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Modeling Report: Surface Erosion Modeling of a Borrow Pit at the *Energy*Solutions Clive, Utah Facility

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1.0 Introduction

Energy*Solutions*, LLC (Energy*Solutions*) operates a low-level radioactive waste (LLW) disposal facility west of the Cedar Mountains in Clive, Utah. The Clive Facility is located approximately 5 km (3 miles) south of Interstate-80, in Tooele County. The facility is approximately 80 km (50 miles) east of Wendover, Utah and approximately 106 km (66 miles) west of Salt Lake City, Utah. The facility sits at an elevation of 1,303 m (4,275 ft) above mean sea level (amsl). Disposal embankments at the facility are designed with a compacted clay liner and a cover composed of clay, soil, and cobble layers above the LLW.

Surface soil is excavated at the Clive site to provide material for clay liners and barriers in the waste cover systems. These excavations have left shallow borrow pits of unconfirmed stability in the vicinity of radioactive waste disposal embankments. While the detachment and movement of soil particles by water and wind is a natural process occurring at very slow rates since the soil was formed, the steeper slopes remaining from the borrow pit construction may act to increase the rate of erosion on the faces of the borrow pits and upslope from them. As accelerated erosion continues the heads of small channels formed at the borrow pit face by surface water flow migrate upslope away from the face.

This report describes the development and application of landscape evolution models for a representative face of a borrow pit to predict the response of the pit face to water erosion processes during runoff events. The models provide a quantitative description of the evolution of slopes and channels over time. The objective of the models is to provide a realistic estimate of the rate of progression of hillslope erosion loss and channel development towards the existing embankments.

There are a number of computer models available for estimating runoff and erosion for a borrow pit. Models such as the United States Department of Agriculture Agricultural Research Service (USDA-ARS) Water Erosion Prediction Project (WEPP) (USDA, 1995) and the Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al., 2011) are process-based models providing estimates of sediment transport dependent on rainfall, soil and cover characteristics, and slope length, steepness, and shape. These models predict the influence of these factors on the runoff response and sediment transport but do not predict the evolving changes in landscape due to runoff and transport.

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 to provide prediction of the evolution of a landform over long time periods makes models such as SIBERIA particularly applicable for radioactive waste site performance assessment modeling. SIBERIA was initially developed for investigations of hydrology and catchment form interactions, but it has since been applied to environmental engineering problems such as evaluation of the stability of mining sites (Coulthard, 2001) and surface erosion modeling of covers for a low-level radioactive waste site (Wilson et al., 2005). Of the available landscape evolution models, SIBERIA has capabilities to address the spatial and temporal resolution needed for modeling erosion of engineered landforms, provides representations of slope processes appropriate for arid and semi-arid settings, and has been corroborated through comparisons to measured erosion rates (Coulthard, 2001).

The objectives of this analysis are to develop a landscape evolution model of erosion for a representative face of a borrow pit at the Clive site, estimate elevation losses due to erosion by surface runoff over a 1000-year time period, and provide an estimate of the spatial extent of hillslope and channel erosion over time. Models are developed for a bare soil case and a case including some armoring of the pit face consisting of 15 percent gravel that extends 20 m upslope from the pit face. The sensitivity of the amount of sediment transport to the magnitude of the rainfall event modeled was evaluated. This analysis does not consider erosion or deposition by wind, effects of vegetation, or potential impacts of climate change.

2.0 Site Description and Borrow Pit Geometry

2.1 Climate

Precipitation measurements taken at the site over the 19-year period 1993 to 2011 show a mean annual value of 21.9 cm (8.62 inches) (MSI, 2012). The distribution of precipitation throughout the year is shown in Figure 1. Precipitation exceeds the annual mean from January through June and again in October and is below the mean for the remaining months.

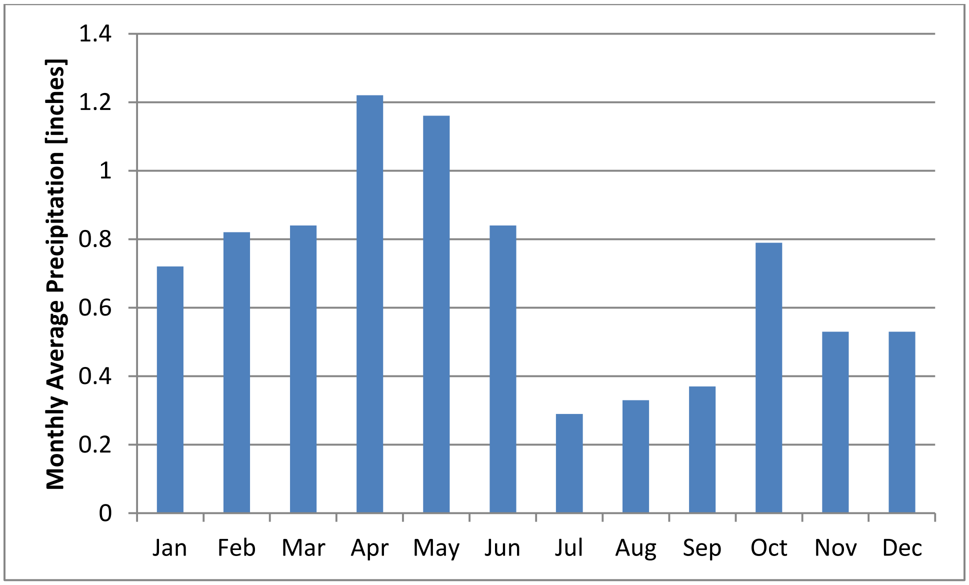

Figure 1: Monthly mean precipitation measured at the Clive Site (MSI, 2012).

The nearest National Oceanic and Atmospheric Administration (NOAA) station with a long-term record is located in Dugway, Utah approximately 64 km (40 miles) to the south. Comparison of precipitation measurements at the Clive site and at the Dugway station done by MSI (2012) shows close correspondence between the monthly mean precipitation values (Figure 2).

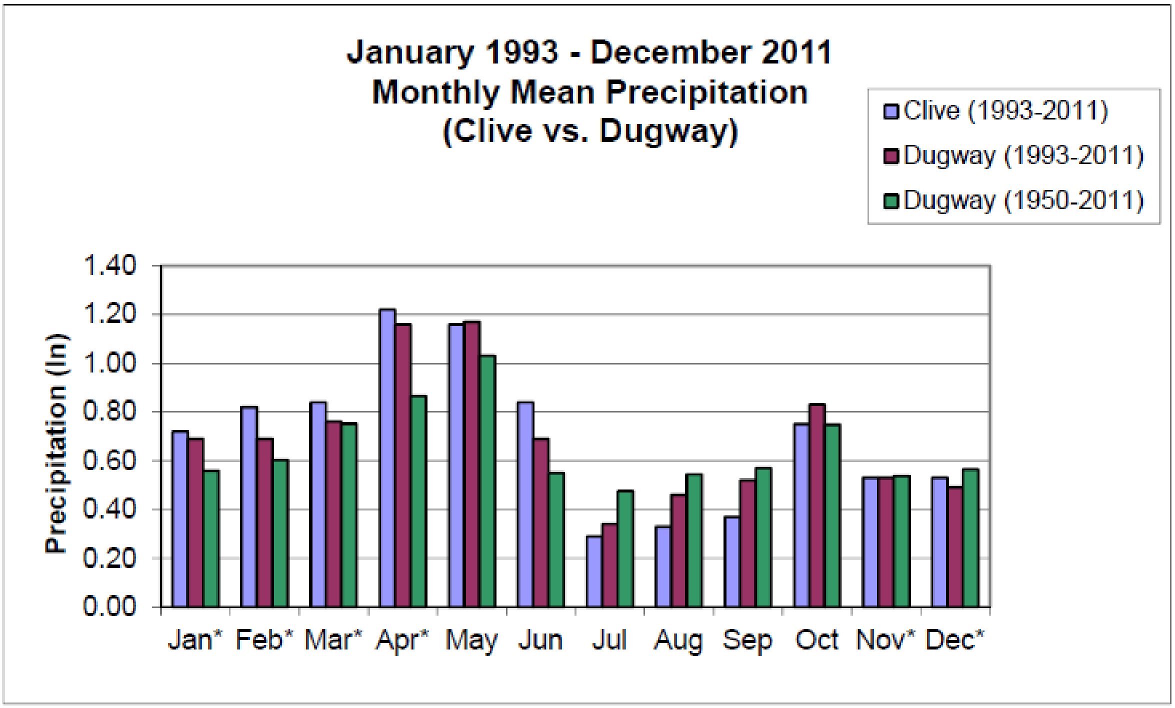

Figure 2: Monthly mean precipitation for Clive and Dugway stations.
***Means based on 18 years of data.**

2.2 Soils

The site is described as being located on lacustrine (lake bed) deposits associated with the former Lake Bonneville (Envirocare, 2004). The sediments underlying the facility are principally interbedded silt, sand, and clay. The upper sediment unit, classified as Unit 4**,** begins at the ground surface and extends to between 1.8 and 5.0 m (6 ft and 16.5 ft) below the ground surface, with an average thickness of 3 m (10 ft). This unit is composed of fine grained low permeability silty clay and clayey silt and is used for constructing clay barriers and liners for the embankments.

