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Title: SURFACE EROSION MODELING FOR THE REPOSITORY WASTE COVER AT LOS ALAMOS NATIONAL LABORATORY TECHNICAL AREA 54, MATERIAL DISPOSAL AREA G

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Los Alamos
NATIONAL LABORATORY

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Acronyms and Abbreviations

ALSM	Airborne laser swath mapping
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DEM	Digital elevation model
HEM	Hillslope Erosion Model
LANL	Los Alamos National Laboratory
MDA	Material Disposal Area
NOAA	National Oceanic & Atmospheric Administration
TA	Technical Area
WEPP	Water Erosion Prediction Project

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1.0 Introduction

Low-level radioactive waste from operations at Los Alamos National Laboratory (LANL or the Laboratory) is currently disposed of in pits excavated into the mesa top at Material Disposal Area (MDA) G of Technical Area (TA) 54. One requirement for the operation of this repository is to limit releases of radioactive material to the environment for a period of 1,000 years or more following the facility's closure. The Laboratory is required to demonstrate that the repository can be successfully closed, which includes showing that the waste pits will not be excavated by long-term surface erosion processes such as rilling and gullying. Toward that end, surface erosion modeling was conducted to estimate the spatial distribution of depth to waste at MDA G after 1,000 years of erosion and sediment transport.

Material Disposal Area G is located on a slender finger mesa, Mesita del Buey, which has complex topography and a challenging layout of legacy waste pits located close to the edge of the mesa and natural drainage features (Figure 1). As a result, the closure cover has a complex topography, and the performance of the cover must be assessed as a three-dimensional unit. The SIBERIA model (Willgoose and Riley, 1998) was selected for the erosion evaluation because it is a well-tested version of a new class of erosion models developed to predict long-term landscape evolution. Like well-known hillslope-based erosion models such as the Water Erosion Prediction Project (WEPP) (Laflen et al., 1995) and KINEROS (Smith et al., 1995), SIBERIA predicts sediment transport derived from shallow sheet and rill processes for a range of soil, runoff, vegetation cover, and hillslope properties. Unlike WEPP and KINEROS, SIBERIA predicts the spatial distribution of deformation across complex, three-dimensional topography over hundreds to thousands of years. This includes the lowering of ridges, the incision or infilling of valleys and hollows, and the development of gullies and fans.

Scientists at LANL worked with cover design engineers at URS Corporation in an iterative process to develop a stable closure cover design (Figure 2). The SIBERIA modeling results described in this report demonstrate that the final, optimized design meets performance criteria across the site for a wide range of potential site and climate conditions that could occur over the 1,000-year compliance period. Section 2 of this report describes the principles behind the SIBERIA model and the methods for defining parameters and running the model. The results of the model simulations are provided in Section 3, and Section 4 discusses these results and some of the uncertainties associated with the modeling.

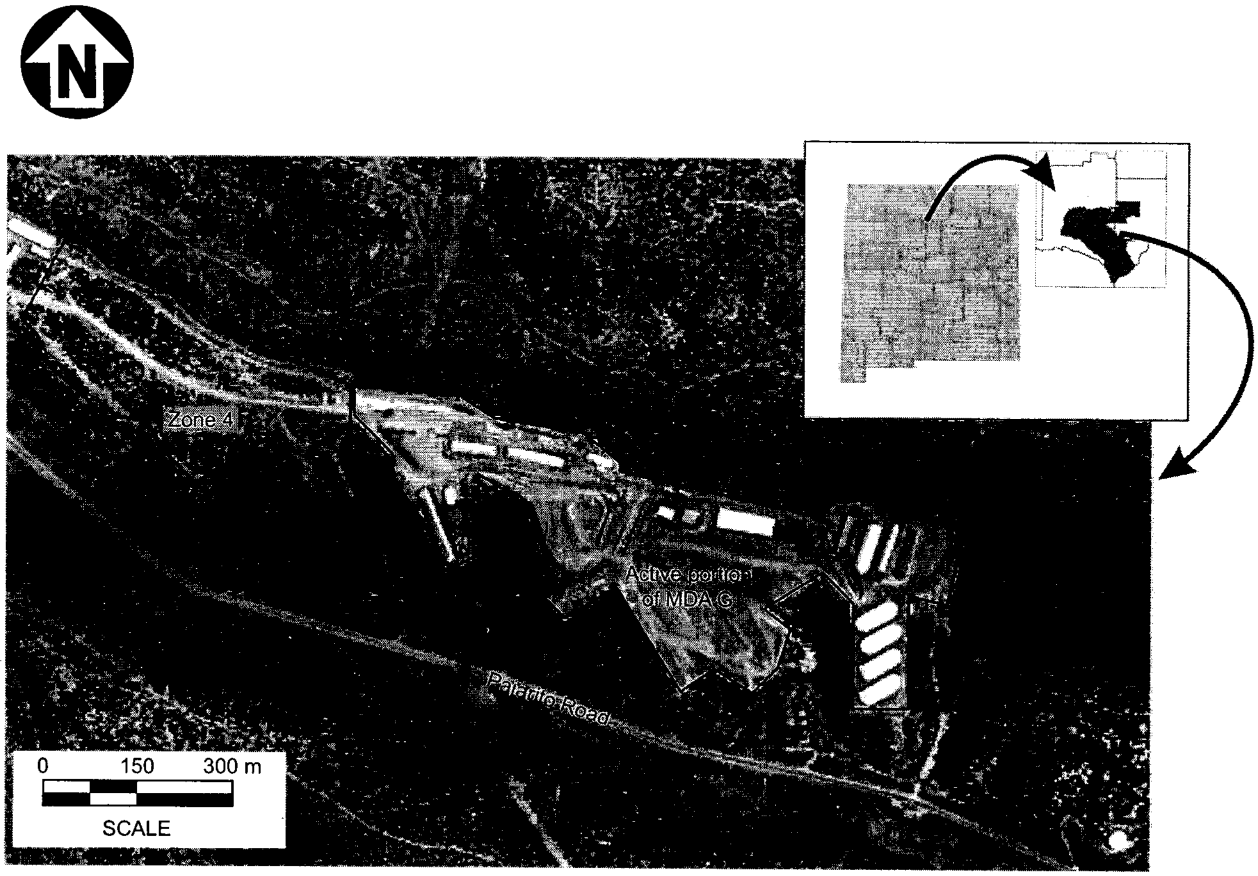


Figure 1
Aerial Photograph of Material Disposal Area G

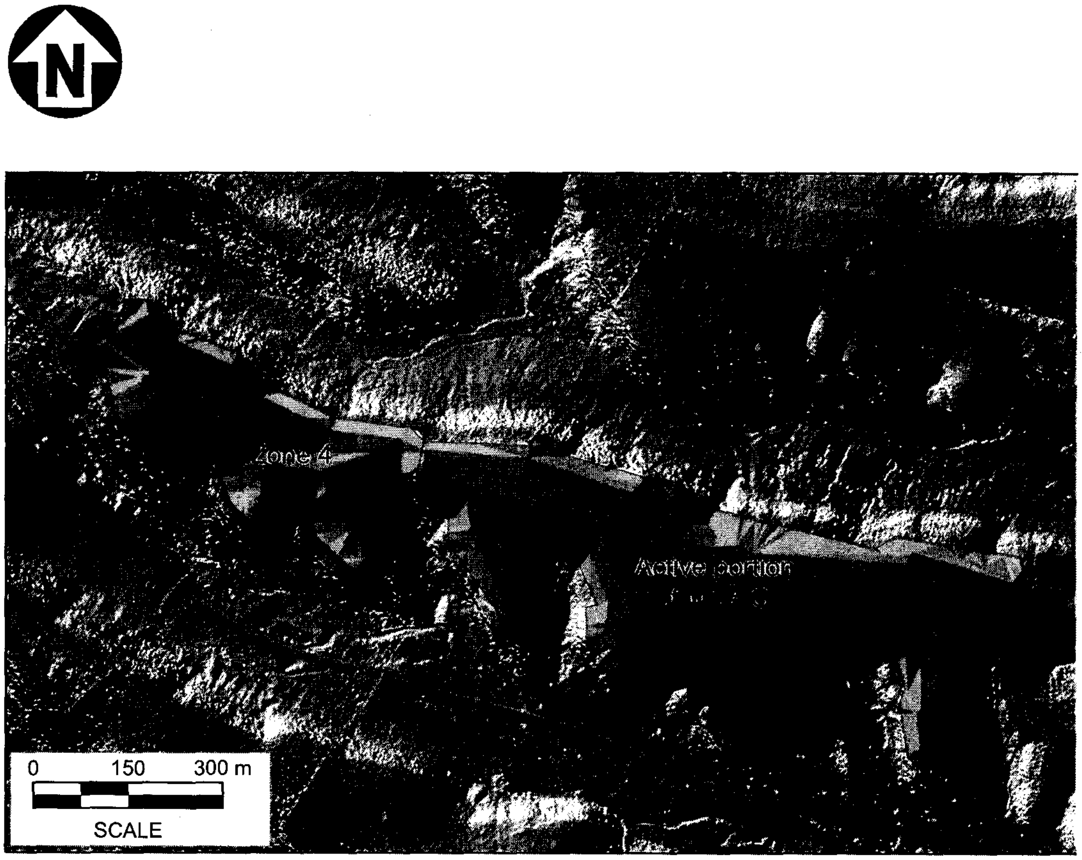


Figure 2
Proposed Configuration of Cover
for Material Disposal Area G

2.0 Methods

The long-term erosion assessment at MDA G was performed using the SIBERIA landscape evolution model (Willgoose et al., 1991a, 1991b). This model predicts steady-state erosion and sediment transport across a landscape that is represented as elevations in a gridded digital elevation model (DEM). The DEM is adjusted each time step (typically 1 year) to account for any change in surface elevation that occurred from erosion or deposition since the last time step. The governing equation for the SIBERIA model is:

$$Q_s = BA^m S^n + D_z S \qquad 1$$

Where

Q_s	=	the annual sediment flux through a grid cell (kg per meter width)
B	=	a coefficient that represents all factors that moderate runoff-driven erosion in the grid cell, except slope and runoff
$A^m S^n$	=	the relationship between contributing area (A), slope (S), and sediment yield
D_z	=	a diffusion coefficient
S	=	the terrain gradient (slope) (%)

Thus, Equation 1 includes sediment transport terms for both runoff-driven (advective) processes ($B A^m$) and gravity-driven (diffusion) processes. The intensity of runoff-driven sediment transport is given by $B A^m S^n$. The coefficient B accounts for all factors (e.g., vegetation cover, degree of soil disturbance, and soil type) that moderate runoff-driven erosion in the grid cell, except for slope and runoff. The $A^m S^n$ value increases as the catchment area above a grid cell increases (i.e., a bigger catchment area feeding into a grid cell equates to a greater runoff volume flowing through the grid cell) and as the gradient of the cell increases. The exponents m and n determine how sediment yield depends on contributing area and slope for a given site, and can be determined empirically (where data are plentiful) or through an optimization process using other hillslope-based models. Diffusive transport includes processes such as rainsplash (sediment particles ejected from the surface by raindrop impacts), tree-throw (sediment tumbled downslope when the root ball of a fallen tree is exposed at the surface), and animal burrow mounds. The diffusion coefficient D_z captures the intensity of these gravity-driven sediment transport processes.

