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Erosion Modeling for the Clive DU PA

Clive DU PA Model v1.4

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Prepared by

NEPTUNE AND COMPANY, INC.

1505 15th St, Suite B, Los Alamos, NM 87544

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1.0 Erosion Model Input Distribution Summary

A summary of parameter values and distributions used in the erosion modeling component of the Clive Depleted Uranium Performance Assessment Model (the Clive DU PA Model) is provided in Table 1. Additional information on the derivation and basis for these inputs is provided in subsequent sections of this report.

For distributions, the following notation is used:

- Discrete represents a discrete distribution of a finite number of pre-defined values.

Table 1. Summary of distributions for erosion modeling

GoldSim Model Parameter	Units	Distribution or Value	Notes
FractionGully	—	discrete	See Section 4.1

2.0 Introduction

The purpose of this white paper is to address specific details of the erosional processes that may affect cover performance. This paper is organized to give a brief overview of erosional processes and present the overall modeling approach, assumptions, and implementation in the Clive DU PA Model.

Above-ground covers of waste repositories are subject to erosion by the forces of wind and water. The proposed waste disposal cell for DU at the Clive facility, which has an engineered above-ground cover, is subject to these erosional processes. Both wind and water erosion are represented in the Clive DU PA Model. Details of wind erosion modeling and the effects on dose to potential receptors are addressed in detail in the *Atmospheric Transport Modeling* white paper, (Atmospheric Modeling.pdf) and are not addressed further in this white paper. Water erosion via the return of Lake Bonneville or a small lake is not discussed in this document, but is addressed in the *Deep Time Assessment* (Deep Time Assessment.pdf). Other water erosional processes are described below.

There are two types of water erosion described in the CSM: sheet erosion and gully erosion (channel formation). The approach used in the Clive DU PA Model to evaluate the influence of erosion on embankment performance uses results from a landscape evolution model of a borrow pit area at the Clive site as an analog for embankment cover erosion.

2.1 Sheet Erosion

Sheet erosion is erosion of soil particles by water flowing overland as a “sheet” in a downslope direction. During rainfall events when rain falls faster than water can infiltrate, runoff can occur, acting as a mechanism for eroding cover materials. Sheet erosion is a uniform process over the area of the cover and depends largely on the steepness and shape of the slope, soil texture, and cover characteristics, as well as rainfall intensity. This is different from erosion that flows in defined channels (i.e., gully erosion), which is discussed in Section 2.2.

In the top slope of the embankment, where slopes are gradual (about 2% slope), sheet erosion will be slower than on the steeper side slopes of the cell (about 20% slope) (*Embankment Modeling* white paper). As soil moves down slope by sheet erosion, it is likely that this material would be replenished by deposition of clean eolian silt from the surrounding environs (i.e., a net balance of zero change). In the end, the total soil volume on the embankment would not change, though there would be a slow movement of soils down slope, along with the contaminants they could potentially contain.

2.2 Gully Erosion

Gully erosion is a process that occurs when water flows in narrow channels, particularly during heavy rainfall events. Gully erosion typically results in a gully that has an approximate "V" cross section that widens (lateral growth) and deepens (vertical growth) through time until the gully stabilizes. The formation of gullies is a concern on uranium mill tailings sites and other long-term above-ground radioactive waste sites (NRC 2010). Gully erosion has the potential to move substantial quantities of both cover materials and waste, should the waste material be buried close to the surface. It occurs when surface water runoff becomes channeled and repeatedly removes soil along drainage lines, creating a depositional fan of the removed materials.

The engineered cover at the Clive facility may be subject to gully erosion via a disturbance attributed to an animal burrow, large animal tracks, the root of a fallen tree or shrub (tree throw), or off-highway vehicle (OHV) track. It is assumed that a notch or nick will be created from these activities at some location on the surface of the cover and the feedback processes inherent in gully formation will cause erosion downward to the surrounding grade and erosion upward toward the top slope of the embankment. As water flows across the inner walls of the notch, erodible solid materials will be transported with it, creating a larger notch (both vertically and laterally) and thus a greater capacity to remove solid material.

