SOFTWARE VALIDATION TEST PLAN AND REPORT FOR EAMS VERSION 2.09 AND SIBERIA VERSION 8.33

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SOFTWARE VALIDATION TEST PLAN AND REPORT FOR EAMS VERSION 2.09 AND SIBERIA VERSION 8.33

This is a software validation test plan and report for acquired software packages Erosion Assessment and Modeling System (EAMS) Version 2.09 and SIBERIA Version 8.33. EAMS (Willgoose, 2002) integrates the large-scale catchment evolution and channel network growth model SIBERIA with an erosion, runoff, and geology database; data input and manipulation software; and data visualization software. EAMS Version 2.09 has two main components: MOSCOW Version 2.04 and Viewer Version 2.06. MOSCOW sets the commands SIBERIA will use to run a simulation. Viewer is used for visualization and includes simple geographic information systems capabilities. Henceforth, the EAMS–MOSCOW–SIBERIA software combination will be referred to as SIBERIA. SIBERIA was recommended to U.S. Nuclear Regulatory Commission (NRC) staff (Walter and Dubreuilh, 2007) as a potentially useful erosion code. This recommendation was based on a review of codes that could simulate erosion-related processes for engineered closure caps installed over radioactive waste processing tanks that are planned for in-place closure under provisions of the National Defense Authorization Act (NDAA) of Fiscal Year 2005. SIBERIA can simulate changes in cover topography and provide information about the potential for localized channel development in a cover. SIBERIA may be used to indicate the susceptibility of engineered closure caps to long-term erosion and the style of resulting erosion features and thus should be useful for evaluating the long-term integrity of engineered closure caps. The NRC staff interest in SIBERIA is mainly from the standpoint of simulating the landscape evolution of engineered waste disposal covers and surrounding terrain over a period on the order of thousands of years.

Based on consideration of possible cover designs that might be proposed for in-place tank closures, the environmental processes affecting the performance of such covers, and the information likely to be available for assessing the performance of these covers, the following features are desirable for erosion assessment codes under as-built and future conditions:

- Physics-based models and database representation of erosion processes appropriate for future cover properties and climate

- Ability to simulate changes in cover topography due to short- and long-term processes

Major physical processes SIBERIA can model include fluvial sediment transport, diffusive sediment transport (e.g., soil creep, rainsplash, and rockslide), vegetation cover effects, and the topographic and erosional effects of tectonic uplift.

This report conforms to the software validation requirements of Technical Operating Procedure 18 (TOP–018)—Development and Control of Scientific and Engineering Software. Software is validated to gain confidence that software successfully implements underlying theory and algorithms. Software validation test plans describe test cases that will provide evidence supporting the correct and successful implementation of software functions.

This report is organized consistent with the existing template for all such software validation exercises. Section 1 provides the scope of the software validation; Section 2 lists the report references; Section 3 describes the software and hardware environment associated with software validation testing; Section 4 describes software assumptions and any constraints, and Section 5 describes the test cases used to validate the functionalities of the software and the

results of the software validation tests. Per NRC staff request, conclusions are provided in Section 6.

1 SCOPE OF SOFTWARE VALIDATION

SIBERIA is a finite-difference landscape erosion and evolution model that simulates development of channels and erosion of hillslopes. SIBERIA (Willgoose, 2005) uses a physics-based approach applied over a two-dimensional topographic surface that allows representation of complex topography and changes to topography based on soil loss and deposition. SIBERIA implements a partial differential equation of the form (Tucker and Bras, 1998)

$$\frac{\partial z}{\partial t} = U - \frac{\partial Q_s}{\partial s} + H(x, y, t) \tag{1}$$

to describe the catchment elevation within a watershed where

z — land surface elevation at lateral location (x, y) [L]
U — rate of tectonic uplift [L/t]
Q_s — fluvial sediment transport flux in the direction, s, of surface water flow [L^2/t]
$H(x, y, t)$ — function [L/t] describing land surface elevation changes due to diffusive transport processes, such as soil creep, rainsplash, and rockslide

The sediment flux in Eq. (1) is a nonlinear function of semiempirical parameters that relate sediment particle transport to surface water flow, land surface slope, and soil properties. SIBERIA computes the evolution of an initial land surface by solving Eq. (1) over a rectangular grid that represents the land surface topography (Willgoose, 2005).

SIBERIA also solves a second partial differential equation for a channel indicator variable that identifies where channels exist on the plane. From these two state variables (land elevation and channel indicator) are derived five other important spatial variables: (i) downhill slope, (ii) contributing area, (iii) discharge, (iv) channel initiation function, and (v) spatial sediment transport. The channel initiation function and spatial sediment transport distributions provide iterative feedback into the two state equations. This nonlinear interaction between elevation and channelization drives the drainage network growth in the model.

SIBERIA was developed to simulate landscape development over geomorphic timescales as a function of hydrology, tectonics, and catchment from within natural drainage basins; thus, the constitutive relationships used in the code are largely based on empirical relationships developed for natural landscapes (Tucker, et al., 2001). Recently, SIBERIA has been adapted for mine site rehabilitation applications. The validation of SIBERIA by others has focused on statistical comparisons between landscapes evolved using the code and observed landscapes. Wilson, et al. (2004) reported difficulty applying SIBERIA to simulate landscape evolution near waste-disposal sites at Los Alamos National Laboratory due to an inability to calibrate the model to reproduce observed landforms. Hydrology and sediment loss field data collection would be necessary to generate site-specific parameter estimates to apply SIBERIA to the evolution of an engineered waste disposal cover.

SIBERIA includes a wide range of features, not all of which are addressed via this software validation exercise. The features and options of SIBERIA not specifically considered in this software validation should be tested as specific modeling needs arise. SIBERIA requires

detailed calibration to site-specific sediment erosion and hydrology data when modeling real landforms. Site-specific data should be used to populate any model constructed for oversight or regulatory purposes. This software validation does not attempt to model real landforms, and calibration activities are thus not included. Because benchmark test cases for landscape evolution codes are unknown, this report describes a "limited validation" of SIBERIA. The scope of this software validation is limited to confirmation that the software represents physically realistic and expected landscape evolution when applied to several stylized problems. Full validation of various features could potentially be enabled through replication of results from appropriately posed laboratory-scale physical analog models of landscape evolution. The selected software validation simulations for engineered soil cover landscape evolution are

- Test Case 1: Comparison of Slope Angle Effect on Output Using 10 and 20 Percent Slopes
- Test Case 2: Comparison of Surface Roughness Effect on Output
- Test Case 3: Effect on Output of Coefficient Magnitude in the Fluvial Sediment Transport Relationship

The expected results of these software validation test cases (Table 1) are that (i) more erosion should occur on a steeper slope than on a shallower slope, all other parameters held constant; (ii) multidirectional, branching channelized erosion should occur on a slope exhibiting roughness, whereas only unidirectional erosion should occur on a perfectly flat slope exhibiting no roughness; and finally, (iii) less erosion should occur when the magnitude of the coefficient in the fluvial sediment transport relationship is smaller than when it is larger, all other parameters held constant. Taken together, these software validation exercises objectively, but non-quantitatively, indicate that the SIBERIA code produces physically realistic and expected landform characteristics with the passage of time. As such, this report documents the activities associated with the "limited validation" of SIBERIA.

2 REFERENCES

Dinwiddie, C. "Software Validation Test Plan and Report for SIBERIA Version 8.33 and EAMS Version 2.09." Scientific Notebook No. 950E. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2008.

Tucker, G.E. and R.L. Bras. "Hill Slope Processes, Drainage Density, and Landscape Morphology." *Water Resources Research*. Vol. 34. pp. 2,751–2,764. 1998.

Table 1. Physical Processes Enabled for Each Test Case

Test Case	Sediment Transport		Vegetation Cover	Tectonic Uplift
	Fluvial	Diffusive		
1	X		X	
2	X		X	
3	X		X	

Tucker, G.E., S.T. Lancaster, N.M. Gasparini, and R.L. Bras. "The Channel-Hill Slope Integrated Landscape Development Model (CHILD)." *Landscape Erosion and Evolution Modeling*. R. Harmon and W.W. Doe III, eds. New York City, New York: Kluwer Academic/Plenum Publishers. 2001.

Walter, G. and P. Dubreuilh. "Evaluation of Approaches To Simulate Engineered Cover Performance and Degradation." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2007.

Willgoose, G. *User Manual for SIBERIA (Version 8.30)*. Scone, New South Wales, Australia: Telluric Research. July 2005.

Willgoose, G. *EAMS (Erosion Assessment and Modeling System) User Manual, Version 2.00.* Callaghan, New South Wales, Australia: LandTech Landform Technologies (A Division of TUNRA). July 2002.

Wilson, C.J., K.J. Corwell, and L.J. Lane. "Challenges in Parameterizing a Landscape Evolution Model to Predict 1,000 Years of Erosion on a Mesa-Top Waste Repository." *EOS Transactions, AGU*. Vol. 85: Fall Supplemental Abstracts. H51C–1141. 2004.