Within the SIBERIA model, Equation 1 represents sediment-transport processes at all scales. In addition, the sediment yield, Q_s, when applied to each time step over long periods of time, is equivalent to the average annual sediment that would result from large and small events of all return periods. Equation 1 is solved for every grid cell in the SIBERIA model domain for each time step. Every grid cell has an upslope contributing area, A, and a slope, S. In any given grid cell the values of A and S may change through time as the landscape deforms; thus, these values are recalculated for each time step. The values of B, m, n and D_z are considered inherent material and site properties for soil and bedrock, even though they may change slowly or catastrophically as a result of long-term soil development or fire. The user may change these values in time through a start-and-stop process. However, because it is virtually impossible to project how time will affect these values at MDA G, in this study they were held constant over time for specific soil and bedrock layers.

2.1 Development of SIBERIA Parameters for Material Disposal Area G

The typical approach for developing values for the SIBERIA parameters B, m, n, and D_z is to calibrate SIBERIA to one or more standard hillslope-runoff erosion models. In principle, SIBERIA can be parameterized directly using long-term rainfall, runoff, and sediment yield data, but these datasets are rare. To derive the relationship for runoff-driven transport ($B\,A^m\,S^n$) empirically, data must exist for a range of hillslope and watershed gradients, S, at a range of area scales, A (hillslope, subwatershed, and watershed).

Multiple rainfall, runoff, and sediment datasets do exist for Mesita del Buey at a range of scales (experimental measurement plot, hillslope, and watershed scales), but these data are neither continuous over time nor of the uniform quality required for direct determination of SIBERIA parameter values. They were, however, sufficient for parameterizing the rainfall-runoff model IRS9 (Stone et al., 1992) and the runoff-sediment yield Hillslope Erosion Model (HEM) (Lane et al., 2001). Both the IRS9 model and the HEM were used to develop parameter values for the advective transport term in SIBERIA.

Although a quantitative path exists for developing the advective term in SIBERIA, determining the diffusion term is still an art. Research by Heimsath et al. (1997) has significantly advanced the quantitative determination of diffusion in equilibrium landscapes. Unfortunately, Mesita del Buey is a poor candidate for the application of these techniques because soil geochronology suggests that the local soils are aeolian and may have been emplaced rapidly about 10,000 years ago. Given this, the diffusivity was constrained by estimating a match between SIBERIA-generated topography and direct observations of headwater drainage lines using data from the field and from airborne laser swath mapping (ALSM) digital topographic maps. For example, if a SIBERIA run predicted that observed well-defined drainage lines at MDA G aggraded (filled-in with sediment) significantly over 1,000 years, then the value used for the diffusion coefficient in that run was probably set too high. If many new drainage lines appeared across the site, then the diffusion coefficient was probably too low.

A final challenge in parameterizing SIBERIA is developing steady-state values for B, m, and n such that the application of Equation 1 on an annual time step in the model domain reproduces nature's highly dynamic runoff and erosion rates. In nature, landscape-forming runoff events occur sporadically, perhaps once every 10, 20, or 1,000 years, rather than every year. Analysis of long-term datasets shows that the cumulative effect of a few "large" runoff events over the monitoring period is greater than the cumulative effect of the smaller runoff events that occur every year. Because SIBERIA is a steady-state model, the user must determine the size (return period) of a landscape-forming event that can be applied annually in the model domain to predict the same long-term sediment yield that would be generated through periodic large events.

Thus, the parameterization of the SIBERIA model for application at MDA G required a multistep approach. This approach, which is explained in more detail in the following sections, consisted of six major steps:

1. Collect, collate, and evaluate precipitation, runoff, and sediment-yield data for Mesita del Buey. These data were used to parameterize the rainfall-runoff ISR9 model and the runoff-erosion HEM, as well as to test SIBERIA results.

2. Evaluate long-term runoff and sediment-yield datasets from an analog site, the semiarid Santa Rita Experimental Range (in Arizona), to estimate the return period for landscape-forming events.

3. Develop rainfall-runoff relationships for MDA G using the selected return period for the landscape-forming events, as determined from data collected at the Santa Rita Experimental Range. Apply the ISR9 model using MDA G soil and vegetation properties and precipitation amounts for events with 2- and 5-year return periods for MDA G. The excess runoff values predicted by ISR9 for the 2- and 5-year events were used as input to the HEM.

4. Apply the HEM to predict sediment yield for hillslopes using a range of slopes and areas.

5. Apply a simulated multiparameter regression annealing technique (Crowell et al., 2004) to obtain values for B, m, and n that minimize the difference between sediment yields predicted by HEM and SIBERIA for the same set of test hillslopes.

6. Estimate D_z by matching SIBERIA results to present-day topography.

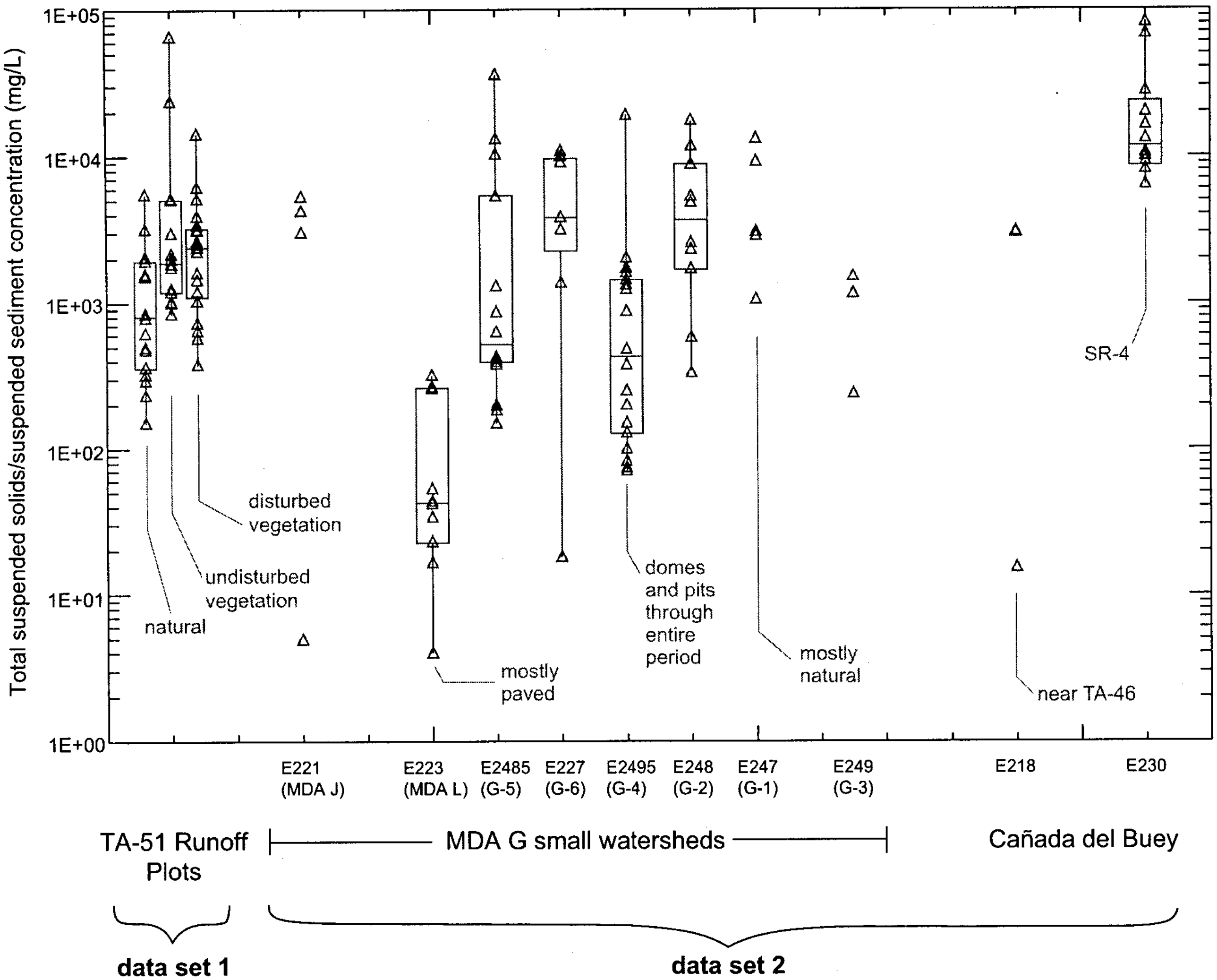
2.1.1 Local Data Analysis

A number of rainfall, runoff, and erosion datasets have been collected at LANL over the past five decades. Several long-term precipitation records for LANL (available at <http://weather.lanl.gov/>) were analyzed in relation to data posted for Mesita del Buey in the National Oceanic & Atmospheric Administration's Atlas 14 (NOAA, 2004) and were found to have similar rainfall frequency characteristics. For reproducibility and ease of analysis, the NOAA Atlas 14 rainfall frequency data were used for all analyses reported in this study; these data were generated from NOAA Atlas 14 for the rain gauge located at the LANL water quality monitoring site E247 (35.83° N 106.24° W). This site lies between the Zone 4 expansion area and the active portion of MDA G, immediately south of Mesita del Buey.