2.3 Vegetation

Vegetation cover at the site is approximately 20 percent with soils supporting a range of native and invasive shrubs. Excavations at the site have shown plant rooting depths extending to approximately 70 cm (30 in) below the ground surface with root density decreasing with depth (SWCA, 2011). The influence of vegetation on erosion was not considered in this preliminary analysis but could be included in future SIBERIA simulations.

2.4 Borrow Pit Description

The location of the borrow pit chosen for this analysis is shown in Figure 3. The borrow pit is roughly rectangular in shape extending approximately 80 m from north to south and 190 m from east to west. The north face is closest to the toe of an embankment 235 m to the north. The faces are approximately 3 m high with a 1:1slope.

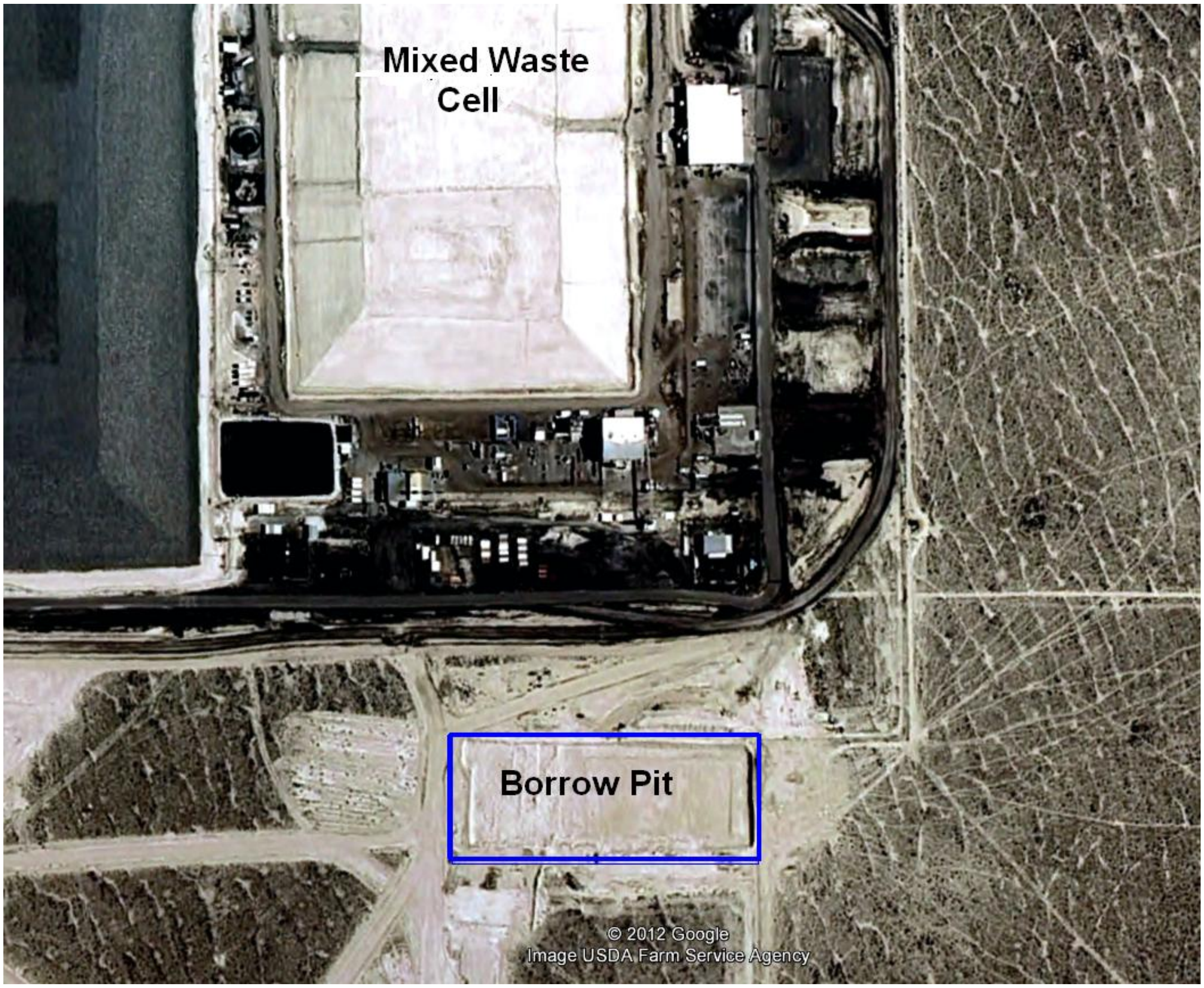

Figure 3: Location of Borrow Pit.

A representative section of the borrow pit face is shown in Figure 4. A close view of the pit face in Figure 5 shows the fine grain nature of the Unit 4 silty clay material.

Figure 4: Representative section of the borrow pit face, looking west.

Figure 5: Close view of the borrow pit face.

3.0 Conceptual and Mathematical Models

A key aspect of the conceptual model implemented in SIBERIA described by Willgoose et al. (1991a, 1991b) is 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. Hydrology and erosion models applied by SIBERIA are based on commonly used soil erosion prediction models that are well documented and generally accepted. SIBERIA however, can be applied to estimates of long-term erosion because of its ability to adjust landform elevations over time in response to erosion processes (Willgoose, 2005). The model explicitly considers the interaction of hillslope erosion processes with the channel growth process. Channel initiation depends on hillslope form, which determines discharge and slope at a point and the resistance of the catchment at that point to channelization (Willgoose, 2005).

Coulthard (2001) describes the model in the following manner. Elevations describing the catchment or landform are assigned to square cells in a subhorizontal grid. At every iteration, runoff discharge for each grid cell is calculated using runoff parameters and the contributing area. When this discharge exceeds a threshold, sediment transport occurs and material moves from one cell to another in the steepest downhill direction. Channel initiation and development is dependent on the discharge. Runoff is not modeled explicitly. There is no mass balance for water or runoff routing in the model (Willgoose, 2005). Discharge is related to the area contributing water to a point using parameters developed through calibration. A diffusive transport process is included to simulate processes such as soil creep, rain splash, rock slides, and animal burrowing (Wilson et al., 2005) that would move material to channels where it could be transported from the system.

SIBERIA is a steady-state erosion and sediment transport model. Simulation of sediment transport requires identification of a rainfall event with a return period that represents the average annual sediment yield for all events over a long period.

Runoff is calculated in SIBERIA through a relationship between the runoff discharge and the area draining through the point as

$$Q = \beta_3 A^{m_3}$$

where

Q = runoff discharge [$L^3/L\text{-}T$],
A = contributing area [L^2], and
β_3 and m_3 are parameters.

The runoff discharge is then used to calculate sediment transport as:

$$Q_s = \beta_1 Q^{m_1} S^{n_1} + D_z S$$

where

Q_s = sediment flux [L^3/L-T],
S = slope [L/L],
D_z = diffusion coefficient [L^3/L-T], and
β_1, m_1, and n_1 are parameters.

The first term in the equation represents fluvial transport processes and the second term diffusive processes. Parameter values in the above equations are estimated by calibration to other erosion models for the borrow pit models. This process is described in the next section.