3 ENVIRONMENT

3.1 Software

SIBERIA Version 8.33 and EAMS Version 2.09 were obtained from Telluric Research (www.telluricresearch.com). The programs were installed on a personal computer with Microsoft® Windows® XP Professional Version 2002 operating system. Write privileges are required for the program directory in which the executables reside.

Input data files for each simulation include a gridded digital terrain model (DTM) and a physical parameter database (see Table 2 for physical parameter types).

Preprocessing with Surfer Version 8.04 produced gridded DTMs. Postprocessing and visualization of output was performed with EAMS-Viewer.

3.2 Hardware

SIBERIA software validation simulations were performed on the personal computer "Atlantis" with a 2.80 GHz Intel® Pentium® IV central processing unit.

4 ASSUMPTIONS AND CONSTRAINTS

SIBERIA simulates important mass transport mechanisms, as will be demonstrated in this report. SIBERIA incorporates dominant physical processes and catchment interactions in a physically realistic model, but does not account for all processes occurring in a catchment. For example, SIBERIA cannot simulate mass transport mechanisms that require knowledge of regolith or soil depth to be modeled, such as plastic transport. Soil depth is variable in space and time; is a function of the geomorphology, geochemistry, and biology of and the climate acting on the catchment; and is considered beyond the scope of reliable modeling according

Table 2. Default Physical Parameters	
Erosion Parameters (ModeErode = 0; ModeRandom = 0)	
Coefficient in the Fluvial Sediment Transport Relationship, β_1 (-)	0.01
Exponent on Discharge in the Fluvial Sediment Transport Relationship, m_1 (-)	1.5
Exponent on Slope in the Fluvial Sediment Transport Relationship, n_1 (-)	2.0
Fluvial Sediment Transport Threshold, q_{st} (m^3/yr·m)	0
Coefficient in the Second Fluvial Transport Relationship, β_{12} (-)	0
Exponent on Discharge in the Second Fluvial Transport Relationship, m_{12} (-)	1.0
Ratio: Overland Transport Rate:Fluvial Channel Transport Rate, O_t (-)	1.0
Bulk Density of Soil, ρ_b (metric tons/m^3)	1.3
Vegetation Cover Factor (same as that for Universal Soil Loss Equation) (-)	1.0
Coefficient of Diffusion in Diffusive Sediment Transport, D_z (m^3/yr·m)	0
Exponent of Nonlinearity in Diffusive Sediment Transport, D_{zn} (-)	1
Diffusive Transport Threshold, D_t (m^3/yr·m)	0
Hydrology Parameters (ModeRunoff = 0; ModeDir = 0)	
Coefficient on Area in the Discharge Relationship, β_3 (m/yr)	1.0
Exponent on Area in the Discharge Relationship, m_3 (-)	1.0
Channel Parameters (ModeChannel = 0)	
Channel Initiation Function (CIF) Threshold, a_t	0
Coefficient on the CIF Relationship, β_5	2.5
Exponent on Discharge in the CIF Relationship, m_5	0.4
Exponent on Slope in the CIF Relationship, n_5	0.3
Discharge Factor Between Fluvial Transport and CIF, a_1	1.0
Rate of Channel Formation, D_{time}	1.0
Coefficient in the Channel Geometry Model, β_4	0
Exponent in the Channel Geometry Model, m_4	0
DTM Parameters	
Easting Dimension of the Grid	32
Northing Dimension of the Grid	42
Grid Resolution (m)	1.0
Easting of the SW Corner of the Grid	0
Northing of the SW Corner of the Grid	0
Tectonic Parameters (ModeUplift = 0)	
Duration of the Tectonic Uplift (yr)	0
Initial Elevation for Blank Runs and Total Uplift for Other Runs, S_{Init}	10
Duration of Total Uplift for Uplift Solver, *notch*	1,000
Amplitude of the Cyclic Uplift, T_{amp} (m)	0
Period of the Cyclic Uplift, T_{period} (yr)	0
Phase of the Cyclic Uplift, T_{phase} ($t = 0$, radians)	0

to the SIBERIA author. Runoff is not directly modeled in SIBERIA, so there is no continuity of water or runoff routing in simulations. The Hortonian runoff mechanism assumes that all points in the catchment are saturated, and thus, uniform erosion occurs at every node in the model domain. A subsurface saturation runoff mechanism is apparently under development but not fully implemented in the current version of SIBERIA; thus, this more physically realistic mechanism, whereby some fraction of nodes in the model domain cause runoff due to full saturation, should not be used within SIBERIA at this time. Temporal variability in rainfall and runoff is not considered; rather, perpetual runoff is assumed with use of a geomorphically

effective, site-specific runoff coefficient. SIBERIA models transport-limited behavior and does not model detachment-limited behavior. The assumption here is that sufficient sediment is always available for transport, and thus all streams are at their carrying capacity. As a result, bedrock channel erosion is not well modeled using SIBERIA, but this limitation should have little impact on the effective modeling of engineered soil covers.

Landscape evolution changes calculated by SIBERIA for the period starting at the end of the institutional control period are likely to be strongly dependent on initial conditions (cover topography, soil properties). For long-term engineered soil cover assessment, a very important initial condition would be the cover topography at the end of institutional control, which is unknown and would have to be assumed. The initial conditions will have some degree of uncertainty because they cannot be accurately known now for the period that follows active institutional control. SIBERIA Version 7.05 (developed for use by Parallel Virtual Machine software) can be used to conduct Monte Carlo probabilistic risk assessment modeling to study the stochastic effects of poorly specified initial conditions, but this capability is not supported in more recent versions of SIBERIA and thus is not validated herein.

5 TEST CASES

5.1 Test Case 1: Comparison of Slope Angle Effect on Output Using 10 and 20 Percent Slopes

5.1.1 Test Input

The lateral extent of an engineered soil cover is defined, and bounding coordinates for a 10 percent and 20 percent soil cover slope are specified (Figure 1). The modeled portion of the engineered soil cover is a sloped, 40 by 30 m [131 by 98 ft] rectangle when projected down to a horizontal datum, as in map view. Depending on whether the 10 percent side slope or the 20 percent side slope is being considered, the maximum nominal elevation of the side slope is 3 m [10 ft] or 6 m [20 ft] above a 0 m [0 ft] horizontal datum, respectively.

Preprocessing to produce gridded DTMs was performed. Otherwise planar topographic surfaces were given a Gaussian surface roughness with mean 0.1 m [0.3 ft] and standard deviation 0.1 m [0.3 ft]. Input data files include the gridded DTMs named *xy6.GRID.XYZ* and *xy3.GRID.XYZ*, and an erosion parameter database named *testcase.sdb*. The selected physical parameters are summarized in Table 2.

5.1.2 Test Procedure

1. In EAMS-MOSCOW: Import a gridded DTM; select simulation start time ($t = 0$); select a text restart file (*.rst2*) as an output file type; specify an output file base name; define the total number of timesteps from which to output data (1 timestep); identify the timestep at which to output data (10,000 years); identify the name of a selected physical parameter database (i.e., SIBERIA database file *testcase.sdb*); select and retrieve the *default* dataset to use in the simulation.

