the 2D model.

It is therefore the conclusion of the hydrological numerical modeling that any localized zones of saturation are the result of precipitation being directed to perched zones at the base of the rock pile which are largely created by the topology above the bedrock.



The resulting flow system is largely controlled by the assumptions regarding the upper crust. This concept was noted as apparent in the numerical modeling program. In Phase II the assumption regarding the osmotic salt crust was disproven by laboratory experiments. This subsequently led to the implementation of an empirical boundary condition in the numerical model in which the crust is allowed to form a cut off in which evaporative flow after a set amount of days is significantly reduced.

The average of the numerical models run with the new boundary condition formulation indicate the approximate same distribution of flows as the hydrological modeling of phase I. The new crust boundary condition indicated overall **evaporation averages of 57%** and **infiltration rates of 43%.** Such values are close enough to the values of the phase I part of the study as to not invalidate the conclusions reached in the first part of the study.

Therefore the conceptual model adopted for hydrological flow for Phase I of the project can be adopted as well for phase II.

5. Reliability Analysis

Reliability of the current system wasestimated through a sensitivity analysis. In each sub-analysis of this project there are variations of parameters chosen which reflect the reasonable limits of such parameters. Variation of these parameters outside these limits is considered unlikely.

Resolution of Discrepancies

Implementation of a crust upper boundary is necessary in the model in order to match measured tensiometer readings.

6. Status of Component Investigation

The numerical modeling for the hydrological program is complete. The hydrological reports are listed in the technical references section.

7. CURRENT CONCLUSION OF THE HYDROLOGICAL MODELING

From the phase I modeling effort the following relevant issues should be noted:

1. The model is most sensitive to the number of days required to form the crust.
2. Approximately 5 years of modeling is required in order to achieve steady-state conditions.
3. Ponding in the lower levels is possible and is largely dependant on the geometry.
4. The average (base case) model indicates an infiltration rate of 57% of precipitation.
5. The zone of influence of pore-water pressure change due to a large storm event seems limited to a depth of 5-10m.
6. The measured average unsaturated soil properties must be modified one standard deviation in each direction (one towards fine and one towards coarse) in order to adequately represent coarse/fine separation of flow. This is required in order to duplicate the desaturation of coarse zones as noted in the field.
7. Large climatic events observed in the 100-year climatic dataset only produce small ponded zones above the bedrock in the numerical model. These small ponded areas are not enough to significantly impact the factor of safety and initiate a failure.

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