In SIBERIA the value of the variable Y is used to describe whether a point in the model is a channel ($Y \cong 1$) or a hillslope ($Y \cong 0$).

The channel indicator function is:

$$\frac{\partial Y}{\partial t} = f(d_t, Y, \frac{a}{a_t})$$

where

d_t = rate of channel growth at a point,
a = channel initiation function, and
a_t = channel initiation function threshold.

The channel initiation function is given by

$$a = \beta_5 Q^{m_5} S^{n_5}$$

where β_5, m_5, and n_5 are parameters. For this modeling default values were used for d_t, β_5, m_5, and n_5.

4.0 Estimating Parameters for a SIBERIA Model for the Clive Site

4.1 Methods

The fluvial transport parameters can be estimated by calibration to erosion plot measurements or to other erosion models. Methods for estimation of the diffusion coefficient are not well established (Willgoose, 2005; Wilson et al., 2005) and will be discussed separately. Long-term rainfall, runoff, and erosion datasets were not available for the Clive site. In the absence of site-specific or analog site data, fluvial parameters for the borrow pit model were estimated by matching to synthetic data produced by the RHEM Model (Nearing et al., 2011).

RHEM is a process-based runoff and erosion model developed specifically for rangeland applications. RHEM was developed using statistical analyses of rainfall simulator data from rangeland sites distributed over 15 western states. These analyses provided parameter estimation equations for the primary infiltration and erodibility parameters which were used to replace the cropland specific equations in the WEPP model. In addition, a rangeland database was used to develop a rangeland specific splash erosion and thin sheet-flow transport equation for the model. Comparison of RHEM simulation results with independent rainfall simulation experiments conducted at six sites demonstrated that RHEM could provide realistic runoff and sediment yield predictions for rangeland conditions.

Data requirements for RHEM simulations include rainfall data, soil texture class of the upper four centimeters of soil and soil cover characteristics. RHEM calculates runoff and sediment yield for a number of rainfall return periods for specified slope lengths, shapes, and percent steepness. The rainfall return period is the likelihood of an event with a specified intensity. The return period is used here as a measure of rainfall intensity. SIBERIA is a steady-state model so a storm intensity (return period) must be chosen as a forcing function applied on an annual timestep that represents the landscape forming effects of events that occur intermittently in nature. The relationship between long-term sediment yield and rainfall return period was examined for runoff and sediment yield data measured at the Santa Rita Experimental Range in southern Arizona by Los Alamos National Laboratory for their surface erosion modeling of a proposed cover for a low-level radioactive waste disposal area (Wilson et al., 2005). The comparison demonstrated that the mean annual sediment yield over a 16-year period was within the range of sediment yields measured for events with 2-year and 5-year return periods. Willgoose (Wilson et al., 2005) recommends a return period of 2.3 years based on his analysis of long-term data from Europe. Following the approach taken by Wilson et al. (2005) parameters for the borrow pit simulations were developed for 2-year and 5-year return periods to provide a range of landscape response to runoff.

Rainfall data for the RHEM simulations were taken from the NOAA station at Dugway, Utah. A soil texture class of silty clay was used based on particle size analyses of cores of Unit 4 material obtained from the site (Bingham, 1991).

4.2 Calibration to RHEM

Values for the parameters for the runoff equation and the fluvial sediment transport equation were estimated by generating a synthetic set of runoff and sediment yield data using RHEM. RHEM simulations were conducted for a bare soil case and a 15-percent gravel case for both 2-year and 5-year return periods. Runoff response and sediment yield were calculated for four values of slope; 85 percent, 90 percent, 95 percent, and 100 percent and for five contributing areas; 5, 25, 50, 75, and 100 m. RHEM provides runoff and sediment yields for 2-year and 10-year return periods so runoff and sediment yields for the 5-year return period were estimated by interpolation. Runoff and sediment yields for these ranges of rainfall rates, slopes, areas and cover types are shown in Table 1 and Table 2.

Table 1: Runoff and sediment yield for the bare soil case for 2-year and 5-year return periods calculated using RHEM for a range of slopes and contributing areas.

Slope [percent]	Area [m^2]	2-yr Runoff [m^2]	5-yr Runoff [m^2]	2-yr Sediment Yield [m^3]	5-yr Sediment Yield [m^3]
85	5	5.340E-2	7.063E-2	5.507E-5	7.847E-5
85	25	2.653E-1	3.516E-1	9.361E-4	1.253E-3
85	50	5.275E-1	7.004E-1	3.231E-3	4.249E-3
85	75	7.868E-1	1.047E+0	6.663E-3	8.790E-3
85	100	1.044E+0	1.391E+0	1.116E-2	1.457E-2
90	5	5.340E-2	7.063E-2	5.507E-5	7.847E-5
90	25	2.653E-1	3.516E-1	9.545E-4	1.278E-3
90	50	5.275E-1	7.004E-1	3.304E-3	4.336E-3
90	75	7.875E-1	1.047E+0	6.773E-3	8.941E-3
90	100	1.045E+0	1.392E+0	1.131E-2	1.480E-2
95	5	5.345E-2	7.066E-2	5.874E-5	8.214E-5
95	25	2.655E-1	3.518E-1	9.728E-4	1.296E-3
95	50	5.275E-1	7.006E-1	3.341E-3	4.387E-3
95	75	7.875E-1	1.047E+0	6.883E-3	9.072E-3
95	100	1.045E+0	1.392E+0	1.153E-2	1.505E-2
100	5	5.345E-2	7.066E-2	5.874E-5	8.214E-5
100	25	2.655E-1	3.518E-1	9.912E-4	1.315E-3
100	50	5.280E-1	7.009E-1	3.414E-3	4.474E-3
100	75	7.875E-1	1.047E+0	6.993E-3	9.203E-3
100	100	1.046E+0	1.393E+0	1.167E-2	1.525E-2

Parameters in the SIBERIA runoff and fluvial sediment transport equations were fit to these data for each cover type using the Microsoft Excel Solver to provide initial estimates of the parameters. One-meter wide grids 150 m long with slopes of 85 percent and 100 percent were constructed using the Erosion Assessment Modeling System (EAMS) (Willgoose, 2002) for sediment yield simulations using SIBERIA. Simulations were conducted for 500 years using the initial parameter estimates, and SIBERIA sediment yield results were compared with the RHEM results. Parameters were then adjusted to improve the fits. The following plots in Figure 6, Figure 7, Figure 8, and Figure 9 show the close agreement between sediment yield with hillslope length for RHEM and SIBERIA simulations for bare and gravel cover, 2-year and 5-year rainfall return periods and slopes of 85 and 100 percent. SIBERIA runoff and fluvial sediment transport parameters estimated from comparison to RHEM simulations are listed in Table 3 and Table 4.

Table 2: Runoff and sediment yield for the 15 percent gravel case for 2-year and 5-year return periods calculated using RHEM for a range of slopes and contributing areas.