3.0 Evapotranspiration Cover Design

The composition of the embankment cover is an important factor in determining its erodibility. At the Clive facility, the cover for the portion of the Federal DU Cell is an evapotranspiration (ET) cover composed of a 6-in. thick Surface Layer of native vegetated Unit 4 material with 15 percent gravel mixture on the top slope and 50 percent gravel mixture for the side slope. The functions of this layer are to control runoff, minimize erosion, and maximize water loss from ET. This layer of silty clay provides storage for water accumulating from precipitation events, enhances losses due to evaporation, and provides a rooting zone for plants that will further decrease the water available for downward movement. Underlying the surface layer is the Evaporative Zone Layer. This layer is also composed of Unit 4 material and is 12 in. thick. The purpose of this layer to provide additional storage for precipitation and additional depth for plant rooting zone to maximize ET. The Frost Protection Layer is below the Evaporative Zone Layer, and is 18 in. thick. The purpose of this layer is to protect layers below from freeze/thaw cycles, wetting/drying cycles, and inhibit plant, animal, or human intrusion.

4.0 Borrow Pit Model Analog

A borrow pit model has been used in the Clive DU PA Model as an analog to evaluate the influence of erosion on embankment performance. Results from landscape evolution modeling at the Clive Site are used to project embankment cover erosion at 10,000 years. The following sections describe the borrow pit model and the implementation of the results into the Clive DU PA Model.

4.1 Simulation of Sheet and Channel Erosion

Landscape evolution models were developed and applied for a face of a borrow pit at the Clive Site in order to predict the response of the pit face and upslope land surface to water erosion processes during runoff events. The models provide a quantitative description of the evolution of slopes and channels (also called gullies in this white paper) over time. The objective of the models was to provide a realistic estimate of the rate of progression of hillslope erosion loss and channel development towards the existing embankments that encase waste. Landscape evolution models are based on the concept that, while the runoff response of a landform to rainfall depends on the shape of the landform, the landform shape also adjusts through erosion processes acting during the runoff event. This concept is applied by considering the interaction of hillslope erosion processes (sheetflow) with channel growth (gully formation) process in the model (Willgoose et al. 1991a, 1991b).

The landscape evolution model SIBERIA (Willgoose, 2005) was selected for this analysis. Landscape evolution models such as SIBERIA capture the interaction between the runoff response and the elevation changes of the landform surface over long time periods. This capability makes models such as SIBERIA particularly well-suited for waste site modeling. The model domain for the borrow pit included the borrow pit floor, a 3-m (10-ft) high pit face at a 1:1 slope and several hundred meters of ground surface upslope from the pit face at a slope of 0.3 percent. The soil was characterized with properties consistent with the Unit 4 silty clay, and had no vegetation or rock cover.

While composed of similar soil the surface layer of the top slope of the ET cover proposed for the Federal DU Cell has a slope of 2 percent, a gravel composition of 15 percent, and will be re-vegetated with a mix of native and non-native species. While the cover top slope has a larger slope of 2 percent as compared with the slope of 0.3 percent for the undisturbed area upslope from the borrow pit face, the top slope characteristics include vegetation and gravel admix that would act to slow erosion and channel formation. Changes in elevation at each node were obtained at 100 y, 500 y, and 1000 y.

Assumptions for this approach include:

- The geometry of the borrow pit wall and upslope area are sufficiently similar to that of the embankment top slope and side slope that the borrow pit serves as an analog.
- The borrow pit materials (Unit 4) are sufficiently similar to the layers of the embankment (Unit 4 with gravel, Unit 4, and radon barrier clays).

- Surface elevation changes at 10,000 y can be extrapolated from SIBERIA model results from 100 y, 500 y and 1000 y.
- The results at 10,000 y approximate steady state of gullies. This steady state assumption is implemented from time zero in this model.
- The area of waste that is deposited on the fan is the same as the area of waste exposed in the gullies, using projections onto the horizontal plane.
- The excavation of ET Cover cells was not considered in the calculations below for contaminants in the excavated mass from the gully because it was assumed that significantly more contaminant mass was in the waste than in the cover and that the material extracted from the waste layers would be on top of the fan.

A subset of the borrow pit model domain was selected to represent the cover. The area extended from 50 m downslope from the edge of the embankment to 10 m upslope from the borrow pit face. The model domain was represented by a grid with nodes at equal 0.75-m spacing. Changes in elevation at each node were obtained at 100 y, 500 y, and 1000 y. Simulations were done for two rainfall intensities. Since only small differences in elevation change were seen between the two rainfall intensities, results for both intensities were combined to provide two estimates of elevation change at each of the three times. The 0.1th, 10th, 20th, and 90th percentiles of the simulated data were calculated at each of the three times. These percentile plots in most cases showed a non-linear relationship between the percentile depth of the area and time.