There are also a number of runoff and sediment-yield datasets for Mesita del Buey, which are of varying duration and quality. The two datasets determined to be of the most use for parameterizing ISR9 and assessing the HEM and SIBERIA results are (1) TA-51 runoff plots and (2) runoff and sediment-concentration data from eight small watersheds draining TA-54 and from two water quality monitoring stations on Cañada del Buey (E218 and E230). The first dataset contains runoff and erosion data for 52 runoff events; these data were collected from six 3×10 m (9.8×30 ft) plots located at TA-51. The second provides runoff and sediment concentration data for watersheds ranging in size from 1 ha to 10 km^2 (2.5 ac to 3.9 mi^2) and includes data for 141 runoff events. Both datasets were preconditioned to remove obviously poor data. Only those events for which rainfall, runoff, and sediment values could be matched, and for which rainfall was greater than runoff, were included.

Sediment concentration data for the TA-51, TA-54, and Cañada del Buey sites are summarized in Figure 3. In order to show both datasets in equivalent units (mg/l), sediment concentration values for the runoff plots were calculated by dividing the amount of sediment eroded during an event by the runoff volume for the same event. For the second dataset (representing the small watersheds at TA-54 and the Cañada del Buey monitoring stations), sediment concentration data were derived from total suspended solids samples collected with an ISCO automated sampler during storm runoff.

It was hoped that the data shown in Figure 3 would enable the estimation of the values of m and n in the $A^m S^n$ term (Equation 1). However, the variation in sediment concentration between subwatersheds appears to be more a result of site conditions (e.g., paving, soil disturbance, and drainage pipes) than a difference in watershed area or gradient, S. In addition, the event data are not equivalent for all sites. Consequently, it was determined that using these data to directly parameterize the SIBERIA model was inappropriate. These data were, however, used as one means of verifying SIBERIA model output.



= Mean and variation of sediment concentration data

Δ = Sediment concentration values (calculated from measured event-sediment volume divided by event-runoff volume)

Sediment concentrations measured using EPA method 160.2
E numbers indicate number of New Mexico surveillance program gauging station
G- numbers indicate TA-54 gauge number

Figure 3
Sediment Concentration Data for Runoff Plots, Small Watersheds, and Cañada del Buey

Hillslope topography and vegetation cover profile data were collected specifically for this project (Lane et al., 2002) and used in the ISR9 analysis to develop excess runoff values (with uncertainty) for the range of conditions expected after closure of the disposal facility. The profiles were located in areas with varying degrees of disturbance and rehabilitation. Data defining the shape of the hillslope as well as canopy and ground cover were collected at 1 m (3.3 ft) intervals along each of the 17 profiles shown in Figure 4.

2.1.2 Definition of a Steady-State Landscape-Forming Event

No long-term, coupled rainfall, runoff, and erosion datasets exist for LANL or nearby areas. As an analog, the long-term record of runoff and sediment-yield data from the Santa Rita Experimental Range in Southern Arizona was analyzed to determine the return period for a steady-state landscape-forming event in a semiarid environment. The analysis of these data showed that the average annual sediment yield for a period of approximately 16 years fell within the range of the sediment yield values from events with return periods of 2 and 5 years (Table 1). This is in agreement with the return period recommended by SIBERIA's author of about 2.3 years, which was based on his analysis of a long-term dataset from Europe (Willgoose, 2004). Rather than choose a single return period for the landscape-forming event, SIBERIA runs were performed for both the 2-and 5-year events. The assumption was that the two events would provide low and high estimates of sediment yield over the 1,000-year time frame of the model, and would account for the uncertainty in using data from an analog site to determine the landscape-forming event for MDA G.

2.1.3 Estimation of Runoff and Erosion

The IRS9 infiltration and runoff model (Stone et al., 1992) was used to estimate runoff volumes. Precipitation data for Los Alamos, New Mexico were taken from the NOAA Atlas 14 for events with 2- and 5-year return periods. The IRS9 model was applied to the 17 hillslope profiles shown in Figure 4 for two soil types, sandy loam and loam. These soil types bound the expected soil texture for the MDA G cover as given in the cover design specifications (Day et al., 2005). It is important to note that, although this cover is composed of multiple layers with different admixture materials, SIBERIA assumes the cover is a single homogenous layer of either loam or sandy loam. The loam cover consists of crushed tuff with a 6 percent admixture of bentonite, and the sandy loam assumes a cover composed of crushed tuff with no bentonite. Both covers include an admixture of 12 percent, by volume, of angular rock. The bentonite adds strength to the cover, inhibiting soil mass wasting on the steeper parts of the cover, but decreasing soil hydraulic conductivity, which in turn increases the amount of runoff available to drive erosion. The angular rock provides protection from surface erosion. As the cover erodes more rock is exposed at the surface, reducing the amount of soil surface exposed to erosion.

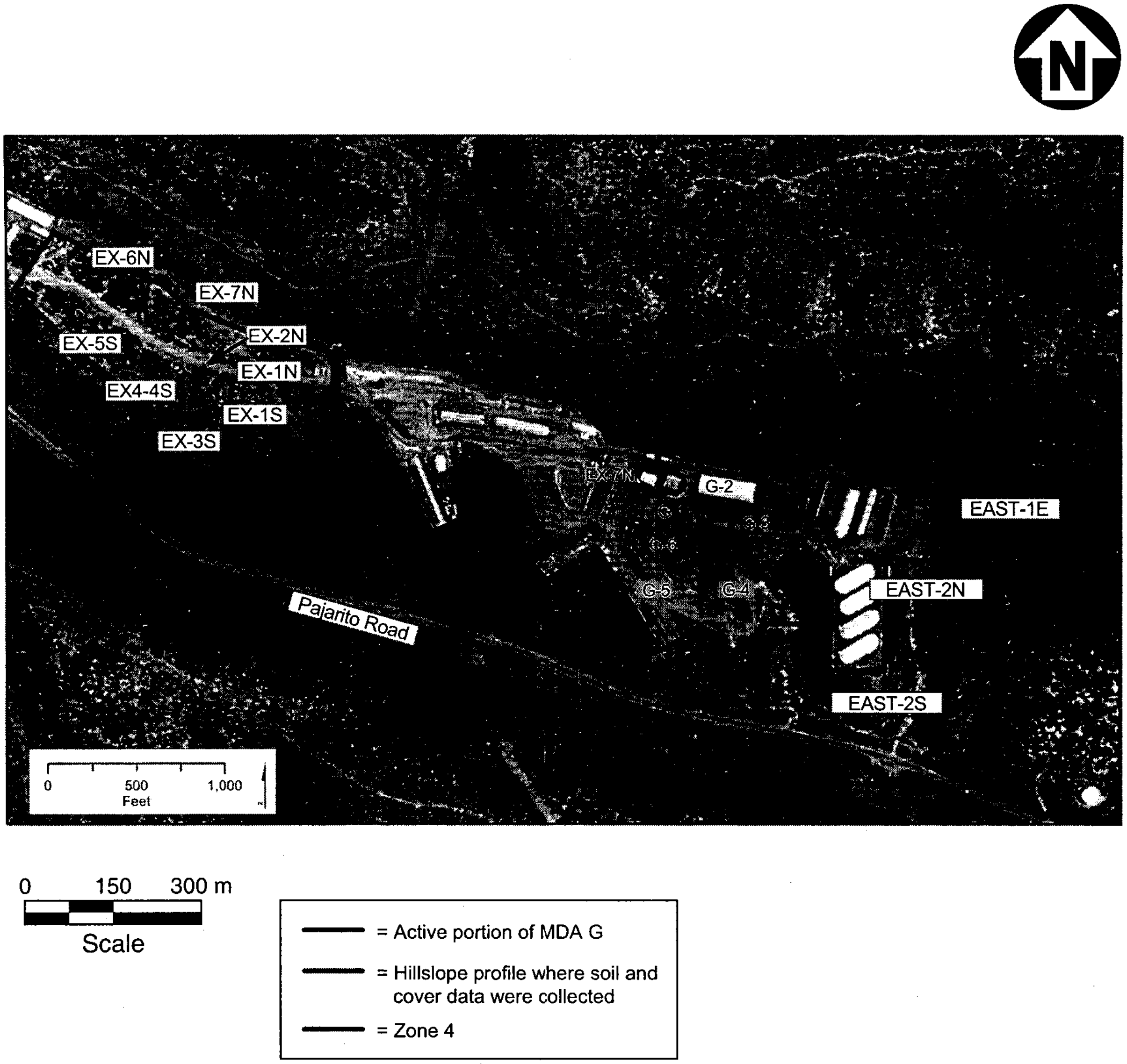


Figure 4
Location of 17 Hillslope Profiles in Vicinity of Material Disposal Area G

Table 1
Characteristics of Four Small Watersheds within the Santa Rita Experimental Range near Tucson, Arizona (analog site)

Watershed ID	Drainage Area (ha)	Grazing System	Vegetation Type	Soil Type	Event Runoff [a] (mm)			Sediment Yield (T/ha)	
					2-Year Event	5-Year Event	16-Year Mean [b]	2-Year Event	5-Year Event
5	4.0E+00	Rotation	Mesquite and grass [c]	Sasabe sandy loam	9.5E+00	2.7E+01	1.7E+01	2.9E+00	6.2E+00
6 [d]	3.1E+00	Rotation	Grass	Diaspar loamy sand	1.3E+00	3.8E+00	1.6E+00	5.4E-02	1.2E-01
7	1.1E+00	Year long	Grass	Sasabe sandy loam	1.6E+01	3.9E+01	2.5E+01	7.8E-01	2.8E+00
8	1.1E+00	Year long	Mesquite and grass [c]	Sasabe sandy loam	2.3E+01	5.1E+01	3.0E+01	1.9E+00	8.0E+00

[a] *Sixteen years of hydrologic data (1976 – 1991) were used in this analysis*

[b] *Mean annual runoff for all runoff events that occurred during the 16-year observation period*

[c] *Mesquite trees (Prosopis velutina (woot.)) and Lehmann lovegrass (Eragrostis lehmanniana (Nees)) as well as lesser amounts of other shrubs and desert grasses*

[d] *Watershed 6 has predominantly loamy sand of the Diaspar soil series and thus its runoff and sediment yield are significantly lower than from the sandy loam of the Sasabe soil series.*

The hydraulic properties of the cover material determine the amount of runoff associated with the two landscape-forming events. A saturated hydraulic conductivity value of 11 mm/hr (0.43 in./hr) was assigned to the sandy loam in accordance with the value provided by Nyhan et al. (1993) for crushed tuff. A value of 6.5 mm/hr (0.26 in./hr) was used for the loam soil; this is about half the value for sandy loam and is a typical value from the literature (Lane, 2004). These hydraulic conductivity values were used in the IRS9 model to calculate runoff values for the rain events with 2- and 5-year return periods. As discussed in more detail in Section 4.2, the values used for saturated hydraulic conductivity are highly uncertain.