Slope [percent]	Area [m^2]	2-yr Runoff [m^2]	5-yr Runoff [m^2]	2-yr Sediment Yield [m^3]	5-yr Sediment Yield [m^3]
85	5	4.725E-2	6.407E-2	4.038E-5	6.103E-5
85	25	2.340E-1	3.178E-1	6.608E-4	9.017E-4
85	50	4.630E-1	6.312E-1	2.313E-3	3.166E-3
85	75	6.893E-1	9.415E-1	4.736E-3	6.450E-3
85	100	9.120E-1	1.249E+0	7.930E-3	1.071E-2
90	5	4.725E-2	6.407E-2	4.038E-5	6.241E-5
90	25	2.340E-1	3.179E-1	6.791E-4	9.201E-4
90	50	4.635E-1	6.315E-1	2.349E-3	3.217E-3
90	75	6.893E-1	9.418E-1	4.846E-3	6.580E-3
90	100	9.120E-1	1.249E+0	8.076E-3	1.088E-2
95	5	4.725E-2	6.407E-2	4.038E-5	6.241E-5
95	25	2.340E-1	3.179E-1	6.975E-4	9.384E-4
95	50	4.635E-1	6.317E-1	2.386E-3	3.267E-3
95	75	6.900E-1	9.423E-1	4.901E-3	6.656E-3
95	100	9.300E-1	1.261E+0	8.223E-3	1.109E-2
100	5	4.725E-2	6.407E-2	4.405E-5	6.470E-5
100	25	2.340E-1	3.179E-1	6.975E-4	9.522E-4
100	50	4.640E-1	6.320E-1	2.423E-3	3.318E-3
100	75	6.900E-1	9.426E-1	4.956E-3	6.752E-3
100	100	9.140E-1	1.251E+0	8.370E-3	1.151E-2

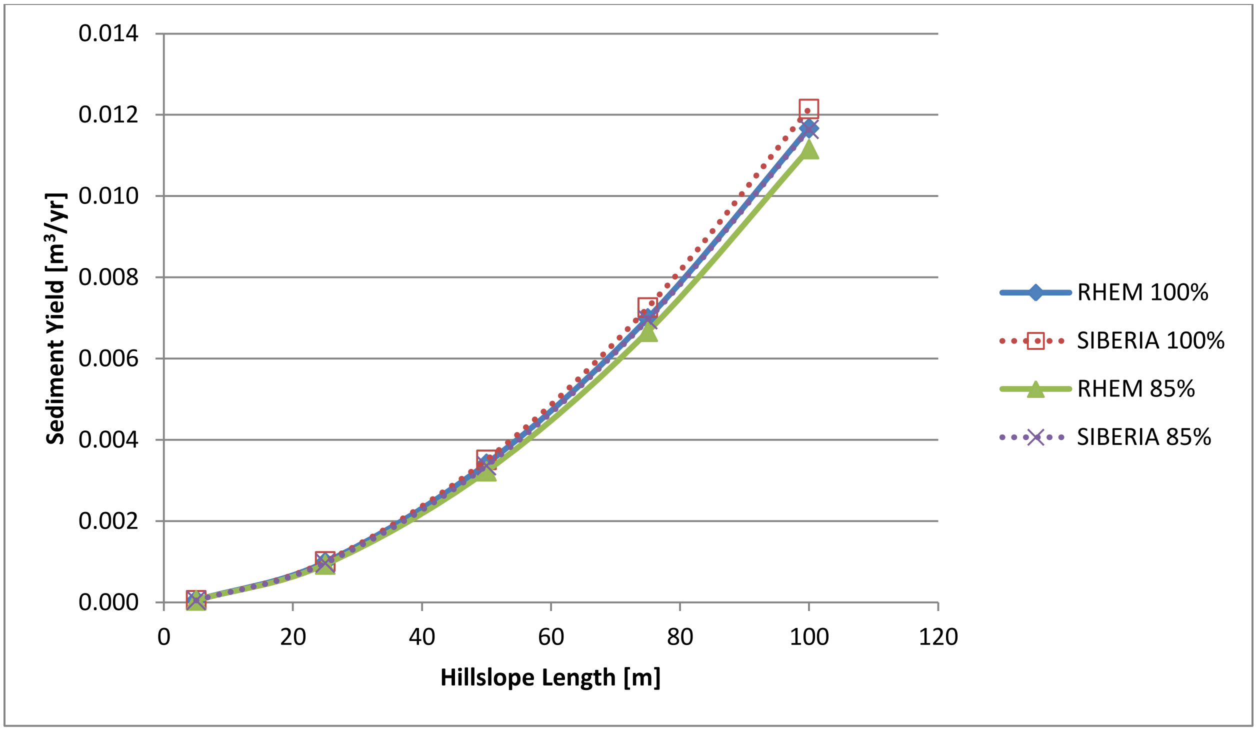

Figure 6: Relationship between sediment yield and hillslope length calculated using RHEM and SIBERIA for a 2-year rainfall return period on bare soil.

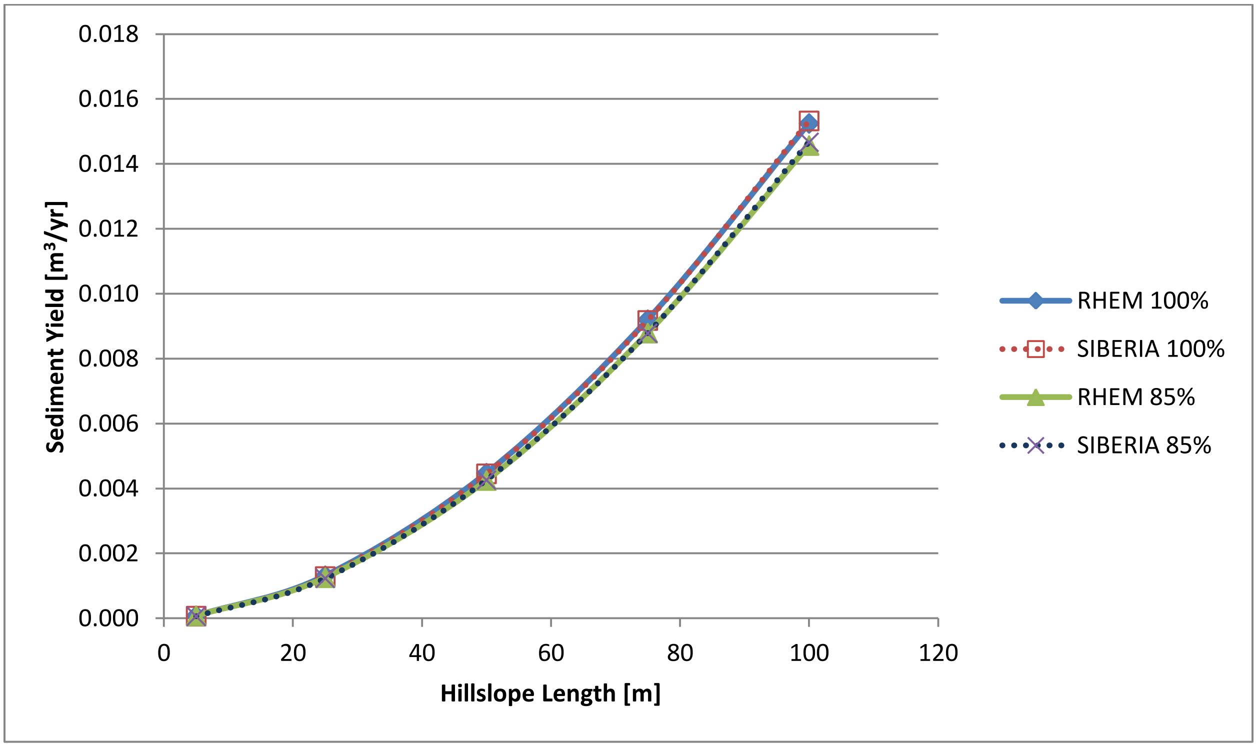

Figure 7: Relationship between sediment yield and hillslope length calculated using RHEM and SIBERIA for a 5-year rainfall return period on bare soil.