A square-root function was fit to the 0.1th, 10th, 20th, and 90th percentiles using the general form:

$$f(t) = A \times \sqrt{t} + \text{error}$$

where

f(t) = percentile depth of the area,
A = amplitude parameter, and
t = time.

The error term was assumed to follow a normal distribution. The `nls()` function in the 'stats' package of the software program *R* was used to estimate the *A* parameter and the error term. The four percentile plots used for the fit are shown in Figure 1.

After the percentile curves were fit using the square root function, parameters were randomly drawn from the *A* distributions for three of the curves, and values of the function at 10,000 y were calculated. For each of the 1,000 iterations, a lognormal distribution was estimated from the resulting percentiles. The proportion of the lognormal distribution that fell within each specified depth profile was calculated through simulation. An example iteration is included below for demonstration purposes:

1. Simulate "*A*" values for the 10th, 20th, and 90th percentile regression fits. The fits for the 0.1th percentile were not used for stability reasons. These values might be 1.59, 0.670, and -0.228, respectively.

2. Project the depth value for each of the curves at 10,000 years. For the "*A*" parameters above, these would be 159 mm, 67.0 mm, and -22.8 mm, respectively.

3. Fit a lognormal distribution to these projected depth fits. This step involves finding the best geometric mean, geometric standard deviation, and shift parameter (lower bound) for the percentiles above. Because the 10th percentile of the data is really the 90th percentile of "depth," the percentiles used for fitting are subtracted from 1. So for fitting purposes, the 10th percentile of the data is the 90th percentile of the fitted distribution (and so on).

4. The parameters of the lognormal distribution with the best fit are: $\mu = 3.22$, $\sigma = 1.56$, $\theta = -26.2$. One thousand values from this lognormal distribution are simulated, and the proportion that fall within each depth range are calculated and saved to a matrix. As a point of reference, the theoretical 10th/80th/90th percentiles of this distribution are -22.77, 67.03, and 158.8, respectively. So the lognormal distribution fits very well to these three percentiles (see Step 2).

5. The matrix of the 1,000 iterations is output to a .csv file and converted to an MS Excel file.

The 1,000 realizations of fraction of cover area for each elevation change (depth) interval are shown in Figure 2. The original output file included 0.5-m depth increments from the beginning of the waste (1.5 m) up to 10 m. It was clear that there are virtually no gullies greater than 3.5 m, so the depth ranges were cut off there, the proportions were re-normalized, and the 3.5-m to 10-m depth ranges were deleted.

4.2 Implementation in the Clive DU PA Model

In the Clive DU PA Model, the area of the waste exposed by the gullies and the volume of the waste removed by the gullies are used in the dose calculations. The area of waste exposed by gullies and the resulting fan of waste from gully excavation of the disposal cell is the exposure area for gullies. The volume of the waste removed by gullies is used to calculate a concentration of radionuclides in the waste that was removed. This concentration of waste is assumed to be spread out over the exposure area of the gullies and fan and is used for dose calculations.