Table 2 shows the results of the ISR9 simulations, including mean runoff values and ranges for each of the soil-type/return-period pairs (Lane, 2004). The percent canopy and ground cover vary significantly among the 17 hillslope profiles; these data can be compared to the range of cover values expected to exist after the closure of MDA G (Figure 5). The effect of cover variation on runoff is evident from the results listed in Table 2. These results also indicate that the average runoff from an annual landscape-forming event is likely to range from about 1 to 18 mm/yr (0.039 to 0.71 in/yr) depending on the soil type, hillslope topography, and cover properties at the site.

2.1.4 Sediment Yield Predictions

The excess runoff estimates calculated by the ISR9 model were used as input to the HEM (Lane et al. 2001) to estimate hillslope erosion resulting from the 2- and 5-year runoff events for both soil types. The HEM is an erosion and sediment transport model that analytically solves the kinematic wave equation for sediment transport on a series of connected hillslope segments. The model calculates the erosion or deposition in each hillslope segment as a function of the segment runoff, gradient, ground cover, canopy cover and soil type. The HEM is well tested and calibrated to hundreds of rainfall simulator experiments performed for the WEPP model calibration. A primary advantage of the HEM over the WEPP and other hillslope erosion models is its ease of use, including the availability of an online version for rapid evaluation of erosion.

For this study, the online version of HEM (USDA, 2002) was modified to run in a batch mode to generate sediment yield values over a wide range of hillslope lengths and gradients for the combinations of soil type and excess runoff shown in Figure 6 and Table 3. Three combinations were selected to represent low-, medium-, and high-erosion scenarios at MDA G; these are described in more detail in Section 2.3. In brief, the low-erosion scenario assumed that the closure cover was composed of sandy loam, the ground and canopy cover were high, and the runoff event had an associated value of 2.6 mm (0.1 in.). The moderate-erosion scenario assumed a sandy loam soil, moderate cover conditions, and a runoff event of 7 mm (0.28 in.). The high-erosion scenario assumed a loam soil, low ground and canopy cover, and a runoff event of 12.4 mm (0.49 in.).

Table 2
Summary of Rainfall-Runoff Simulation Results for Hillslope Profiles at TA-54

Hillslope Profile ID	Amount of Cover (%) [a]		Estimated Runoff (mm) [b]			
			2-Year, 6-Hour Storm		5-Year, 6-Hour Storm	
	Canopy	Ground	Sandy Loam [c]	Loam [d]	Sandy Loam [c]	Loam [d]
Area G-1 SE	6.1E+01	2.3E+01	1.1E+00	5.0E+00	4.8E+00	1.0E+01
Area G-2 S	6.4E+01	2.4E+01	8.0E-01	4.7E+00	4.3E+00	9.7E+00
Area G-3 S	6.3E+01	2.2E+01	1.0E+00	5.0E+00	4.6E+00	1.0E+01
Area G-4 NE	2.0E+01	3.3E+01	3.4E+00	7.6E+00	8.3E+00	1.4E+01
Area G-5 NE	2.4E+01	4.6E+01	2.2E+00	6.4E+00	6.8E+00	1.2E+01
Area G-6 NE	2.6E+01	4.1E+01	2.4E+00	6.6E+00	7.0E+00	1.3E+01
EX-1N NE	8.0E+00	2.7E+01	5.0E+00	9.3E+00	1.0E+01	1.6E+01
EX-1S SE	2.9E+00	7.9E+00	6.7E+00	1.1E+01	1.3E+01	1.8E+01
EX-2N NE	1.5E+01	4.4E+01	3.0E+00	7.2E+00	7.9E+00	1.4E+01
EX-3S SE	2.6E+01	4.0E+01	2.4E+00	6.7E+00	7.1E+00	1.3E+01
EX-4S S	1.2E+01	3.2E+01	4.3E+00	8.5E+00	9.2E+00	1.5E+01
EX-5S S	6.9E+00	1.7E+01	5.8E+00	1.0E+01	1.1E+01	1.7E+01
EX-6N NE	3.2E+01	6.1E+01	8.0E-01	4.7E+00	4.3E+00	9.7E+00
EX-7N NE	2.7E+01	5.7E+01	1.4E+00	5.4E+00	5.4E+00	1.1E+01
East-1E SE	2.9E+01	7.2E+01	5.0E-01	4.2E+00	3.6E+00	9.1E+00
East-2N N	2.9E+01	6.9E+01	6.0E-01	4.4E+00	3.8E+00	9.3E+00
East-2S SW	1.8E+01	5.4E+01	2.2E+00	6.4E+00	6.7E+00	1.2E+01
Statistical Summary of Hillslope Profile Values						
Mean	2.7E+01	3.9E+01	2.6E+00	6.7E+00	7.0E+00	1.2E+01
Standard Deviation (SD)	1.9E+01	1.9E+01	1.9E+00	2.1E+00	2.7E+00	2.6E+00
Coefficient of Variation	7.0E-01	5.0E-01	7.0E-01	3.0E-01	4.0E-01	2.0E-01
Mean – SD	8.0E+00	2.0E+01	7.0E-01	4.6E+00	4.3E+00	9.8E+00
Mean + SD	4.6E+01	5.8E+01	4.5E+00	8.8E+00	9.7E+00	1.5E+01

[a] *All data were collected in July and August 2002.*

[b] *The initial soil water condition was assumed to be wet (tension of approximately 0.33 bar).*

[c] *Sandy loam was used to simulate crushed tuff.*

[d] *Loam was used to simulate a mixture of crushed tuff and 6 percent clay admixture.*

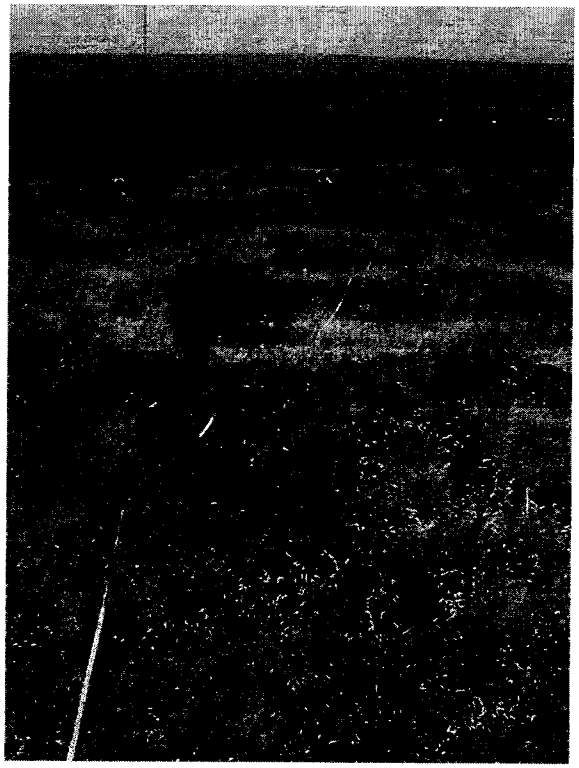


Figure 5a
Example of highest ground
and canopy cover conditions in area
(90% ground cover, 90% canopy cover).

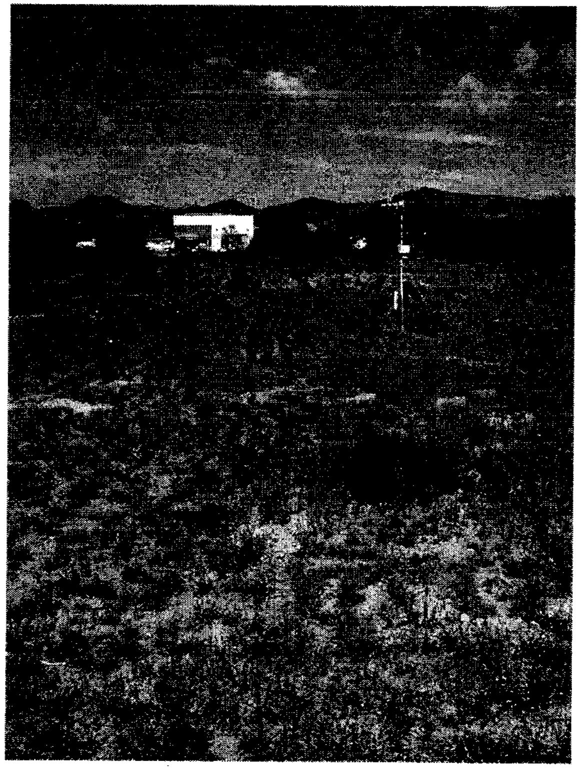


Figure 5b
Example of well-established
ground cover following rehabilitation
(30% ground cover, 90% canopy cover).