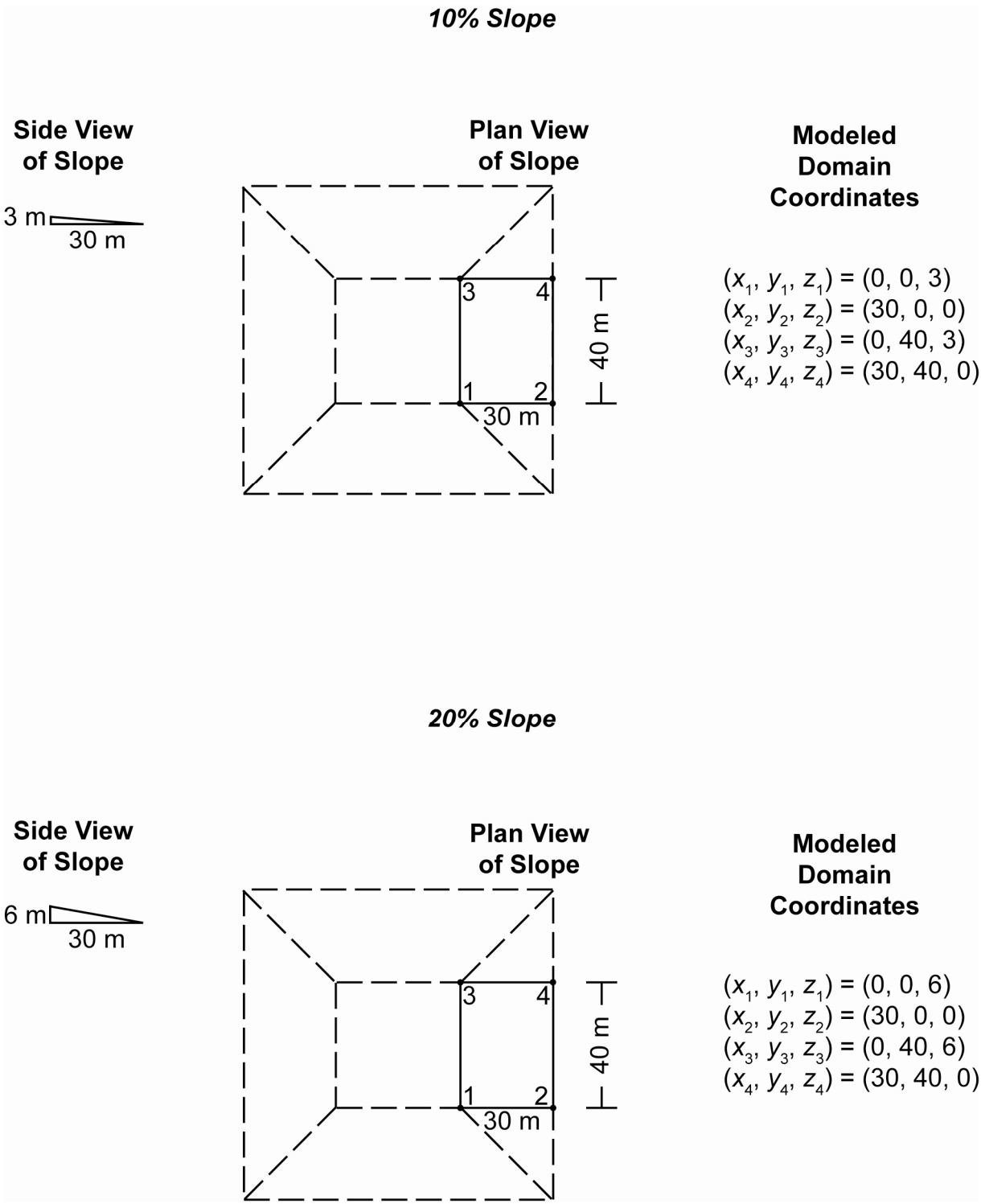

Figure 1. Test Case 1: Defined Lateral Extent of an Engineered Soil Cover and Specified Coordinates for Gridding One of Four Side Slopes (Slopes Specified as 10 or 20 Percent)

2. In EAMS-MOSCOW: Select the Edit Parameters–Run Parameters option: set the total simulation run time (10,000 years), set automated adaptive timestepping by entering any negative number in the timestep window (e.g., "–1"), and select 1,000-year intervals for outputting statistics; select the Edit Parameters–Erosion Parameters option: change parameter ModeErode from 20 to 0; select the Edit Parameters–Hydrology Parameters option: change parameter ModeRunoff from 20 to 0 and parameter ModeDir from 1 to 0; select the Edit Parameters–Advanced Parameters #2 option and change parameter ModeSolver from 5 to 4.

3. In EAMS-MOSCOW: Select *Prepare and Run Siberia* from the SIBERIA menu. When finished running, exit from EAMS-MOSCOW.

4. Do the above steps twice, once for the 10 percent slope with input file *xy3.GRID.xyz* and once for the 20 percent slope with input file *xy6.GRID.xyz*.

5. In EAMS-Viewer: Visualize the initial and final landscapes; difference the initial and final landscapes to visualize the elevation difference after 10,000 years.

6. Using data from *siberia-xy3.output* and *siberia-xy6.output*, use Microsoft Excel® to generate a graph of selected landscape evolution characteristics (see Figure 4) as a function of time.

7. Using statistics from *xy3-0010000.rsu* and *xy6-0010000.rsu*, compare the mean elevation change over the grid of finite difference nodes.

By default, SIBERIA output includes eight model variables in each *.rst2* file. The first six variables are (i) slope; (ii) a spatial random variation variable; (iii) a channel/gully indicator variable; (iv) elevation; (v) area draining through each node; and (vi) drainage direction at each node. As selectively implemented in the *siberia.setup* file by the interactive user, additional nodal data was output to the *.rsu* file, including the change in elevation at a node (mm) as measured from the initial elevation at that node (ZCHANGE).

To validate SIBERIA, the mean ZCHANGE will be examined for the 20 and 10 percent side slopes, and a variety of landscape evolution characteristics will be examined for physically realistic adherence to expectations.

5.1.3 Results

All other parameters equal, the SIBERIA simulation for a 20 percent side slope should produce more sediment erosion than a SIBERIA simulation for a 10 percent side slope.

The simulations for Test Case 1 were performed on August 21, 2008. Simulation results are contained in the output files listed in Table 3 and are located on the SIBERIA software validation CD associated with Scientific Notebook 950E (Dinwiddie, 2008). Landscape evolution for the two different side slopes are shown in Figures 2 and 3. To understand the graphics capabilities and limitations of SIBERIA, all landform results are directly displayed from EAMS-Viewer, rather than exported to more sophisticated, third-party software. To correctly interpret the resulting figures, the reader must realize the color stretch EAMS-Viewer uses stretches twice as much for an initially 6-m-high [20-ft-high] slope than for an initially 3-m-high [10-ft-high] slope. As such,

Table 3. Output Files From Test Case 1 Simulations		
***.rst2* Files**	***.output* and *.rsu* Files**	***.bnd* and *.xyz* Files**
20 Percent Slope		
xy6-start.rst2	*siberia-xy6.output*	*xy6.bnd*
xy6-0010000.rst2	*xy6-0010000.rsu*	*xy6-0010000.grid.xyz*
10 Percent Slope		
xy3-start.rst2	*siberia-xy3.output*	*xy3.bnd*
xy3-0010000.rst2	*xy3-0010000.rsu*	*xy3-0010000.grid.xyz*

the lower elevation residual slope in Figure 2 shows both red and green tones, whereas the slightly more elevated residual slope in Figure 3 appears nearly entirely red-toned. This outcome does not imply that the residual slope of Figure 3 is at a lower elevation than the residual slope of Figure 2; in fact, the opposite is true. Limitations of EAMS-Viewer include the lack of axes and a color bar.

For algorithmic purposes, SIBERIA automatically adds bounding nodes outside the domain of the actively degrading DEM. For a one-dimensional slope, EAMS-Viewer displays these bounding points as having the initial elevation of the DEM (e.g., Figures 2 and 3). This output does not suggest that the thin bounding nodes of the DEM remain in place in perpetuity; rather, this boundary of nodes external to the DEM can serve as a visual cue for extent of landscape erosion.

The mean nodal grid elevation change (i.e., mean "ZCHANGE") for the 10 and 20 percent side slopes over the simulation period of 10,000 years was 1,031 and 2,311 mm [40.59 and 90.98 in]. Graphing a variety of landscape evolution characteristics (Figure 4) for the 10 and 20 percent side slopes over the simulation period illustrates that the 20 percent side slope degrades to nearly the same final condition as the 10 percent side slope over the same simulation period. There is some ambiguity in the software documentation regarding whether "Total Active Mass" is intended to mean "Total Active Volume." Here we interpret "Total Active Mass" to mean "Total Active Volume" in cubic meters rather than total active mass in metric tons, as shown in Figure 4, consistent with initial 10 percent side slope and 20 percent side slope wedges of 1,800 and 3,600 m^3 [63,600 and 127,100 ft^3]. It is thus shown that all other parameters equal, the SIBERIA simulation for a 20 percent side slope produces more sediment erosion than the simulation for a 10 percent side slope. This outcome is physically realistic and meets expectations, and the results of this software validation test are acceptable. Note, however, that the computed magnitude of erosion for each simulation cannot be independently evaluated.

5.2 Test Case 2: Comparison of Surface Roughness Effect on Output

5.2.1 Test Input

A 100 by 100-m [328 by 328-ft] engineered soil cover is defined, and bounding coordinates for a 20 percent soil cover slope are specified (Figure 5) as the initial rudimentary geometry for Test Case 2. Preprocessing to produce gridded DTMs was performed. Input data files include perfectly flat-surfaced and rough-surfaced, gridded DTMs of nominally 6-m [20-ft]-high waste disposal mounds named *umound6.GRID.XYZ* and *rmound6.GRID.XYZ*, and the erosion parameter database named *testcase.sdb*. The selected *default* dataset of physical parameters