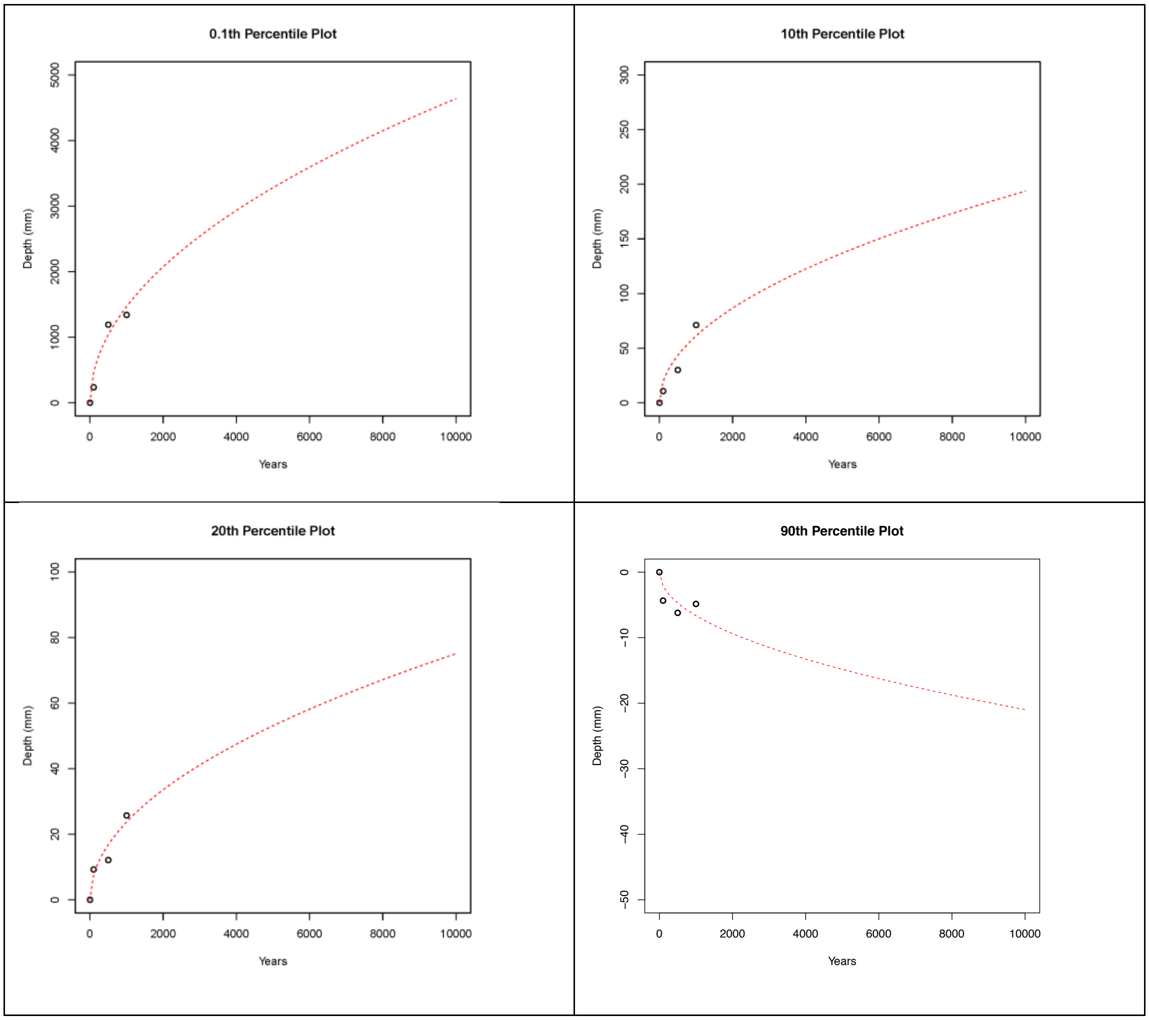


Figure 1. Percentile depth of the area with time and fitted functions.