Figure 5
Photographs Showing Expected Range in Canopy and Ground Cover after Site Closure

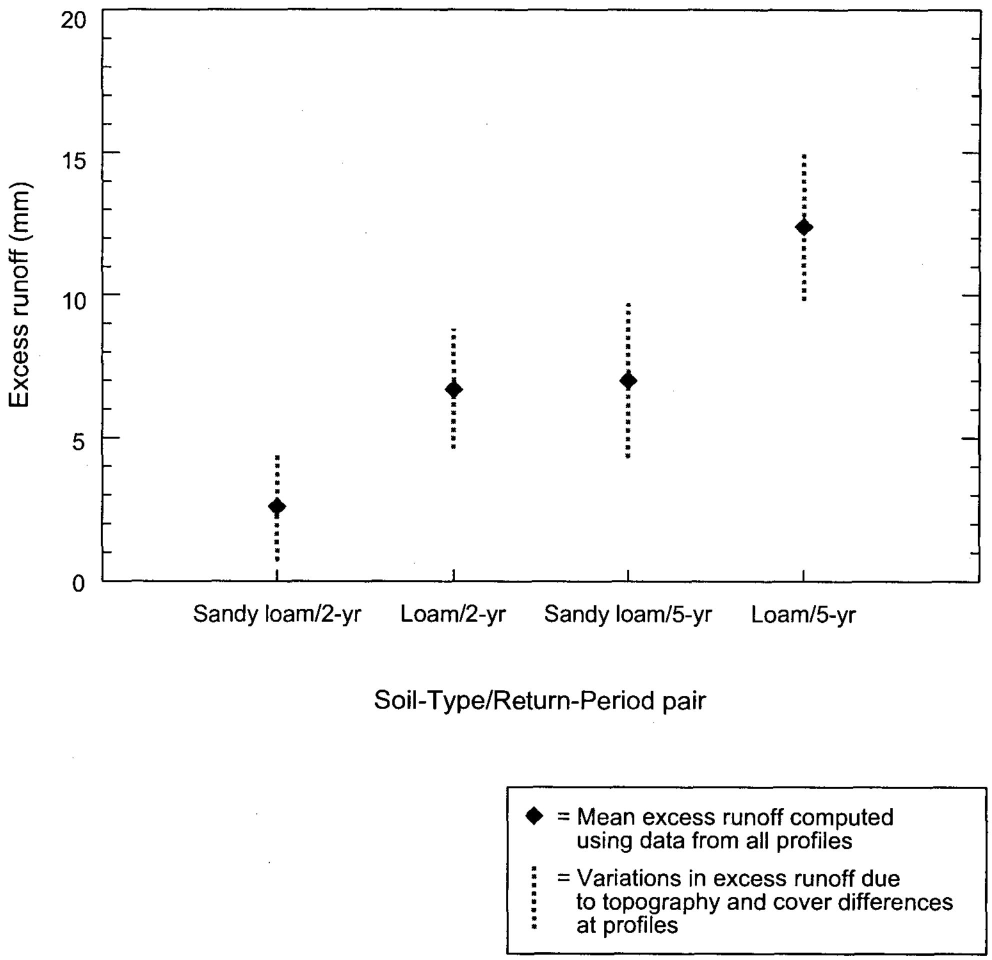


Figure 6
Mean Excess Runoff Values and Ranges for Soil-Type/Return-Period Pairs

Table 3
Summarized Input and Output for the Three Erosion Scenarios Used in SIBERIA Model

Model Parameters	Erosion Scenarios over 1,000-Year Period		
	Low	Moderate	High
Hillslope Erosion Model Parameters			
Soil Texture	Sandy Loam	Sandy Loam	Loam
Canopy Cover / Ground Cover (%)	70 / 70	30 / 70	30 / 30
Landscape-Forming Event (return period in years)	2	5	5
Excess Runoff (mm)	2.6	7	1.2
SIBERIA Model Parameters			
B	9.4E-06	4.2E-05	6.8E-04
m	1.6E+00	1.6E+00	1.3E+00
n	8.6E-01	8.7E-01	8.6E-01
D_z	1.0E-03	2.5E-03	5.0E-03
SIBERIA Model Sediment Yield (T/ha/yr)			
100 years	5.0E-01	1.3E+00	3.2E+00
500 years	4.0E-01	1.1E+00	2.5E+00
1000 years	4.0E-01	1.0E+00	2.3E+00

The HEM runs were performed for the low-, moderate-, and high-erosion parameter sets shown in Table 3 on eight artificial hillslopes. The hillslopes, which were constructed to represent the range of lengths and gradients found on the proposed MDA G closure cover, are shown in Figure 7. The hillslope sediment yields from each set of HEM runs (low, moderate, and high erosion) were then compared to sediment yields from three sets of SIBERIA runs (low, moderate, and high erosion) performed on the same artificial hillslopes. An optimization routine was applied to find the SIBERIA parameters that minimized the difference in sediment yield predicted by the two models for the same profiles. This optimization process is described below.

2.1.5 Optimization of SIBERIA Advective Transport Parameters

The SIBERIA parameter values for the advective transport term $B\ A^m\ S^n$ (Equation 1) were developed using an optimization process called simulated annealing (Press et al., 1996). The process requires the user to specify a set of target values and an equation that, when solved with the right parameter values, will match the target values. In this analysis, the HEM sediment yields from the artificial hillslopes shown in Figure 7 were the target values and Equation 1 was the equation of interest. The simulated-annealing algorithm was used to minimize the difference between the HEM-predicted target yields and the SIBERIA sediment yields for trial sets of B, m, n and D_z values. The optimal set of B, m, and n values shows a minimal difference between HEM and SIBERIA sediment yields for all hillslope length and gradient combinations of interest.

For a given profile, the HEM provides total sediment flux (kg), runoff volume (m^3), mean sediment concentration (%), and inter-rill and rill detachment and deposition rates (kg/m) on a per-meter-width basis. The SIBERIA model provides outputs allowing an equivalent total mass flux to be calculated along a flow path identical to the HEM profiles. Parameters B, m, n, and D_z were varied by the simulated-annealing code to minimize an objective function that is formulated as an "energy" in constraining a randomized exploration of the parameter space. The objective function used was the sum of the squared differences between the net sediment fluxes that were calculated by the two models along the artificial planar hillslopes. The simulated-annealing code calculation was evaluated for low-, moderate- and high-erosion scenarios on length-and-slope combinations derived from the artificial hillslopes shown in Figure 7. Lengths ranged from 30 to 130 m (98 to 430 ft) and were sampled every meter, while gradients ranged from 2 to 16 percent at 2 percent intervals. This yielded 808 hillslope cases (101 slope lengths times 8 gradients). The upper length was chosen to avoid edge effects at the hillslope profile ends. The shortest hillslope length was chosen to limit effects due to differences in how diffusion is calculated for short slope lengths in the HEM and SIBERIA models. Figure 8 shows the correlation between the sediment yields predicted by HEM and SIBERIA for the optimal set of values selected for B, m, n, and D_z by the simulated-annealing algorithm for the low-erosion scenario case; a similarly good match was seen for the moderate and high erosion scenarios. Table 3 summarizes the optimized SIBERIA parameter values for all three erosion scenarios.

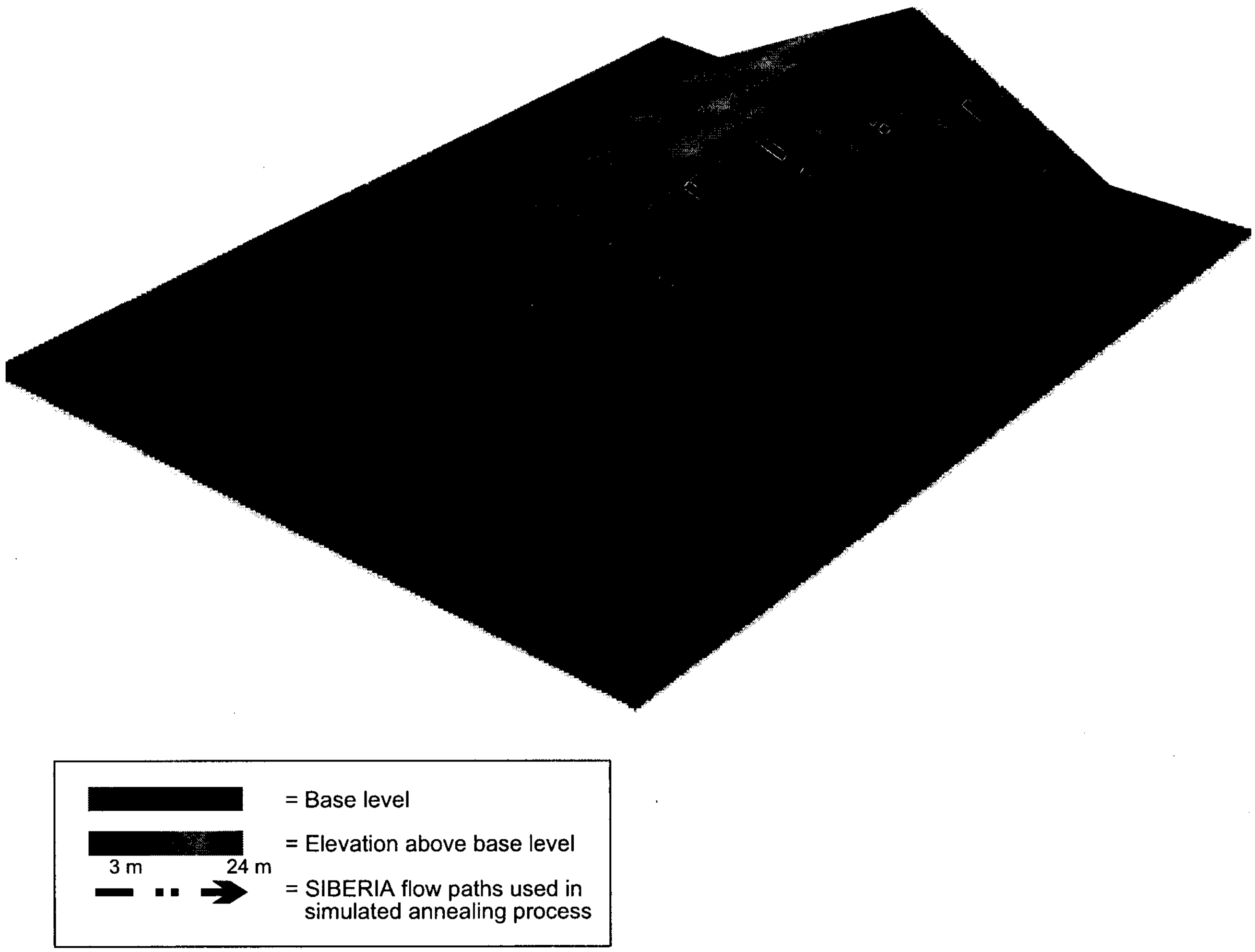


Figure 7
Artificial Surface Showing HEM Profiles and SIBERIA Flow Paths Used during Simulated Annealing