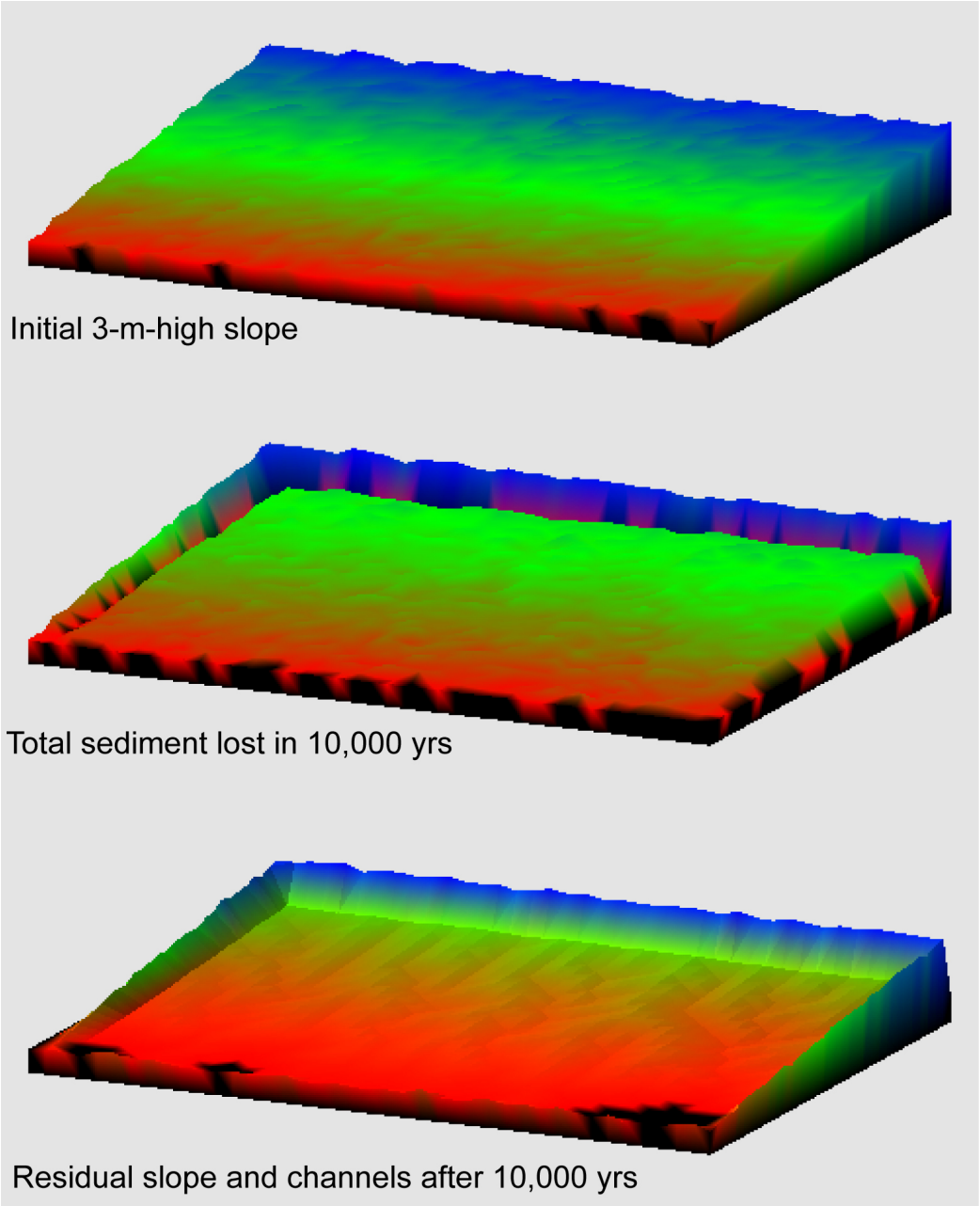

Figure 2. Test Case 1: Landscape Evolution of 3-m-High [10-ft-High] Slope Over 10,000 Years (Cool Colors Represent Higher Elevations Than Warm Colors)

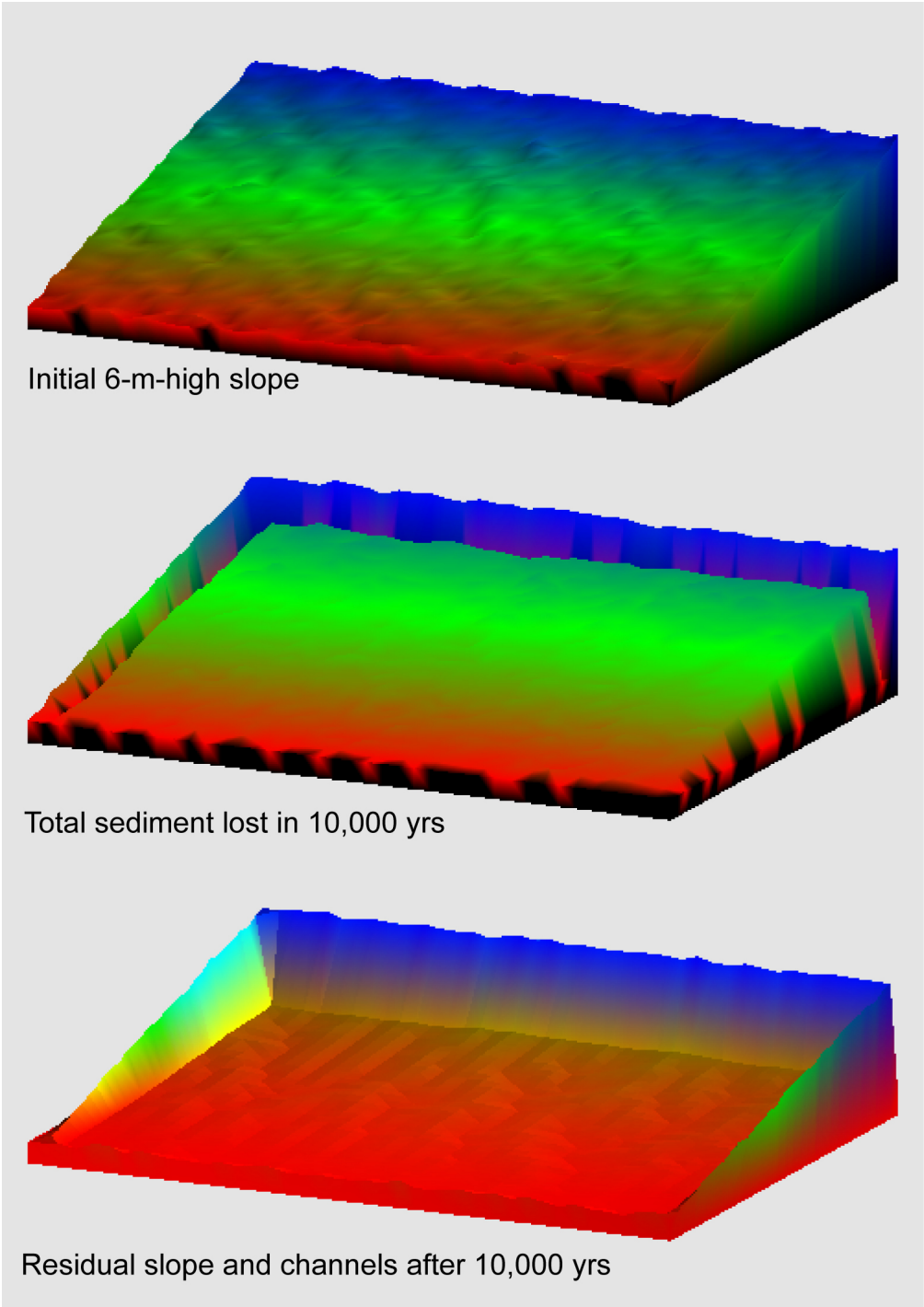

Figure 3. Test Case 1: Landscape Evolution of 6-m-High [20-ft-High] Slope Over 10,000 Years (Cool Colors Represent Higher Elevations Than Warm Colors)

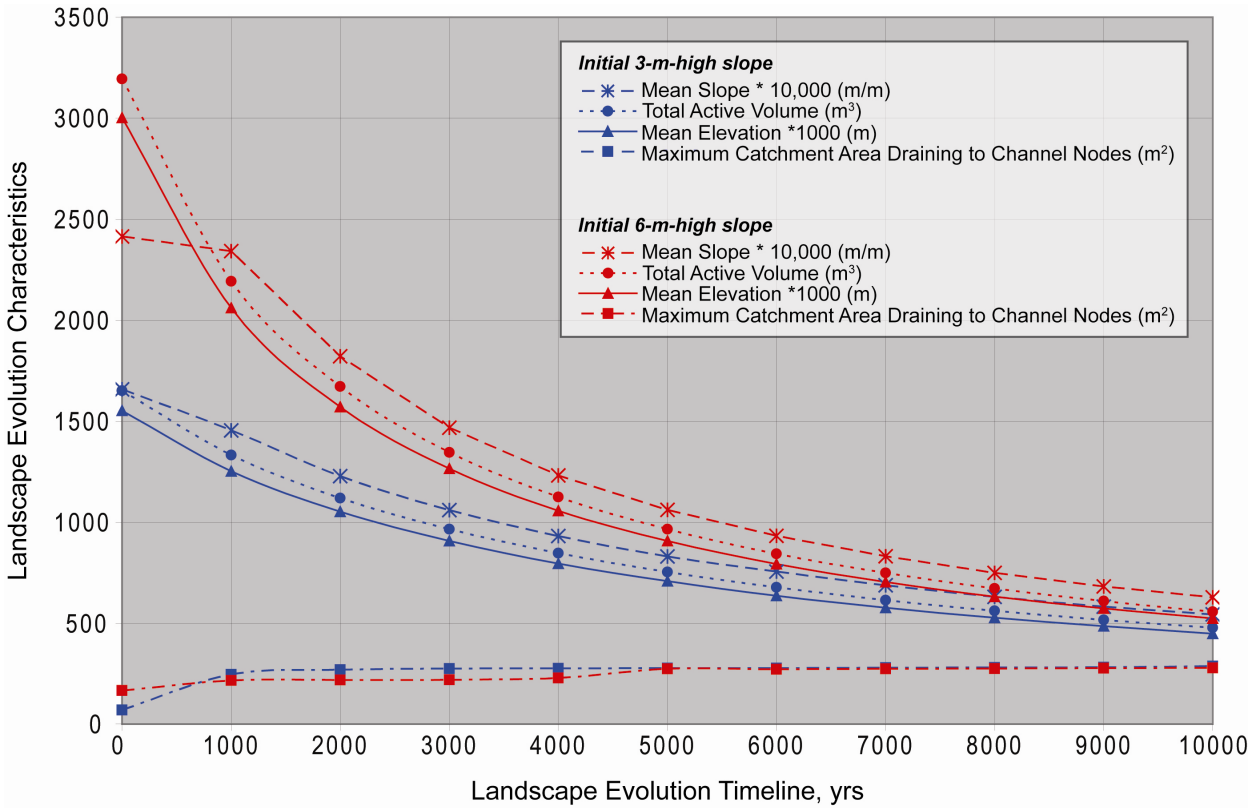

Figure 4. Test Case 1: 20 and 10 Percent Slopes Evolve to Nearly the Same State After 10,000 Years