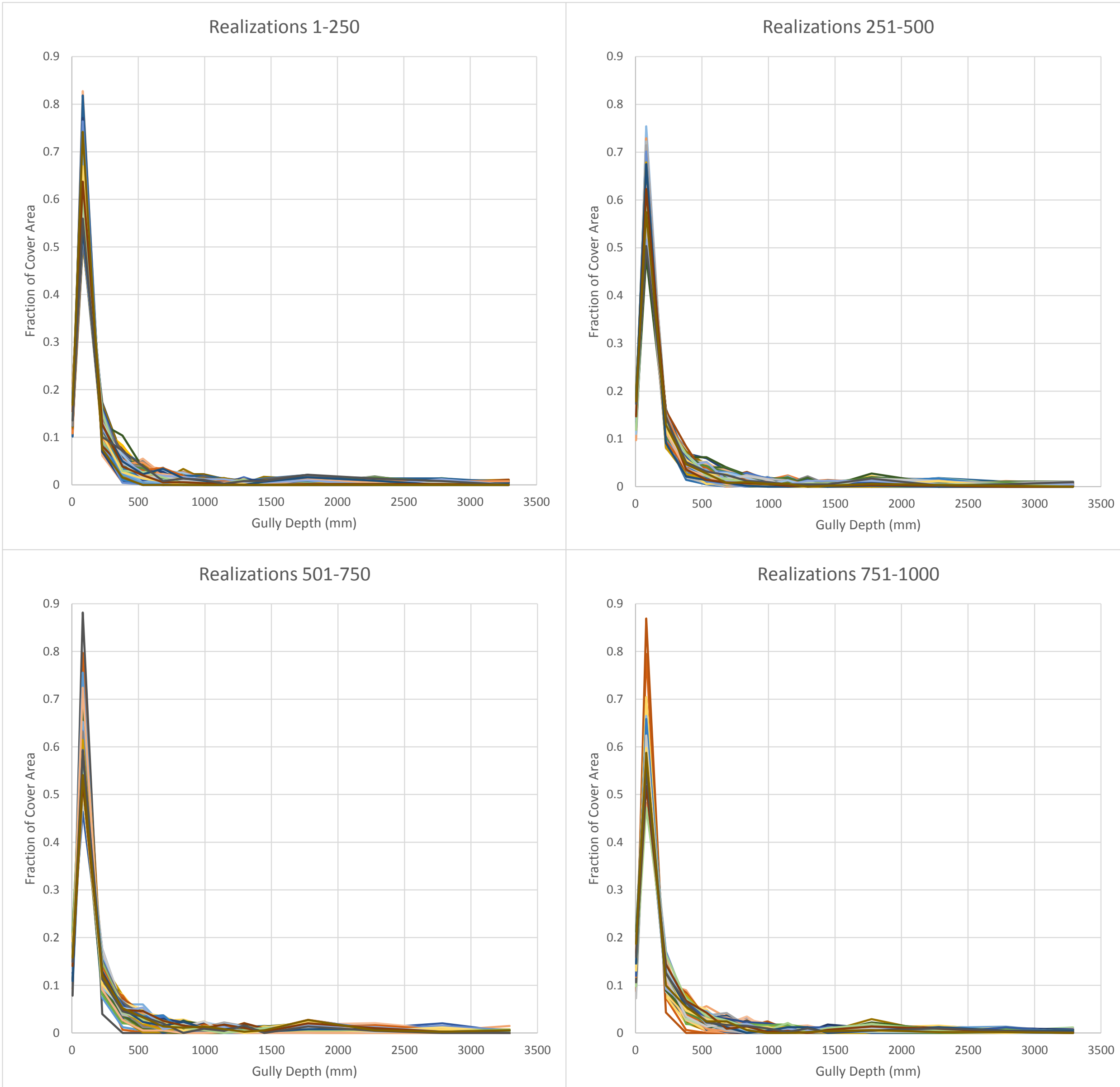


Figure 2. The 1,000 realizations of fraction of cover area for each elevation change (depth) interval.

The results of the 1,000 realizations described in the Section above (MS Excel file `SimulatedErosionDepthProportions.xlsx`) provide the proportion of the area of the cover or waste layer that has a gully "end" at the defined cell depths, where a gully "end" is defined as a cell for which the gully enters in the top of that SIBERIA cell but does not exit out the bottom of the cell. The gully could exit on the side of the cell, but it would still be considered to be an "end" of a gully in that cell as can be seen in the example illustrations in Figure 3 below. The 1,000 realizations of the fraction of cover area as a function of depth for 15 depth increments are stored in the GoldSim model as a lookup table. Each realization has an assigned index value ranging from 1 to 1,000.

At the start of each GoldSim simulation, a value is drawn randomly from a discrete distribution of integers ranging from 1 to 1,000. This number corresponds to the realization number in the lookup table that will be used for the gully area–depth distribution for that GoldSim simulation. Since the borrow pit analog showed gullies impacting only the upper 4 layers of waste, the fraction of gully area from the lookup table for the lower 4 gully depth increments are collected in a data element in the GoldSim model.

The area of waste exposed by gullies for each waste cell layer is calculated by multiplying the fraction of gully area by the entire waste area for the topslope. This calculation assumes that the fraction of borrow pit model grid cells that contain the end of a gully is the same as the fraction of the topslope area exposed by the gully. This assumption is valid since grid spacing for the borrow pit model is uniform.

The exposure area of the fan is assumed to be the same as the exposure area of the gullies. This assumption is supported by output figures from the SIBERIA model such as Figure 4 (from the file `5YR_Rainfall_1000YR_Bare.png`). The fan appears to be similar in size to the area exposed by the gully. The total exposed waste area is calculated by summing the area of the gullies and the area of the fan. These areas are used for exposure assessment in the GoldSim Model.