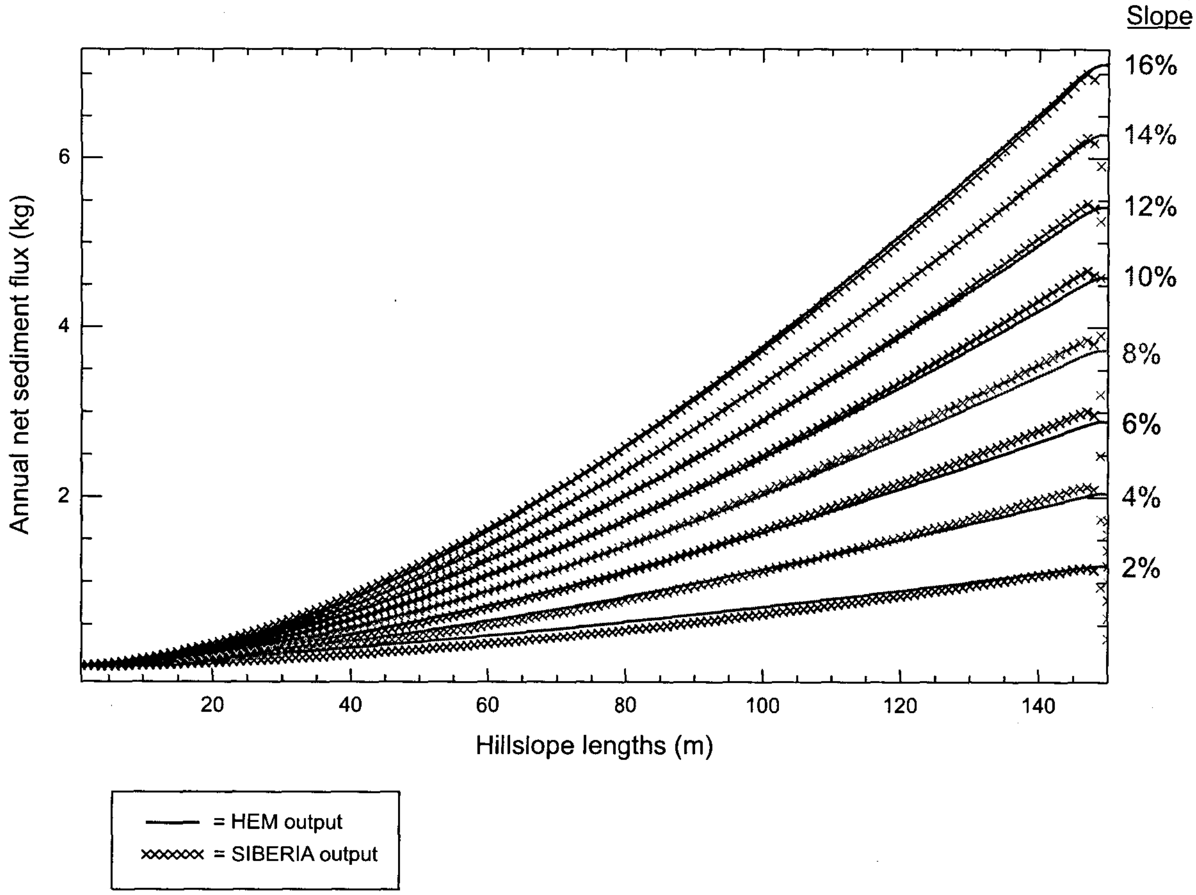


Figure 8
Correlation in Sediment Yield between the HEM and SIBERIA Model for a Range of Slopes and Hillslope Lengths (low-erosion scenario)

2.1.6 *Estimation of the Diffusion Coefficient*

Within the SIBERIA model, diffusion is added to advective transport as the product of the diffusion coefficient, D_z, and the hillslope gradient, *S*. Advective and diffusive processes are thought to be largely in balance in the undisturbed portions of Mesita del Buey because there are no well-developed, deep gullies or deep colluvial fills in headwater regions on the mesa. Values given for D_z in the literature range over several orders of magnitude; it was not possible to select a meaningful value among these for the specific site conditions. Although the simulated-annealing procedure found D_z values for the three erosion scenarios, these values do not include the full range of diffusion processes represented by SIBERIA because the HEM includes only that component of diffusion caused by rainsplash. In reality, biotic and other processes contribute significantly to diffusion in the landscape over long time scales and must be considered.

To determine a site-specific D_z value, SIBERIA runs were made using a range of D_z values. The resulting topography was visually inspected and compared to current topography as represented by the DEM derived from ALSM. The comparison focused on gullies and hollows; if SIBERIA predicted the development of deep colluvial fills in the hollows, it was assumed that diffusion was too high relative to advective processes (fluvial transport), whereas if SIBERIA predicted excessive gullying, diffusion was considered too low relative to advective processes. For this analysis, D_z values of 1.0×10^{-4}, 0.0025, and 0.005 were used as input to the moderate-erosion scenario to assess the impact of diffusion on the landscape over 1,000 years of erosion.

The low D_z value of 1.0×10^{-4} led to the development of a highly dissected gully network, which currently does not exist at TA-54. As a result, this value was rejected as being too low for the current model. The middle D_z value of 0.0025 resulted in a landscape with more of the characteristics of the current landscape, whereas the high D_z value resulted in a landscape that looked much more rounded than the current landscape. Because the results associated with the middle value seemed to best represent conditions at MDA G, and because no better method for estimating the D_z was available, the value of 0.0025 was chosen as the moderate-erosion D_z value and the best value for MDA G.

A D_z value of 0.001 was chosen for the low-erosion scenario. This value was selected because a low diffusion rate coupled with a low advective-erosion rate should yield the correct balance between the two processes and result in a landscape that looks somewhat similar to the current landscape; this diffusion rate would also result in slower overall erosion than the moderate- and high-erosion scenarios. Similarly, a D_z value of 0.005 was used in combination with a high erosion rate for the high-erosion scenario. A more rigorous test of the effect of D_z on landscape form is desirable, but experts in the field of landscape evolution modeling suggest that this approach was reasonable given the state of the science (Dietrich, 2004; Willgoose, 2004; Bras, 2004).

2.2 SIBERIA Model Domain Configuration

The SIBERIA model domain is represented by a DEM that consists of current topography from the LANL 2000 ALSM survey (Carey and Cole, 2002) and the proposed cover elevations supplied by URS Corporation personnel. The domain has two layers. The top layer is composed of cover material and extends from the surface of the final cover, through the interim cover, to bedrock. The cover material proposed by Day et al. (2005) is moderately compacted crushed tuff, augmented with bentonite and angular gravel, overlain with a topsoil and pea gravel mixture approximately 5-mm (0.2-in.) thick. The gravel admixtures are used to aid in the establishment of vegetation during the active institutional control period and will help increase soil surface cover and reduce erosion. The second layer is composed of the mesa bedrock material. This layer also includes armoring material (i.e., riprap) emplaced around the edges of the cover, where the transition from mesa-top to cliff occurs. The armoring is included to reduce erosion at the cover-cliff boundary, slow runoff, and capture sediment eroded from the cover.

The current version of SIBERIA does not automatically track the depth of a given layer, though it does account for the spatial extent of a material type that is exposed at the surface of the model domain. In nature, the rate of downcutting in a gully slows once the base of the gully reaches bedrock. To simulate this situation, SIBERIA was run in a "start-stop-start" mode. The model was stopped after every 20 years of simulated time and each cell was checked to determine if its elevation had dropped below the bedrock surface. Cells that had reached bedrock were relabeled as such so that erosion would proceed at a slower rate, and the model was restarted.

The disposal facility was divided into two model regions: the active portion of MDA G and the Zone 4 expansion area (Figure 1). The same SIBERIA parameter values for erosion were used for both areas; however, the cover size and depth and pit configurations are quite different between the two sites

2.3 Model Scenarios

The objective of the erosion modeling was to estimate the spatial distribution of depth to waste at MDA G after 1,000 years of erosion and sediment transport. Any such estimates are uncertain due to potential variations in climate, soil properties, evolution of the vegetation structure, and other factors over the 1,000-year time frame. To help constrain the uncertainty, three scenarios were developed that are expected to result in low, moderate, and high rates of erosion at the site. Each of the long-term outcomes is plausible on the basis of long-term erosion rates reported in the literature (Kirchner et al., 2001) and local current observations. The parameter values for each scenario were developed from soil, vegetation, rainfall, runoff, erosion, and sediment-yield data collected over a range of time frames at the Laboratory and at an analog site (Santa Rita Experimental Watershed, AZ), as described above. Soil properties for the simulations are based on material specifications provided by the cover design engineers (Day et al., 2005).

The low-erosion scenario assumes that the soil will have the erosion and runoff properties of a sandy loam (crushed tuff and gravel with no clay admixture) with high infiltration capacity, a thick vegetation cover of native grasses (canopy cover of 70 percent, ground cover of 70 percent), and an annual design runoff of 2.6 mm (1.0 in.). The moderate-erosion scenario represents an estimate of the average conditions that currently exist at the site. This scenario also assumes a sandy loam with mixed-grass and shrub vegetation cover similar to the current, relatively undisturbed conditions that exist in Zone 4 at TA-54 and at the eastern end of Mesita del Buey (i.e., canopy cover of 30 percent, ground cover of 70 percent). The annual design runoff for the moderate scenario is 7.0 mm (0.28 in.). The high-erosion scenario assumes a loam soil (crushed tuff and gravel mixed with bentonite), a sparse vegetation cover within the range of conditions found on Mesita del Buey (i.e., canopy cover of 30 percent, ground cover of 30 percent), and an annual design runoff of 12 mm (0.48 in.). These scenario parameters are summarized in Table 3.