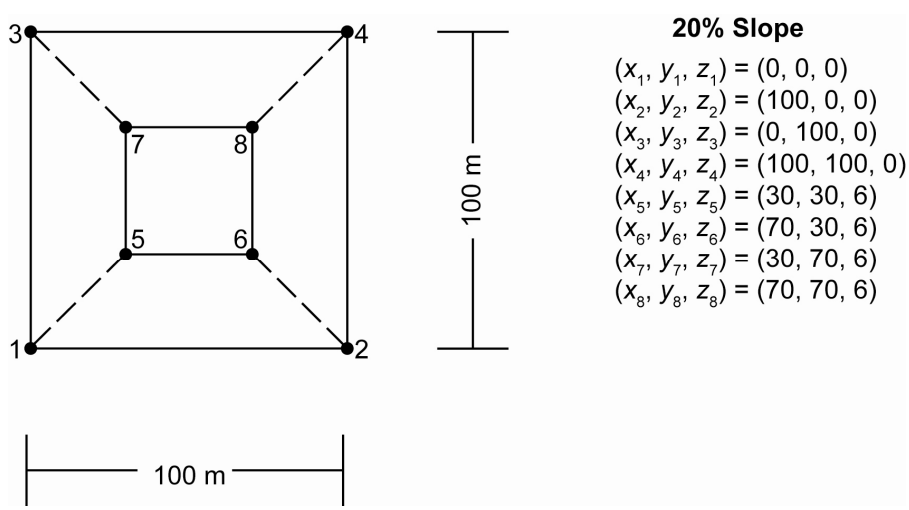

Figure 5. Test Case 2: Initial Rudimentary Topography of Simulated Engineered Soil Cover

for Test Case 2 are the same as for Test Case 1 and are as summarized in Table 1. The rough-surfaced DTM was given a Gaussian surface roughness with mean 0.1 m [0.3 ft] and standard deviation 0.1 m [0.3 ft].

5.2.2 Test Procedure

1. In EAMS-MOSCOW: Import a gridded DTM; select simulation start time ($t = 0$); select a text restart file (*.rst2*) as an output file type; specify an output file base name; define the total number of timesteps from which to output data (1 timestep); identify the timestep at which to output data (1,000 years); identify name of selected physical parameter database (i.e., SIBERIA database file *testcase.sdb*); select and retrieve the *default* dataset to use in the simulation.

2. In EAMS-MOSCOW: Select the Edit Parameters–Run Parameters option: set the total simulation run time (1,000 years), set automated adaptive timestepping by entering any negative number in the timestep window (e.g., "–1"), and select 100-year intervals for outputting statistics; select the Edit Parameters–Erosion Parameters option: change parameter ModeErode from 20 to 0; select the Edit Parameters–Hydrology Parameters option: change parameter ModeRunoff from 20 to 0 and parameter ModeDir from 1 to 0; select the Edit Parameters–Advanced Parameters #2 option and change parameter ModeSolver from 5 to 4.

3. In EAMS-MOSCOW: Select *Prepare and Run Siberia* from the SIBERIA menu. When finished running, exit from EAMS-MOSCOW.

4. Do the above steps twice, once for the mound exhibiting perfectly flat topographic surfaces and once for the mound exhibiting rough topographic surfaces.

5. Using the "Max. Area" data from *siberia-umound6.output* and *siberia-rmound6.output*, use Microsoft Excel to generate a graph of maximum catchment area draining to channel nodes as a function of time and initial surface roughness.

6. In EAMS-Viewer: Visualize the initial and final landscapes; difference the initial and final landscapes to visualize the elevation difference after 1,000 years.

5.2.3 Results

All other parameters equal, the SIBERIA simulation for a waste disposal mound exhibiting perfectly flat topographic surfaces should result in mainly unidirectional channelized erosion, whereas the SIBERIA simulation for a waste disposal mound exhibiting Gaussian surface roughness with mean 0.1 m [0.3 ft] and standard deviation 0.1 m [0.3 ft] should result in a more tortuous, multidirectional channelized erosion.

The simulations for Test Case 2 were performed on August 22, 2008. Simulation results are contained in the output files listed in Table 4 and are located on the SIBERIA software validation CD associated with Scientific Notebook 950E (Dinwiddie, 2008).

Graphing the maximum catchment area draining to any channel node as a function of time for each simulation suggests that the initial roughness of the rough DTM both initiates and continues development of more laterally extensive catchment areas (Figure 6). The facets of

Table 4. Output Files From Test Case 2 Simulations		
***.rst2* Files**	***.output* and *.rsu* Files**	***.bnd* and *.xyz* Files**
Smooth Initial Topographic Surfaces		
umound6-start.rst2	*siberia-umound6.output*	*umound6.bnd*
umound6-0001000.rst2	*umound6-0001000.rsu*	*umound6-0001000.grid.xyz*
Rough Initial Topographic Surfaces		
rmound6-start.rst2	*siberia-rmound6.output*	*rmound6.bnd*
rmound6-0001000.rst2	*rmound6-0001000.rsu*	*rmound6-0001000.grid.xyz*

the rough DTM are oriented randomly and facilitate lateral growth of catchment areas, whereas the slopes associated with each node of the initially smooth DTM are all initially oriented toward the far boundaries of the mound and thus favor unidirectional downslope movement. While channelized flow develops with time for the initially smooth mound, the maximum catchment area size is relatively constrained in comparison.

Landscape evolution for the initially smooth and initially rough waste disposal mounds is shown in Figures 7, 8, and 9.

The essentially unidirectional orientation of channels developed over a 1,000-year period when starting with an unrealistic, perfectly flat-surfaced mound is shown by Figures 7 and 9A. In contrast, the physically realistic multidirectional orientations of developed channels after a 1,000-year period when starting with a realistically rough-surfaced mound are shown by Figures 8 and 9B. The unidirectional channels of Figures 7 and 9A are thought to initiate because of numerical instabilities that occur precisely at locations of abrupt slope change between the flat top and angled sides of the perfectly smooth-sided mound. Once a numerical

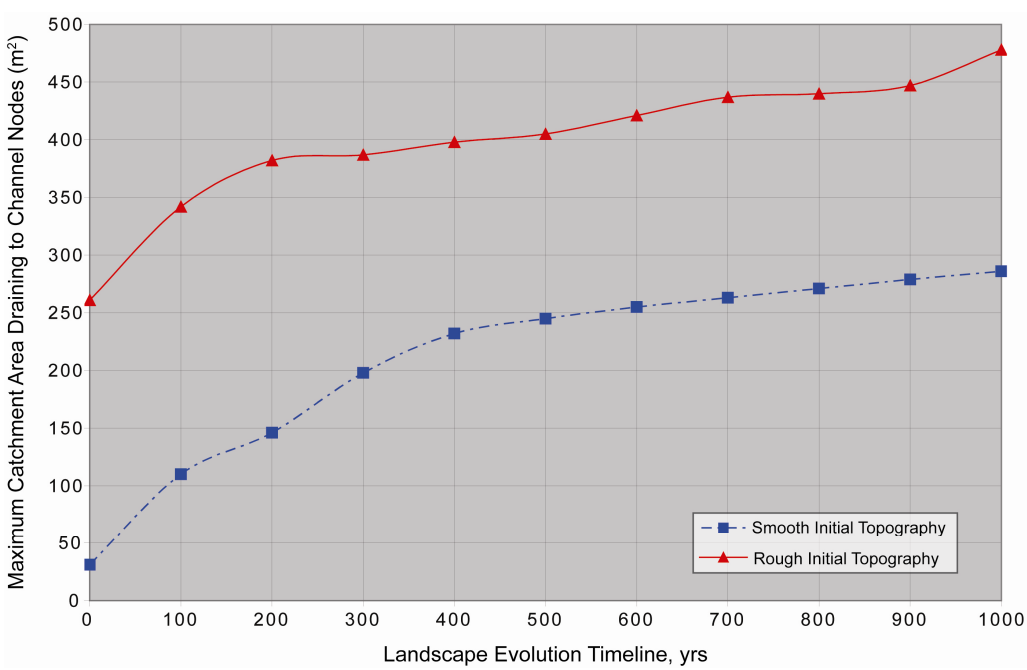

Figure 6. Test Case 2: Maximum Catchment Area Draining to a Channel Node in the Grid as a Function of Time and Surface Topography