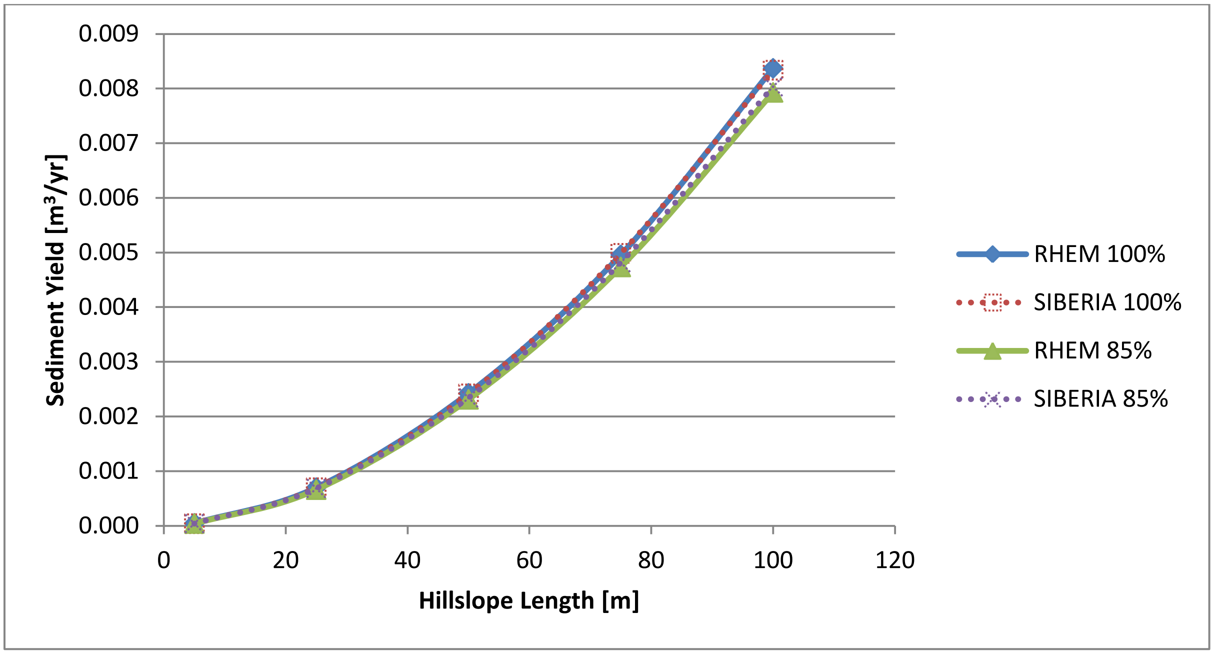

Figure 8: Relationship between sediment yield and hillslope length calculated using RHEM and SIBERIA for a 2-year rainfall return period on soil with 15 percent gravel.

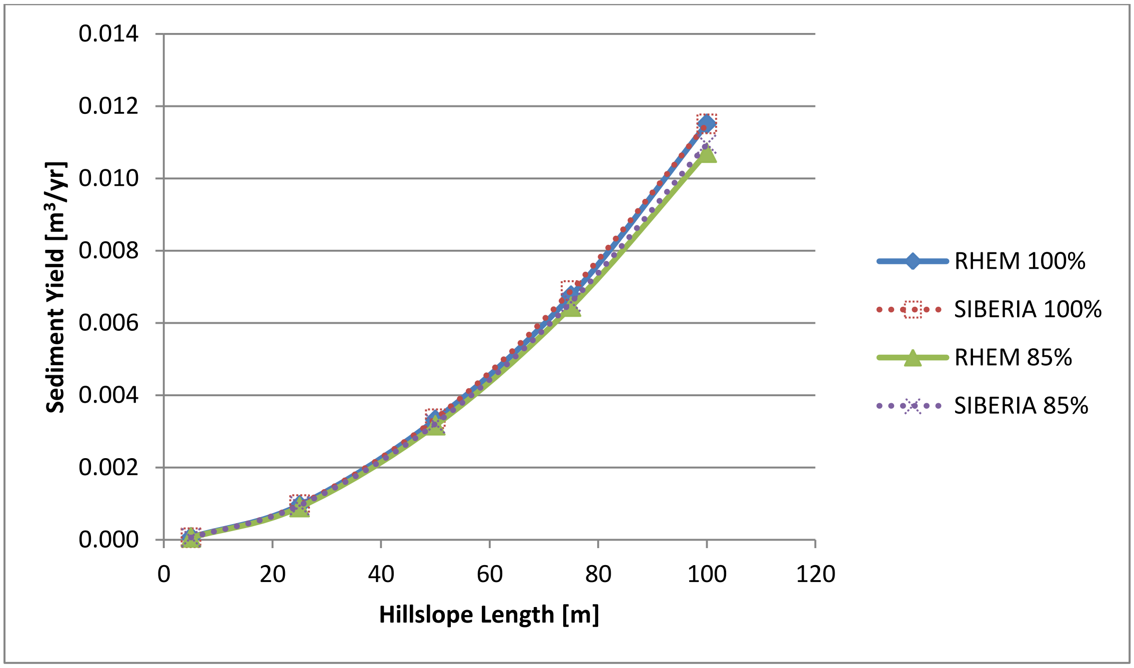

Figure 9: Relationship between sediment yield and hillslope length calculated using RHEM and SIBERIA for a 5-year rainfall return period on soil with 15 percent gravel.

Table 3: Runoff and fluvial sediment transport parameters for bare soil.

Hillslope Erosion Parameters (RHEM)	
Climate Station	Dugway,Utah
Soil Texture Class	Silty Clay
Canopy Cover %	0
Basal Plant Cover %	0
Rock Cover %	0
Litter Cover %	0
Cryptogams Cover %	0

SIBERIA Parameters		2-Year Return Period	5-Year Return Period
β_3	Coefficient between discharge and area	0.01106	0.01447
m_3	Exponent on the area of discharge	0.9878	0.9916
β_1	Coefficient in the fluvial transport equation	0.03984	0.02971
m_1	Exponent on the discharge in the sediment transport equation	1.808	1.793
n_1	Exponent on the slope in the sediment transport equation	0.2702	0.2679
D_z	Coefficient of diffusivity in sediment transport	0.0001	0.0001

Table 4: Runoff and fluvial sediment transport parameters for 15 percent gravel cover.

Hillslope Erosion Parameters (RHEM)	
Climate Station	Dugway,Utah
Soil Texture Class	Silty Clay
Canopy Cover %	0
Basal Plant Cover %	0
Rock Cover %	15
Litter Cover %	0
Cryptogams Cover %	0

SIBERIA Parameters		2-Year Return Period	5-Year Return Period
β_3	Coefficient between discharge and area	0.009799	0.01318
m_3	Exponent on the area of discharge	0.9855	0.9889
β_1	Coefficient in the fluvial transport equation	0.03456	0.02690
m_1	Exponent on the discharge in the sediment transport equation	1.810	1.797
n_1	Exponent on the slope in the sediment transport equation	0.2707	0.3513
D_z	Coefficient of diffusivity in sediment transport	0.0001	0.0001

Sediment is also transported through diffusive processes that move sediment slowly downslope (Roering et al., 1999). Examples of diffusive processes include rainsplash, animal burrowing, and soil creep. Soil creep is the slow downward movement of weathered or loose soil due to gravity (Handy and Spangler, 2007). Sediment transport by diffusive processes is modeled in SIBERIA as the function of a diffusion coefficient (D_z) and the slope. Estimates of D_z cannot be made using erosion models such as RHEM since the only diffusive process considered by models of this type is splash erosion. The approach used by Wilson et al. (2005) to estimate D_z was to use SIBERIA to develop a number of realizations of long-term landscape elevation using a range of diffusion coefficient values and to compare these realizations to current topography. Diffusion coefficient values of 0.001, 0.0025, and 0.005 were chosen by Wilson et al. (2005) to represent low, moderate, and high erosion scenarios. Long-term realizations are not useful for estimating the diffusion coefficient for the borrow pit since it is a relatively recent feature in the landscape. The diffusion coefficient was estimated for the borrow pit simulations by using SIBERIA to develop realizations of the borrow pit topography over shorter time periods for values of D_z of 0.0001, 0.0025, and 0.005. Values of the diffusion coefficient of 0.0025 and 0.005 produced an excessive number and depth of rills in the pit face–more than is currently seen. A D_z value of 0.0001 was used for the borrow pit simulations since the realization using this value more closely resembled the current condition of the pit face.

5.0 Borrow Pit Models

5.1 Model Domain

The model domain for the SIBERIA simulations is shown in Figure 10 . The model domain extends south from the toe of the Mixed Waste embankment 235 m to the north face of the borrow pit. The surface modeled south of the embankment and the borrow pit is 190 m wide. The pit face is 3 m high and is at a 1:1 (100%) slope. The borrow pit extends 80 m from north to south and the east and west faces of the pit are not modeled so that the north pit face is visible when model elevations are displayed. For these simulations it was assumed that all soil piles, buildings, and asphalt have been removed from the area between the face on the north side of the pit and the Mixed Waste embankment.