Next the volume of waste removed by gullies is calculated for each layer. The volume of waste removed by the gully is estimated as the sum of the volume above every gully bottom or "end" as shown in Figure 3. The volume of waste removed by the gully in each layer of the waste is the waste removed by the cell of the gully bottom plus the sum of all of the waste removed above that bottom cell. It is assumed that the gully is a vertical excavation straight up from the bottom of the gully to the top. This assumption is conservative but makes the best estimate available given the level of spatial discretization of the borrow pit modeling.

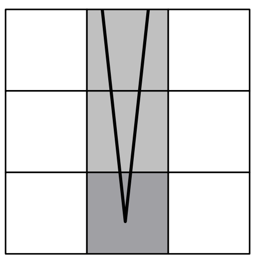
First the volume of waste removed by the gully from the lowest GoldSim cell representing the gully is calculated by multiplying the waste cell volume by the fraction of gully area for each layer. Then a multiplier matrix is created consisting of zeros and ones. This multiplier is used to account for waste in layers above the layer representing the bottom of the gully. For example, the multiplier for a gully ending in the first layer would be [1,0,0,0]. The multiplier for a gully ending in the second layer would be [1,1,0,0], etc. Multiplying the matrix by the volume of waste removed by the gully from the lowest GoldSim cell described above gives the total amount of waste by layer removed by gullies.

Fraction of gully illustration

To clarify the fractions given in the elements FractionWasteCellsGullyEnds and FractionCapCellsGullyEnds, the illustrations are provided below. The fraction of the cap or waste cells in which a gully "ends" was extracted from the SIBERIA output. These fractions denote the proportion of the area in a Cap Cell or Waste Cell for which a SIBERIA modeling cell had a gully enter (from the top) but not exit (from the bottom). The dark gray cells below are the cells that would be counted as having a gully end. The light gray cells are removed in addition to the dark gray cells for volume of gully calculations. Note that because we are counting discrete cells, the area and volume estimates are conservative.

Example 1.

Gully cross-section with grids denoting cells and cell layers in Siberia. The gullies are roughly drawn in as "V"s. The fraction of cells in which the gully "ends", is represented by the dark gray cells. The area of waste exposed by the gullies is that fraction times the surface area of that layer. The volume of waste removed by the gully is the sum of all the cells for which the gully ends (dark gray cells), plus the sum of the cells directly above, represented by light gray cells.



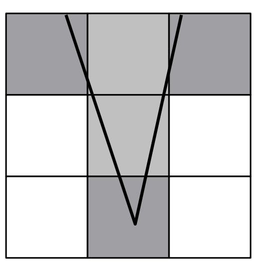
cell layer 1: 0/3 of the cells are counted for the fraction of gully ends;
1/3 of the cells are removed by gullies for gully volume calculations.

cell layer 2: 0/3 of the cells are counted for the fraction of gully ends;
1/3 of the cells are removed by gullies for gully volume calculations.

cell layer 3: 1/3 of the cells are counted for the fraction of gully ends;
1/3 of the cells are removed by gullies for gully volume calculations.

Example 2.

The gully now has "ends" in the first layer since the gully in those cells does not go through to the layer beneath. Thus the fraction of cells in which the gully ends is greater than in Example 1. The volume of the waste removed by the gully similarly increases.



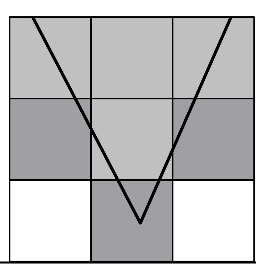
cell layer 1: 2/3 of the cells are counted for the fraction of gully ends;
3/3 of the cells are removed by gullies for gully volume calculations.

cell layer 2: 0/3 of the cells are counted for the fraction of gully ends;
1/3 of the cells are removed by gullies for gully volume calculations.

cell layer 3: 1/3 of the cells are counted for the fraction of gully ends;
1/3 of the cells are removed by gullies for gully volume calculations.

Example 3

This wider gully now has "ends" in the second layer since the gully in those cells does not go through to the layer beneath. Thus the fraction of cells in which the gully ends is greater than in Example 1 or 2. The volume of the waste removed by the gully increases.



cell layer 1: 0/3 of the cells are counted for the fraction of gully ends;
3/3 of the cells are removed by gullies for gully volume calculations.

cell layer 2: 2/3 of the cells are counted for the fraction of gully ends;
3/3 of the cells are removed by gullies for gully volume calculations.

cell layer 3: 1/3 of the cells are counted for the fraction of gully ends;
1/3 of the cells are removed by gullies for gully volume calculations.