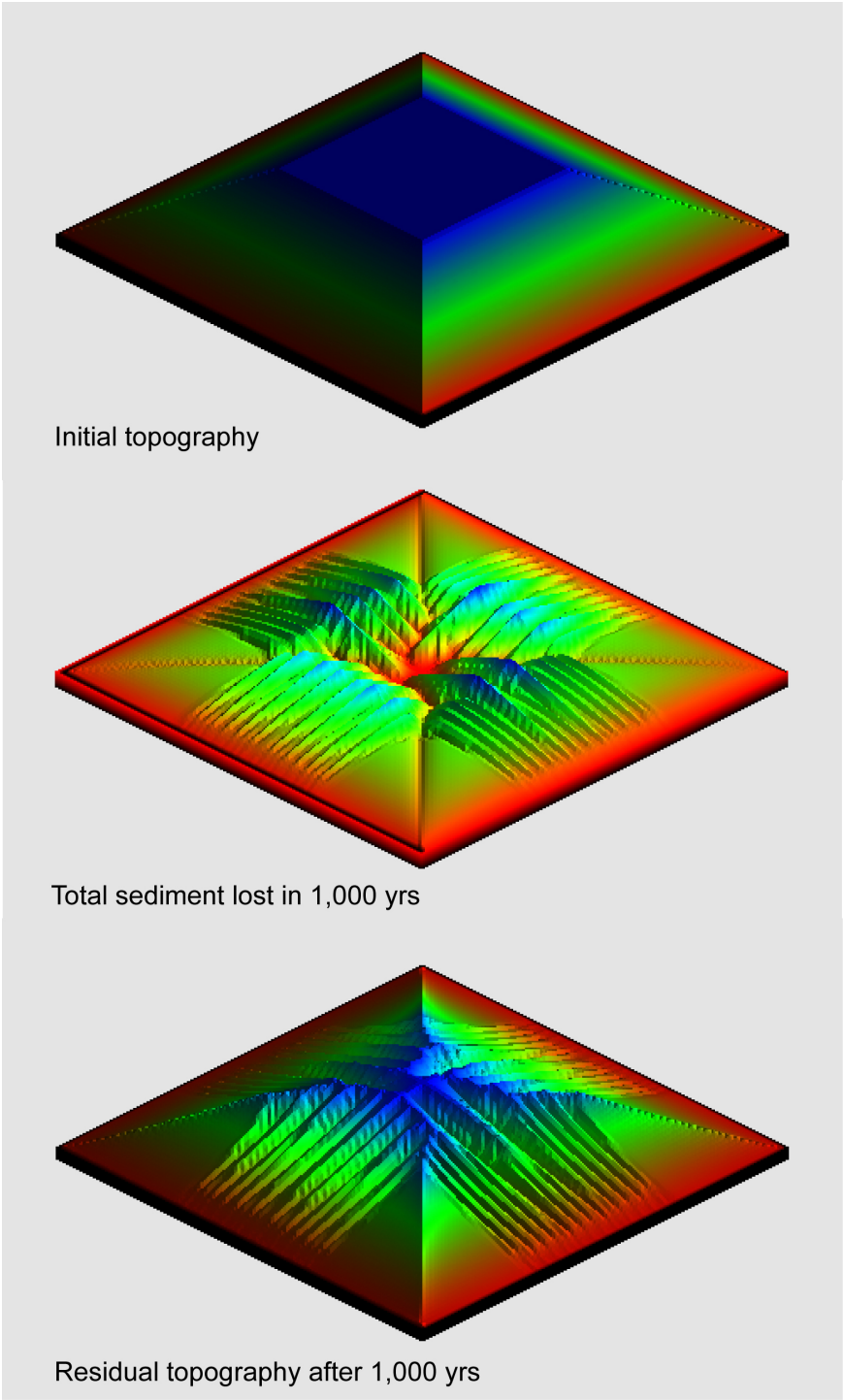

Figure 7. Test Case 2: Landscape Evolution Over 1,000 Years of 6-m-High [20-ft-High] Mound With Smooth Initial Surfaces (Cool Colors Represent Higher Elevations Than Warm Colors)

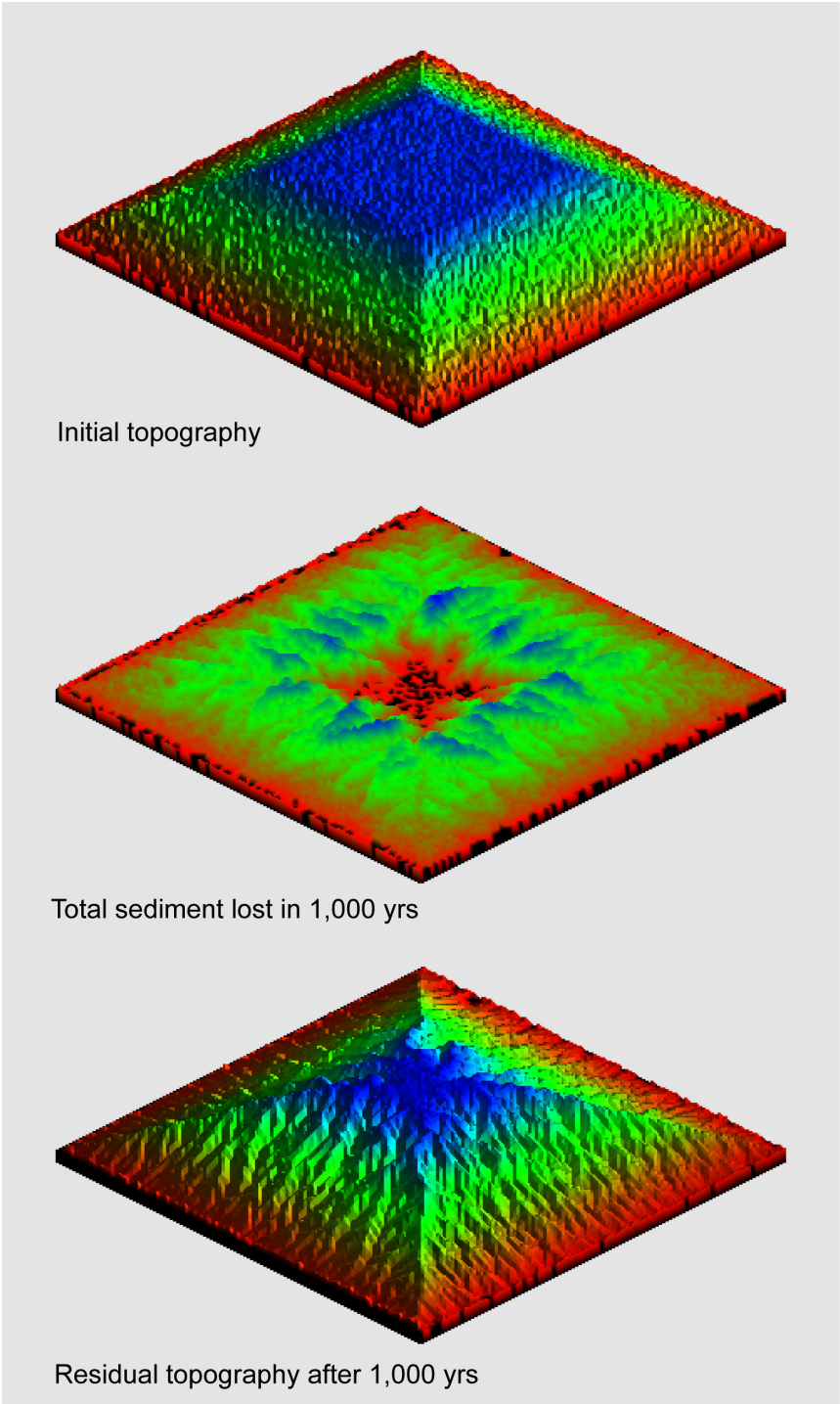

Figure 8. Test Case 2: Landscape Evolution Over 1,000 Years of 6-m-High [20-ft-High] Mound With Rough Initial Surfaces (Cool Colors Represent Higher Elevations Than Warm Colors)