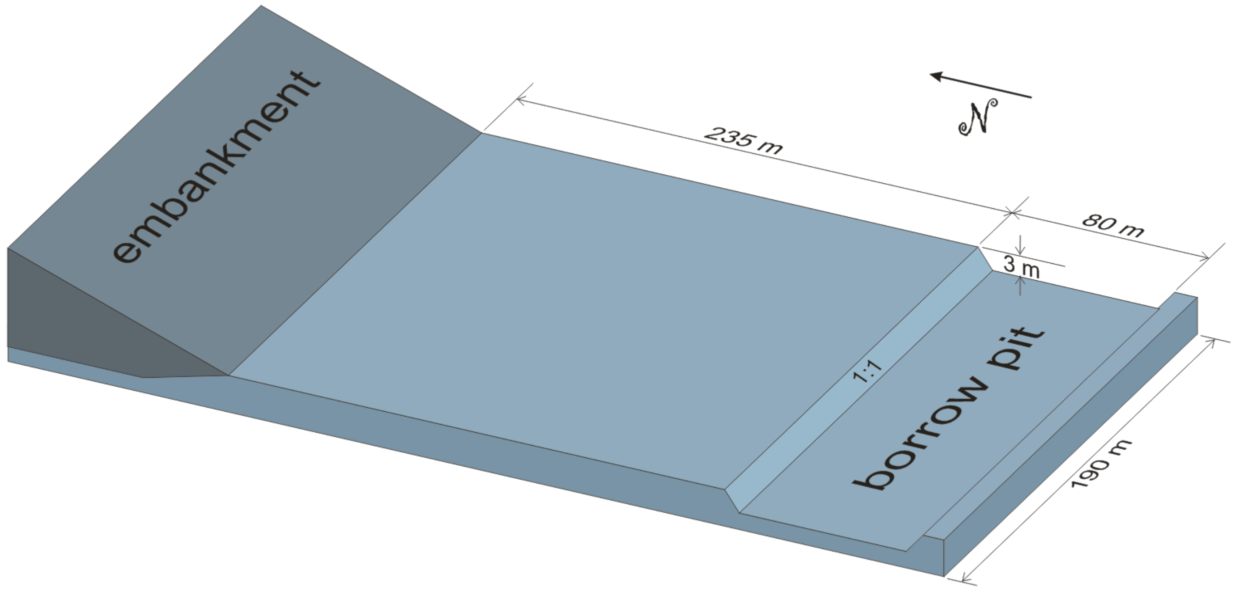

Figure 10: Model domain.

A computational grid of the model domain was constructed using EAMS with a node spacing of 0.75 m. Models were run for 100, 500, and 1000 years for bare soil and for a 15 percent gravel mixture that covered the pit face and extended 20 m upslope. For the bare soil case, a single set of runoff and sediment transport parameters for each rainfall return period for the Unit 4 material was used for the entire domain. For the case with 15 percent gravel covering only a portion of the model domain, SIBERIA's feature allowing specification of spatially varying runoff and erosion parameters was used to represent both the bare soil and the gravel regions. Erosion was modeled for steady-state rainfall events with 2-year and 5-year return periods.

5.2 Results

Erosion is reported as the cumulative average elevation change in the area extending from the pit face to the edge of the Mixed Waste embankment. Sediment yields in tons/acre or metric tonnes/hectare (Mg/ha) can be calculated from these values using the measured Unit 4 dry bulk density of 1.362 g/cm^3. Average elevation change and the average elevation change rate are shown in Table 5 for all cases for simulation times of 100, 500, and 1000 years.

Comparison of the 2-year and 5-year results at 1000 years for bare soil shows a small influence of return period on the average elevation change. For this case there is an increase of approximately 10 percent in elevation change with the higher rainfall. An even smaller influence of return period is seen for the gravel case. For this case the higher rainfall results in only a 5 percent increase in elevation change at 1000 years.

Table 5: Average elevation change and the average elevation change rate for all cases for simulation times of 100, 500, and 1000 years.

Rainfall Return Period [yr]	SimulationTime [yr]	Cover	Upslope Average Cumulative Elevation Change [mm]	Upslope Average Elevation Change Rate for Simulation Period [mm/yr]
2	100	Bare	-8.3	-0.083
2	500	Bare	-28.5	-0.057
2	1000	Bare	-43.1	-0.043
5	100	Bare	-9.1	-0.091
5	500	Bare	-32.5	-0.065
5	1000	Bare	-47.9	-0.048
2	100	15 % Gravel	-8.3	-0.083
2	500	15 % Gravel	-26.1	-0.052
2	1000	15 % Gravel	-40.3	-0.040
5	100	15 % Gravel	-8.2	-0.082
5	500	15 % Gravel	-27	-0.054
5	1000	15 % Gravel	-42.4	-0.042

The landscape elevation at 1000 years for the bare soil case for the 2-year and the 5-year rainfall return periods are shown in Figure 11 and Figure 12. Colors correspond to relative elevation with the bottom of the pit being zero. The figure shows the formation of a channel network beginning at the pit face and migrating upslope. The accumulation of sediment from the erosion of the pit face can be seen on the pit bottom next to the face.

The average change in elevation from the upslope end of the model extending into the borrow pit for the bare soil case for both rainfall return periods is shown in Figure 13 and Figure 14 for simulation periods of 100, 500, and 1000 years. Negative values on these plots indicate erosion while positive values indicate deposition. The nearly vertical line at 235 m is the pit face. The bottom of the vertical line corresponds to the top of the pit face where the most erosion is occurring. The top of the line is the point of maximum deposition at the bottom of the pit face. The change in elevation at the pit face and in the adjacent upslope area due to sediment transport increases with time for both rainfall return periods. Similar results were obtained for the simulations with the 15 percent gravel region. A comparison between the bare soil case and the gravel case at 1000 years for a 5-year rainfall return period is shown in Figure 15. This figure shows a small reduction in the amount of sediment eroded at the pit face due to the gravel, consistent with the values shown in Table 5. The average distance over which erosion exceeding 2.5 cm (1 inch) was estimated to extend upslope toward the nearest embankment was 14 m (45 ft) at 100 years, 55 m (180 ft) at 500 years, and 72 m (235 ft) at 1000 years. These are the averages of all cases modeled since only small differences in elevation change were seen for the two rainfall return periods and the bare soil and gravel cases.