Figure 3. Method for estimating gully volume from SIBERIA elevation change results.

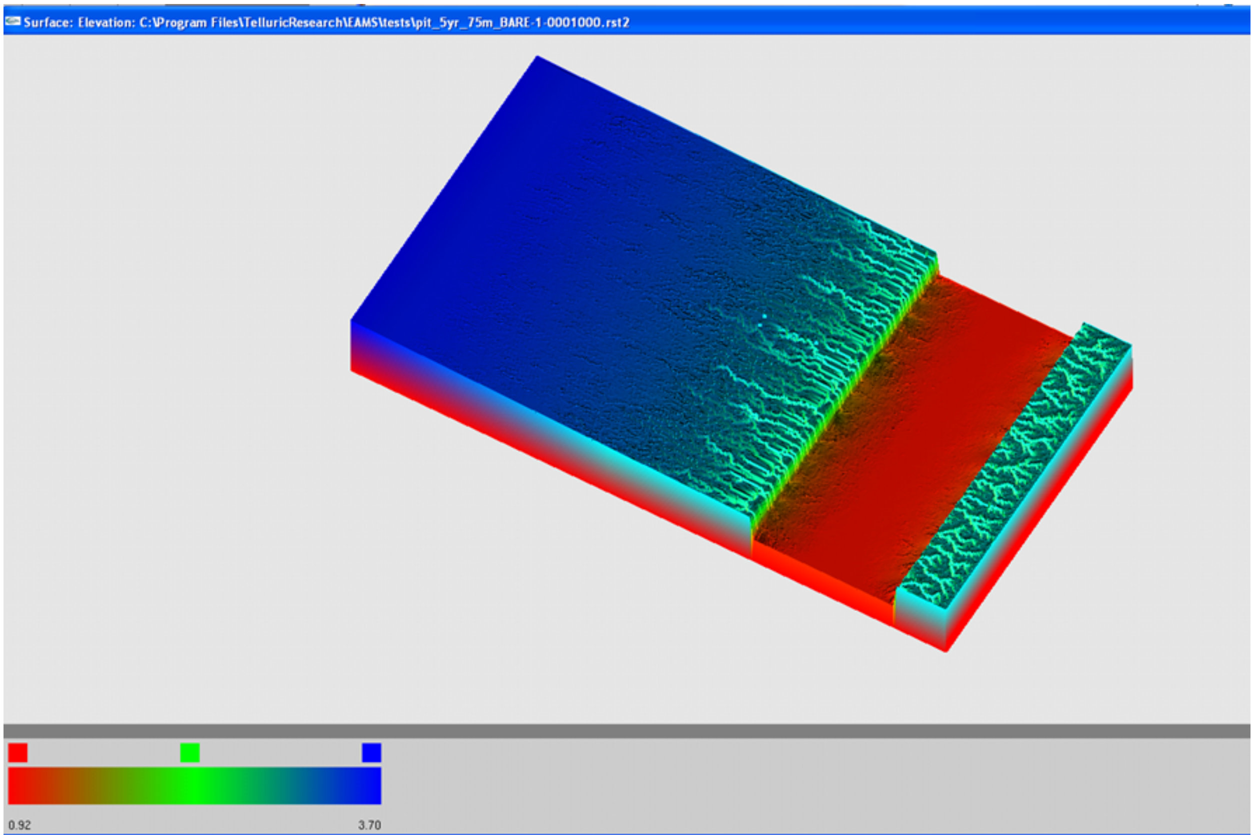


Figure 4. Visualization of SIBERIA model simulation of elevation change for bare soil case for the borrow pit at 1,000 years.
Vertical exaggeration is 18× making the pit face appear nearly vertical.

The volume removed by the gully from each waste layer is multiplied by the concentration of each radionuclide in that waste layer to get the mass of radionuclides removed by the gully over time. The activity mass of radionuclides per mass of soil removed is used in the dose calculations related to gully formation. Note that gully formation in the Clive DU PA Model does not change over time. The gully areas and volumes are fixed for a realization.

5.0 References

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