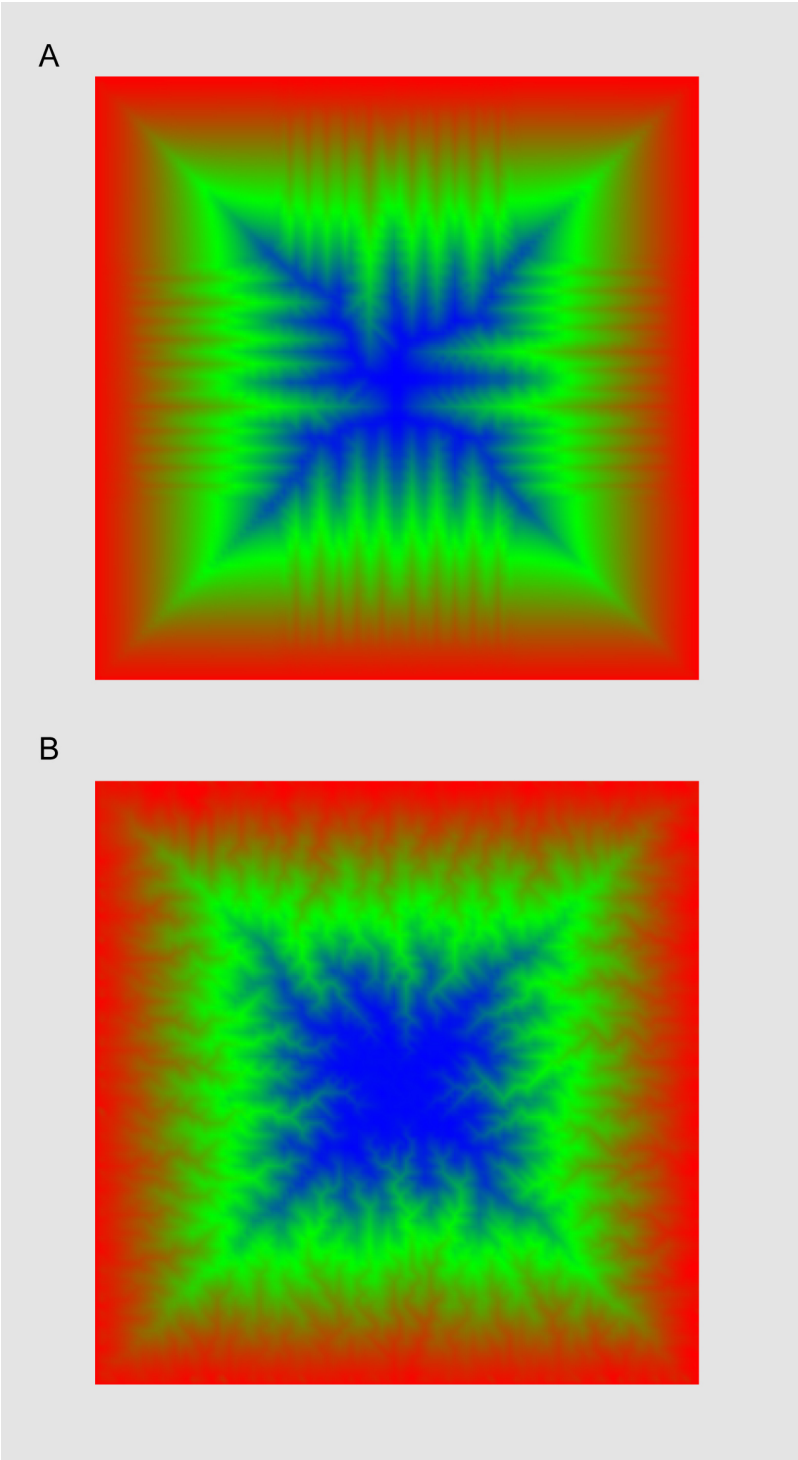

Figure 9. Test Case 2: Map Views of Eroded Landscapes After 1,000 Years: (A) Initially Smooth Mound and (B) Initially Rough Mound (Cool Colors Represent Higher Elevations Than Warm Colors)

instability initiates channel development, the channel continues to incise and grow with the passage of time. This interpretation is supported by the observation that unidirectional channels did not form in the corner areas of the degraded landscape of Figures 7 and 9A. The corner areas, while subject to interfaces between two side slopes, are not subject to the same numerical instabilities that may occur only at an interface between a horizontal top surface and a side slope. When a SIBERIA model of a perfectly smooth, one-dimensional side slope (in the absence of abrupt interfaces between surfaces) is run, channels do not form at all—only uniform (non-channelized) downhill erosion takes place, as would be expected for an ideal slope exhibiting no roughness. Even though perfectly smooth surfaces do not occur in nature, SIBERIA tends to produce sensible, interpretable output. It is thus shown that an unrealistic, simulated waste disposal mound exhibiting perfectly flat topographic surfaces results in mainly unidirectional channelized erosion, whereas a more realistic simulated waste disposal mound exhibiting Gaussian surface roughness {mean 0.1 m [0.3 ft]; standard deviation 0.1 m [0.3 ft]} results in a more tortuous, multidirectional channelized erosion. This outcome is physically realistic and meets expectations, and the results of this software validation test are acceptable. Note, however, that the computed magnitude of erosion for each simulation cannot be independently evaluated.

5.3 Test Case 3: Effect on Output of Coefficient Magnitude in the Fluvial Sediment Transport Relationship

5.3.1 Test Input

The nominally 6-m-high [20-ft-high], 20 percent engineered soil cover slope from Test Case 1 serves as the initial geometry for Test Case 3. As before, this slope was given a Gaussian surface roughness with mean 0.1 m [0.3 ft] and standard deviation 0.1 m [0.3 ft].

Input data files include the Test Case 1 gridded DTM named *xy6.GRID.XYZ* and the erosion parameter database named *testcase.sdb*. Test Case 3 compares the output from the nominally 6-m [20-ft]-high slope obtained from Test Case 1 with new output obtained when repeating the simulation with a revised coefficient in the fluvial sediment transport relationship that is smaller by a factor of 10 compared to that used in Test Case 1. Thus, the selected physical parameters are as summarized in Table 1, with the exception that the dimensionless “Coefficient in the Fluvial Sediment Transport Relationship” is modified from 0.01 to 0.001.

5.3.2 Test Procedure

1. In EAMS-MOSCOW: Import the gridded DTM *xy6.GRID.XYZ*; select simulation start time ($t = 0$); select a text restart file (*.rst2*) as an output file type; specify an output file base name; define the total number of timesteps from which to output data (1 timestep); identify the timestep at which to output data (10,000 years); identify name of selected physical parameter database (i.e., SIBERIA database file *testcase.sdb*); select and retrieve the *default* dataset to use in the simulation.

2. In EAMS-MOSCOW: Select the Edit Parameters–Run Parameters option: set the total simulation run time (10,000 years), set automated adaptive timestepping by entering any negative number in the timestep window (e.g., “–1”), and select 1,000-year intervals for outputting statistics; select the Edit Parameters–Erosion Parameters option: change parameter ModeErode from 20 to 0; change parameter Coefficient in the Fluvial Sediment Transport Relationship from 0.01 to 0.001; select the Edit

Parameters–Hydrology Parameters option: change parameter ModeRunoff from 20 to 0 and parameter ModeDir from 1 to 0; select the Edit Parameters–Advanced Parameters #2 option and change parameter ModeSolver from 5 to 4.

3. In EAMS-MOSCOW: Select *Prepare and Run Siberia* from the SIBERIA menu. When finished running, exit from EAMS-MOSCOW.

4. In EAMS-Viewer: Visualize the initial and final landscapes; difference the initial and final landscapes to visualize the elevation difference after 10,000 years.

5. With data from *siberia-xy6.output* (Test Case 1) and *siberia-xy6beta1.output* (Test Case 3), use Microsoft Excel to generate a graph of selected landscape evolution characteristics as a function of time.

6. Using statistics from *xy6-0010000.rsu* (Test Case 1) and *xy6beta1-0010000.rsu* (Test Case 3), compare resulting mean elevation change over the grids of finite difference nodes.

5.3.3 Results

All other parameters equal, the Test Case 3 SIBERIA simulation with the reduced magnitude of the coefficient in the fluvial sediment transport relationship should result in less sediment erosion than the Test Case 1 SIBERIA simulation for the same initial side slope and 10 times larger coefficient.

The simulation for Test Case 3 was performed on August 26, 2008. Simulation results are contained in the output files listed in Table 5 and are located on the SIBERIA software validation CD associated with Scientific Notebook 950E (Dinwiddie, 2008).

Graphing a variety of landscape evolution characteristics (Figure 10) for the large (Test Case 1) and small (Test Case 3) coefficients for the fluvial sediment transport relationship over the simulation period illustrates that the SIBERIA simulation with a smaller coefficient produces less sediment erosion than the simulation with the larger coefficient.

Landscape evolution for the simulation with the revised, smaller magnitude coefficient is shown in Figure 11 and should be compared against Figure 3.