3.0 Results

The SIBERIA simulations were performed for a range of different cover designs in an iterative process that involved close coordination with the cover designers at URS Corporation. The process enabled the development of an optimized design that was expected to satisfy the performance criteria. Results of the SIBERIA simulations for the final conceptual cover are shown in Figures 9, 10 and 11. These figures show the remaining cover depths, after 1,000 years, over portions of the facility occupied (now and in the future) by pits and shafts. An orange–green color scale indicates how well the cover performs over the pits. Green and yellow shades indicate depth to waste values in excess of 2.5 m (8.2 ft), whereas dark orange indicates that the cover is approaching a thickness of only 1 m (3.3 ft). The blue–red color scale on these figures shows the cumulative change in elevation across the site at the end of the 1,000-year-simulation period. Blue shows deposition (net accumulation) and red shows net erosion.

Examination of Figure 9 reveals that, for the moderate-erosion scenario, 2.5 m (8.2 ft) or more of cover remains over the majority of the disposal units at MDA G 1,000 years after facility closure. Away from the disposal units, areas of erosion and deposition are observed. Gully formation is seen in areas marked by long slope lengths (e.g., in the vicinity of pits 20, 21, and 22) and along the edges of the mesa. Figures 10a and 10b show similar results for the low- and high-erosion scenarios at MDA G. While greater erosion is noted in some portions of the facility under high erosion conditions, a minimum of 1.75 m (5.7 ft) of cover appears to exist over most, if not all, of the disposal units. Figure 11 shows the depth-to-waste results for the moderate-erosion scenario at the Zone 4 expansion area. Results from all three scenarios show that a minimum of 1.75 m (5.7 ft) of cover exists across the site at the end of the 1,000-year simulation period.

Although Figures 9 through 11 show results at the end of the 1,000-year simulation period, SIBERIA allows the user to track depth-to-waste and sediment-yield information at all points across the facility through time. Depth-to-waste values, which were saved every 20 years for the whole facility, are the basis for determining the rate at which waste may be brought to the surface by means of biologic mechanisms such as root uptake and leaf drop. In addition, time-dependent sediment-yield values from the portions of the cover located over the pits and shafts were tracked independently of areas that were located away from waste, such as cliff faces. In the following discussion, these two sediment source areas are loosely referred to as pit-affected and clean-sediment contributing areas, respectively.

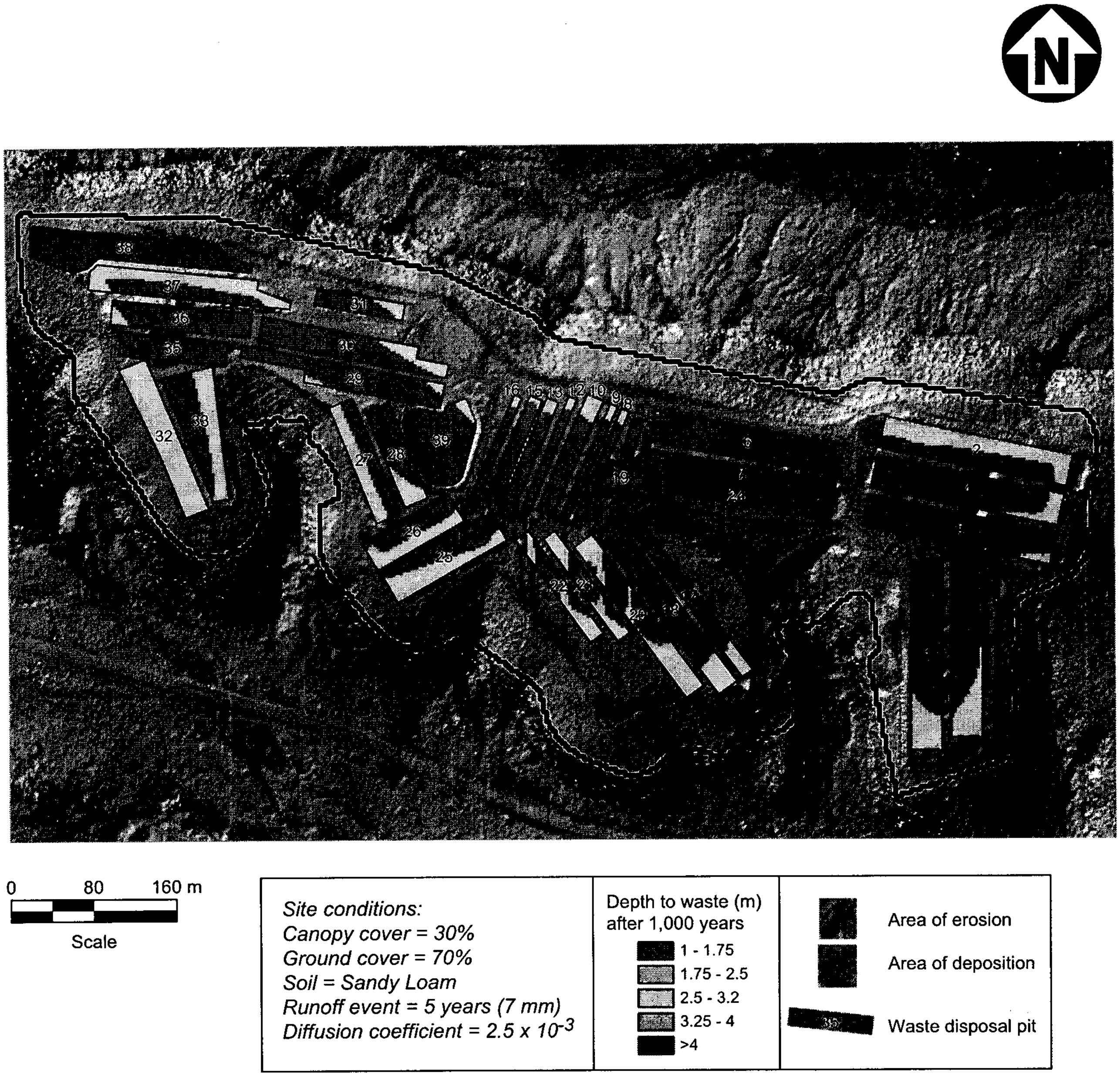


Figure 9
Erosion and Deposition at MDA G for Moderate-Erosion Scenario (as predicted by SIBERIA model after 1,000 years)

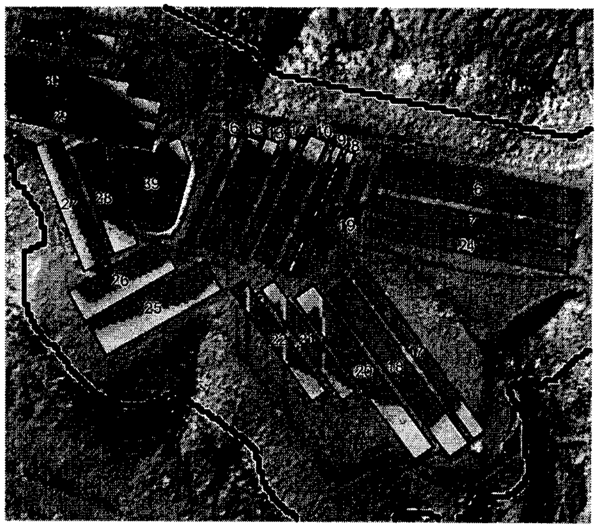


Figure 10a.
Low-erosion scenario (70% canopy cover, 70% ground cover, sandy loam soil, 2-year runoff event [2.6 mm], and diffusion coefficient of 1.0×10^{-4}.

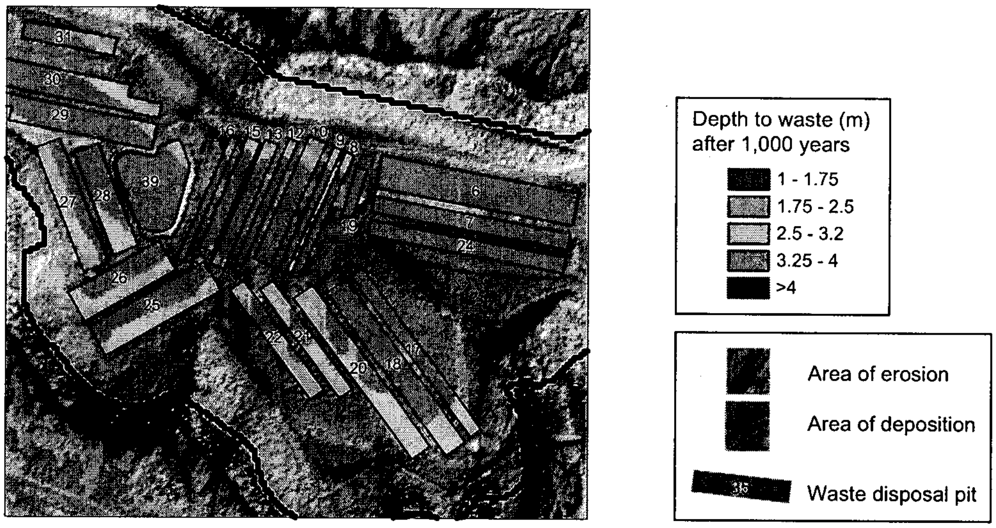


Figure 10b.
High-erosion scenario (30% canopy cover, 30% ground cover, sandy loam soil, 5-year runoff event [12 mm], and diffusion coefficient of 2.5×10^{-3}.