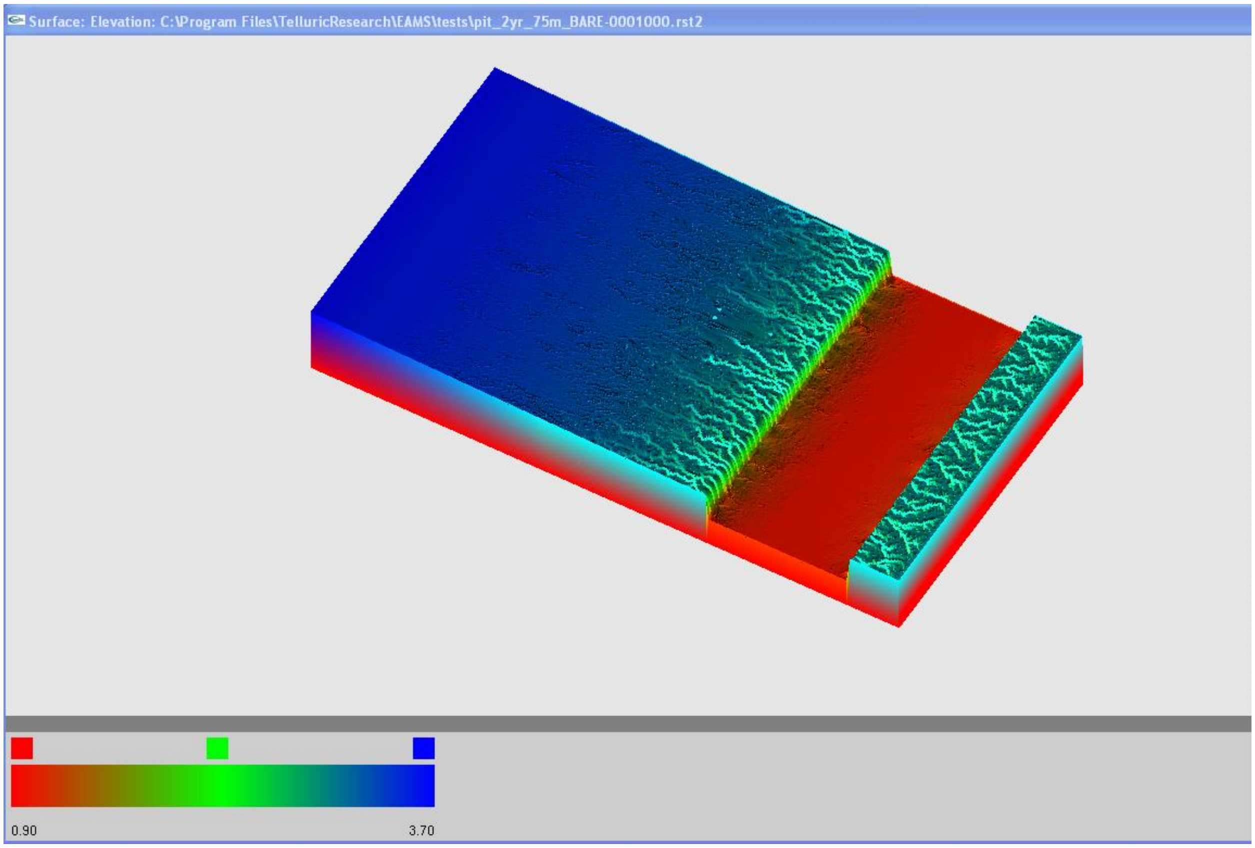

Figure 11: Bare soil case with 2-year rainfall at 1000 years. Vertical exaggeration is 18 x making the pit face appear nearly vertical.

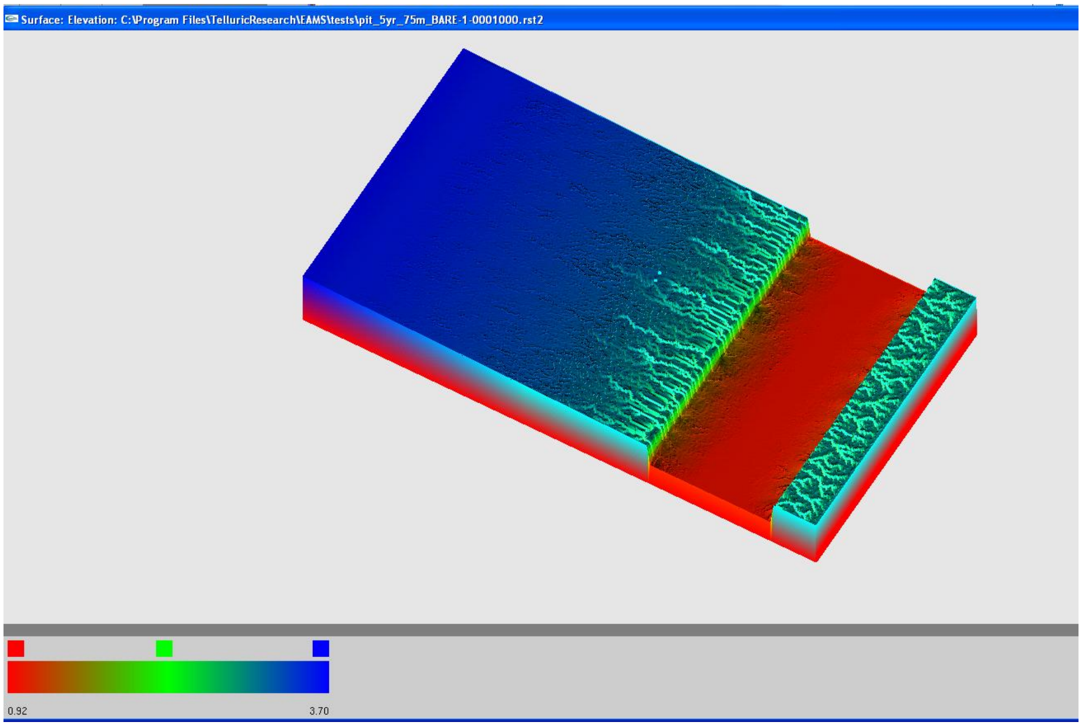

Figure 12: Bare soil case with 5-year rainfall at 1000 years. Vertical exaggeration is 18 x making the pit face appear nearly vertical.

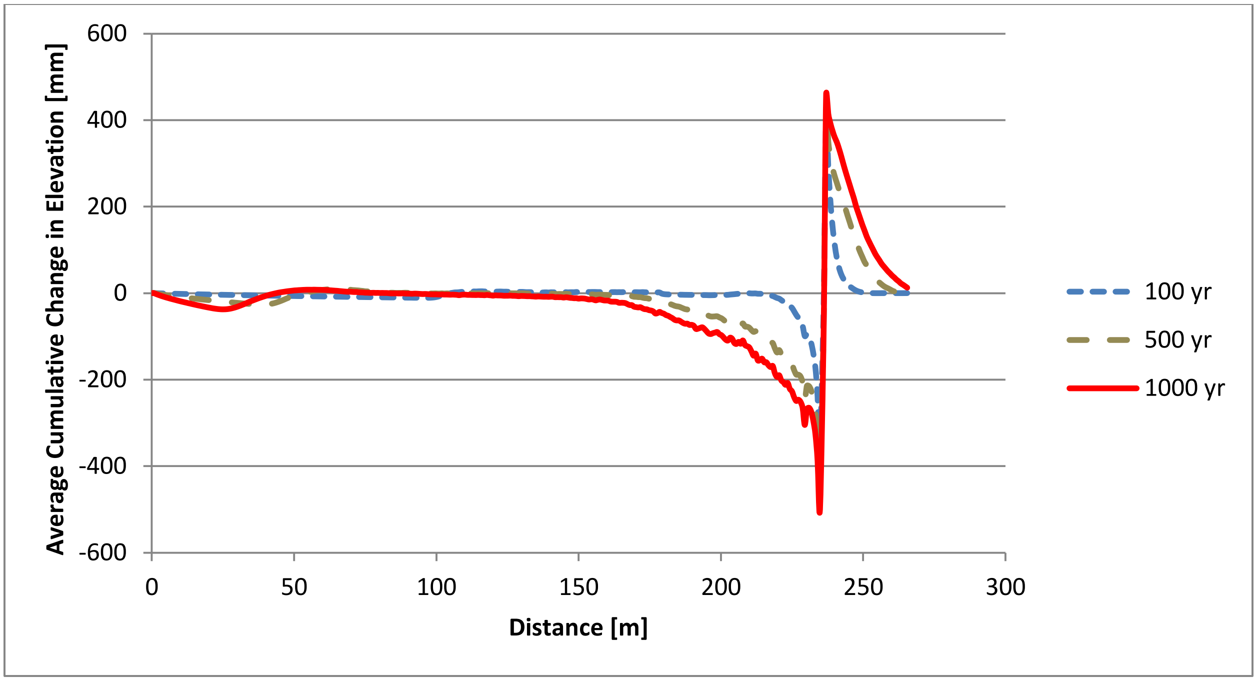

Figure 13: Average change in elevation from the upslope end of the model extending into the borrow pit for bare soil case with 2-year rainfall at 100, 500, and 1000 years. Positive values indicate deposition and negative values erosion.