The mean nodal grid elevation change (i.e., mean “ZCHANGE”) for the large (Test Case 1) and small (Test Case 3) coefficients for the fluvial sediment transport relationship over the simulation period of 10,000 years was 2,311 and 862 mm [90.98 and 33.94 in]. It is thus shown that all

Table 5. Output Files From Test Case 3 Simulation Using Revised, Smaller Magnitude Coefficient for the Fluvial Sediment Transport Relationship

***.rst2* Files**	***.output* and *.rsu* Files**	***.bnd* and *.xyz* Files**
xy6beta1-start.rst2	*siberia-xy6beta1.output*	*xy6beta1.bnd*
xy6beta1-0010000.rst2	*xy6beta1-0010000.rsu*	*xy6beta1-0010000.grid.xyz*

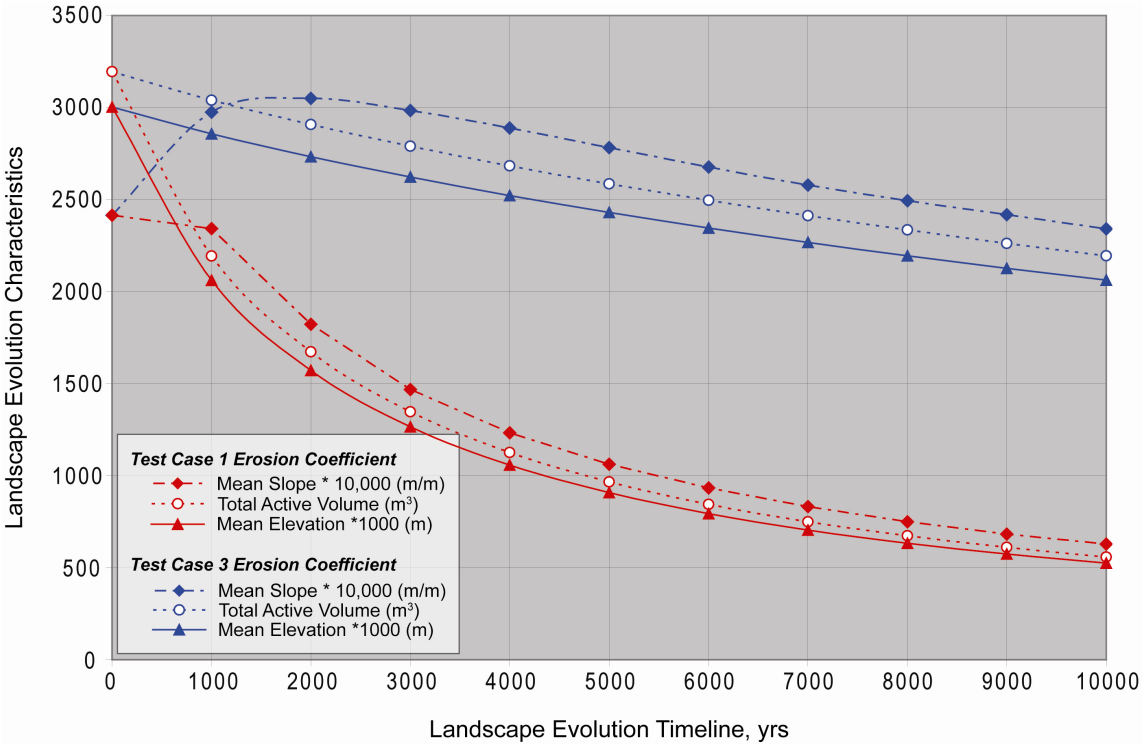

Figure 10. Test Case 3: The 20 Percent Engineered Soil Cover Slope With Smaller Magnitude Coefficient for the Fluvial Sediment Transport Relationship Produces Less Sediment Erosion

other parameters equal, the SIBERIA simulation with a smaller coefficient produces less sediment erosion than the simulation with the larger coefficient. This outcome is physically realistic, meets expectations, and the results of this software validation test are acceptable. Note, however, that the computed magnitude of erosion cannot be independently evaluated.

6 CONCLUSIONS

The final status of SIBERIA as a result of this software validation is that its functionalities addressed in Test Cases 1–3 have undergone limited validation, consistent with TOP–18. Not every functionality of SIBERIA was tested herein. Additional test cases would be required, for example, for limited validation of tectonic uplift and diffusive sediment transport capabilities of SIBERIA.

Were laboratory-scale physical analog models of landscape evolution available, they might provide an avenue for direct comparison of model results with the characteristics of a well-controlled landscape developed on a relatively short time interval. Full validation of SIBERIA could be enabled by such comparisons.

Additional capabilities for SIBERIA under development include a soils model, a layers model, and a detachment model. The layers model will allow for up to 5 layers for erosion and deposition, and the detachment model can only be used in combination with the layers model. The soils model cannot be used in combination with the layers model. These extended models

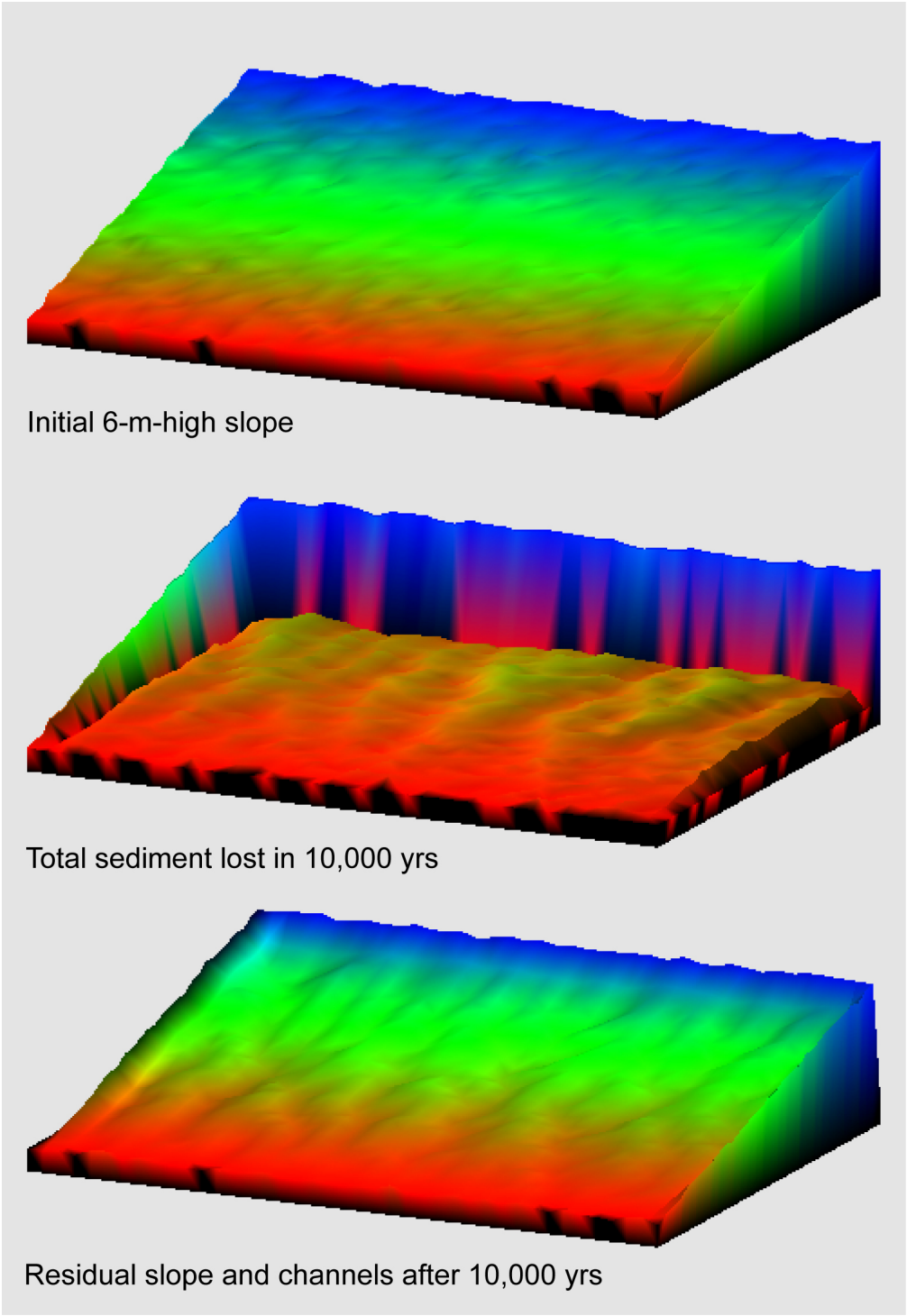

Figure 11. Test Case 3: Landscape Evolution of 6-m-High [20-ft-High] Slope Over 10,000 Years Using a Revised, Smaller Magnitude Coefficient for the Fluvial Sediment Transport Relationship (Cool Colors Represent Higher Elevations Than Warm Colors)

are poorly documented in the user manual. Researching relevant, peer-reviewed literature to understand virtually undocumented, transitional (i.e., in nonfinal form) capabilities of SIBERIA was deemed beyond the scope of this software validation report. Reviewing the peer-reviewed literature concerning use of SIBERIA, however, is a logical and important next step in the process of understanding the utility of this code for specific application to NDAA sites.

SIBERIA offers the capability to simulate changes in engineered closure cap topography. Calculated changes are likely to be strongly dependent on initial conditions (cover topography, soil properties) that will not be accurately known after the period of institutional control. Nevertheless, SIBERIA may indicate the susceptibility of an engineered cover to long-term erosion and provide information about the anticipated style of erosion features and thus be useful for evaluating the long-term integrity of engineered soil covers.