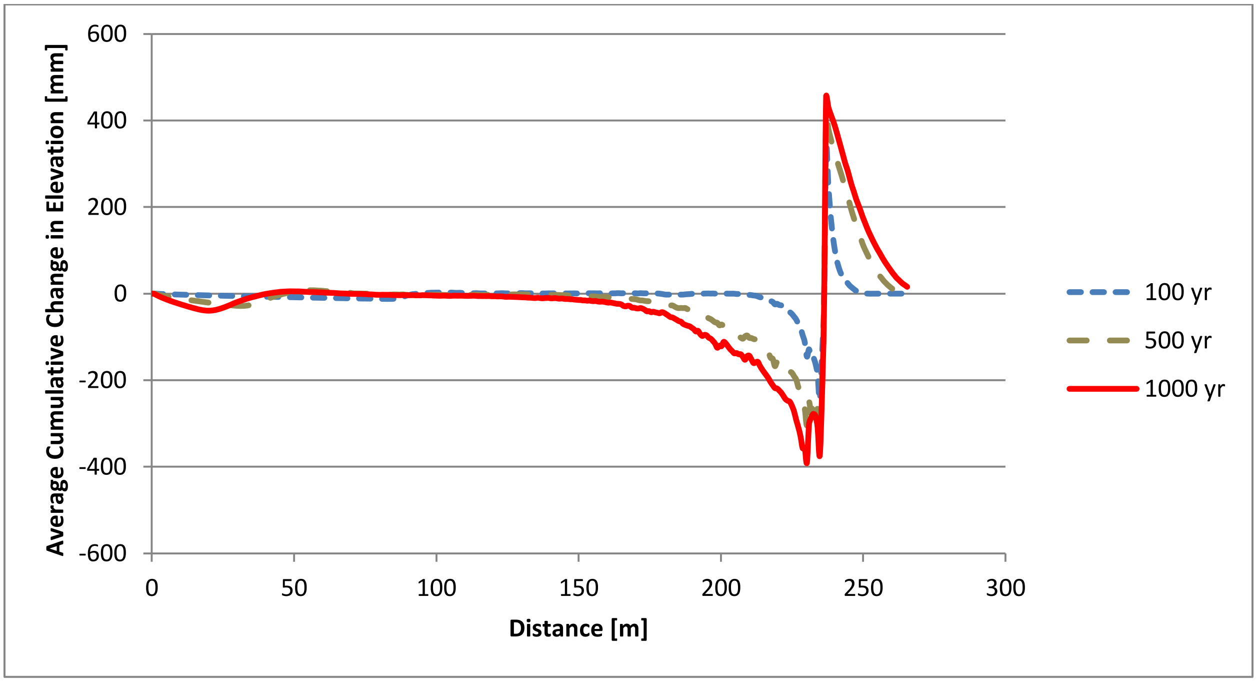

Figure 14: Average change in elevation from the upslope end of the model extending into the borrow pit for bare soil case with 5-year rainfall at 100, 500, and 1000 years. Positive values indicate deposition and negative values erosion.

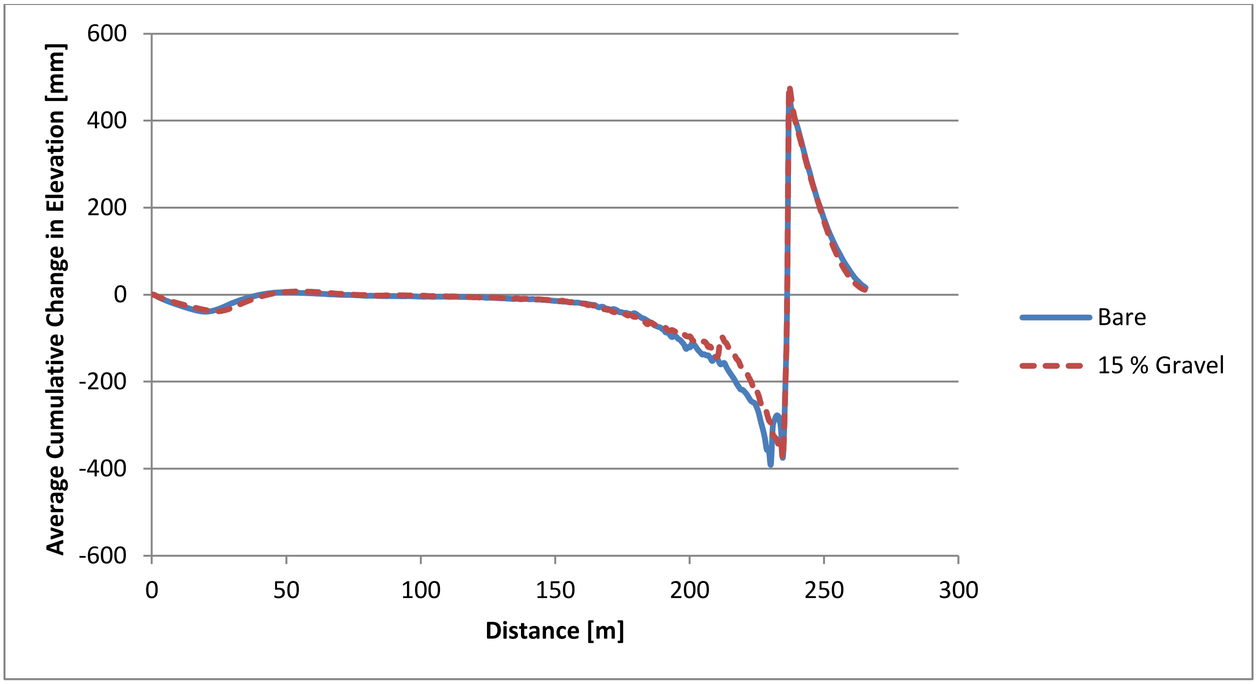

Figure 15: Comparison between bare soil and 15 percent gravel cases at 1000 years for 5-year rainfall return period.

5.3 Model Uncertainty

While other investigators have described limitations of the SIBERIA model for their particular site (Wilson et al., 2005) the primary model structure uncertainty for the borrow pit face simulations is the requirement of steady-state runoff. Simulating sediment transport using SIBERIA requires that a steady-state storm intensity (return period) be chosen as a forcing function that is applied on a uniform (usually annual) timestep. This steady-state value is intended to represent the landscape forming effects of events that occur intermittently in nature. Simplifying transient climate to steady state may influence the results under some conditions. SIBERIA, however, is one of the few landscape evolution models that has been corroborated with experimental and field measurements. The effect of the assumption of steady state was addressed in a preliminary manner in this analysis by evaluating sediment transport for two rainfall return periods.

Neither site-specific nor analog site sediment transport data were available for the Clive Site. In the absence of field data, model parameters were determined through comparison with synthetic data generated using the hillslope erosion model RHEM. RHEM model parameters are based on a statistical analysis of data obtained from rainfall simulator experiments conducted on 49 rangeland sites across 15 western states (Nearing et al., 2011). These analyses provided the parameter estimation equations that are used in RHEM. The most important site characteristics for determining the parameter estimation equations for RHEM simulations for the borrow pit are the rock cover and amount of clay in the soil (Nearing et al., 2011) since vegetation and litter were not considered for the borrow pit simulations. While the soil properties based on textural classes used in RHEM provide a reasonable representation of runoff and sediment transport at the site, site-specific rainfall simulator measurements or the identification of an analog site with a long-term record of runoff and sediment yield data would reduce the uncertainty of the parameters used in the SIBERIA model.

6.0 Conclusions

Simulations of sediment transport at a borrow pit at the Clive site were conducted using the SIBERIA landscape evolution model for a 1000-year period considering a range of landscape forming rainfall intensities. Two cases of spatially distributed erosion properties were modeled. These were bare soil and 15 percent gravel armoring covering the pit face and a portion of the upslope model domain. Runoff and erosion parameters for the SIBERIA models were estimated by comparison to single slope runoff and sediment transport results produced by the RHEM model.

At 1000 years the pit face showed changes in elevation of the slope and the formation of channels due to sediment transport. Elevation loss and the channel network extended upslope from the pit face. Differences in average elevation change at 1000 years were seen for the 2-year and 5-year rainfall return periods and for the different surface materials. Average elevation loss increased 10 percent for the bare soil and 5 percent for the 15 percent gravel for the higher intensity rainfall conditions. The effect of the gravel armoring was to reduce the average elevation loss by 10 percent for the 5-year rainfall event. The average distance for all cases over which erosion exceeding 2.5 cm (1 in) was estimated to extend upslope toward the nearest embankment was 14 m (45 ft) at 100 years, 55 m (180 ft) at 500 years, and 72 m (235 ft) at 1000 years. Considering additional armoring and including the influence of plant and litter cover would reduce the effects of erosion.

SIBERIA model predictions of long-term erosion effects for the borrow pits should be considered as approximate assessments of their evolution. The lack of site-specific runoff and sediment-yield data and the assumption of steady-state landscape forming events make long-term predictions uncertain. Although there are associated uncertainties, the SIBERIA model is the best available approach for physically based long-term simulation of hillslope and channel erosion processes. SIBERIA models can provide realistic quantitative information that can be used to inform planning decisions.

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