Figure 10
Erosion and Deposition at MDA G for Low- and High-Erosion Scenarios (as predicted by SIBERIA after 1,000 years)

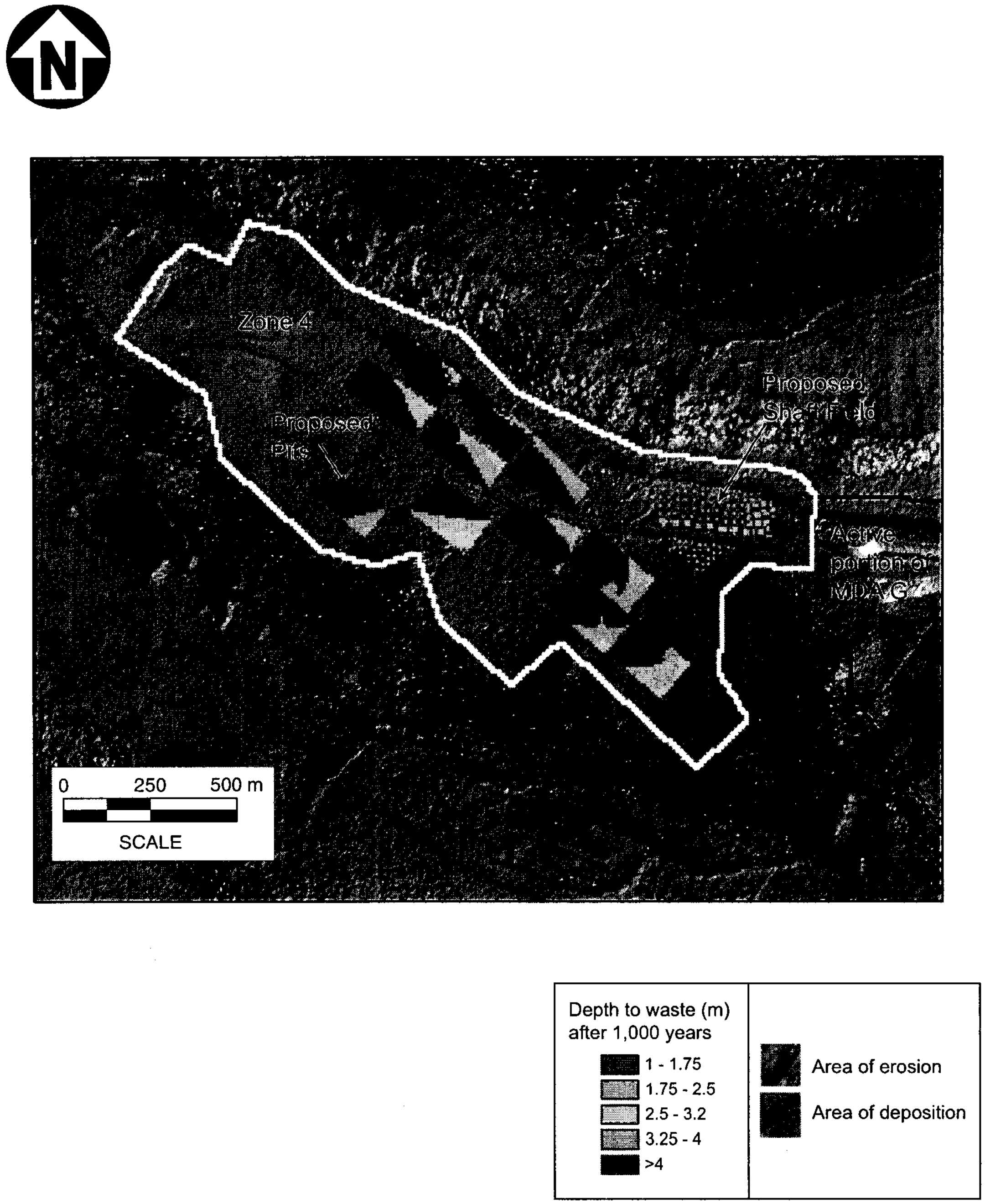


Figure 11
Erosion and Deposition at Zone 4 for Moderate-Erosion Scenario (as predicted by SIBERIA model after 1,000 years)

The time-dependent sediment-yield values can be used to determine how much potentially contaminated sediment may be delivered to different parts of the Cañada del Buey and Pajarito Canyon floodplains. Figure 12 shows how the surface of MDA G is divided into sediment source areas (indicated by the divisions of the mesa-top) that drain into catchments within each canyon. The boundaries of the catchments were estimated on the basis of visual inspection of the topographic features along the edges of Mesita del Buey and the water drop diagram developed in conjunction with the cover design effort (Day et al., 2005, Figure 4).

Pit-affected sediment eroded from a grid cell over a given disposal unit within a drainage is assigned the disposal unit and drainage name, and is transferred across the lower boundary of the drainage into the corresponding catchment in the canyon. In this manner the total amount of potentially contaminated sediment, as well as the type and concentration of the contaminated sediment delivered to the canyon can be tracked through time. Table 4 summarizes the delivery of sediment to each of the catchments shown in Figure 12 for the moderate-erosion scenario. Although the data have been stored as a function of time and disposal unit, Table 4 shows the total sediment yield into each catchment for the 1,000-year time frame. For example, over the 1,000-year period, Pajarito Canyon catchment PC2 was projected to receive 8,995 T (9,915 t) of sediment from uncontaminated portions of MDA G and 766 T (844 t) from pit-affected areas; thus, the pit-affected sediment is 8 percent of the total sediment delivered from the mesa to PC2. Note that the drainage boundaries may change through time. For example, between 0 and 100 years the cover over a given pit may spill sediment to PC2, but from 100 to 200 years, some or all of the cover over that pit may spill into another drainage, and therefore be deposited in another catchment. These shifts in sediment yield are also tracked.

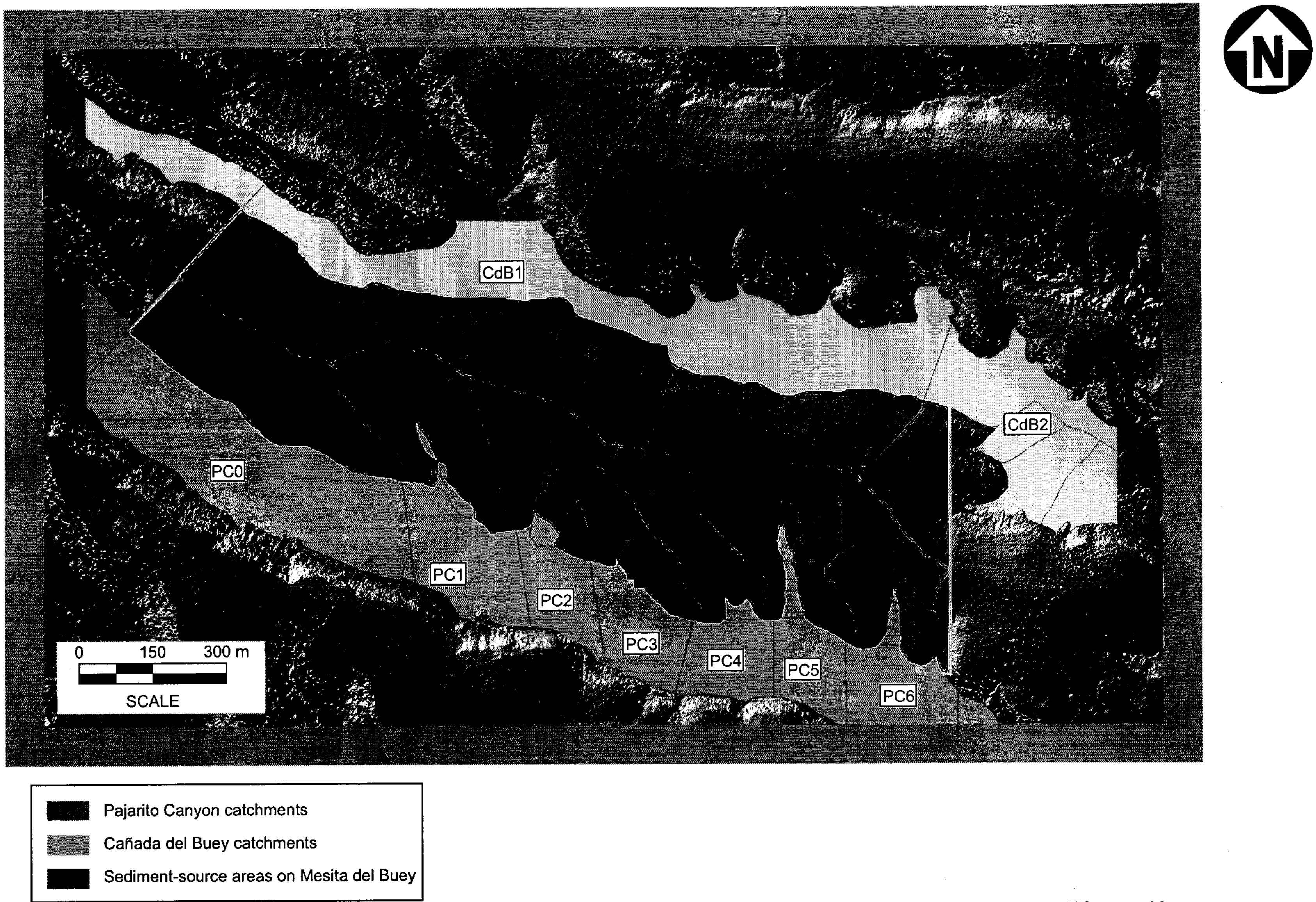


Figure 12
MDA G Sediment-Source Areas and Sediment Catchments in Habitable Canyon Bottoms

Table 4
Summary of Sediment Delivery from MDA G to Canyon Catchments over 1,000 Years

Canyon Catchment Number	Mass of Sediment Delivered (T)		Pit-Affected Sediment as % of Total Sediment
	Clean Sediment	Pit-Affected Sediment	
PC0	5,644	767	12
PC1	16,987	580	3
PC2	8,995	766	8
PC3	8,823	1,251	12
PC4	5,405	1,400	21
PC5	6,549	1,340	17
PC6	5,435	478	8
CdB1	39,930	3,482	8
CdB2	1,005	153	13

PC = Pajarito Canyon catchment *CdB = Cañada del Buey catchment*

4.0 Discussion and Qualifications

The SIBERIA simulations represent a significant step forward in cover-performance modeling, as they allow the feedback between erosion and the shape of the repository cover to be explored over a highly complex topography. This work represents a robust application of SIBERIA and reflects the opinion of the authors that landscape evolution models provide the best current option for assessing the performance of a cover exposed to long-term erosion. Nevertheless, significant uncertainty exists in the predictions. These uncertainties are the result of both model structure, as discussed in Section 4.1, and lack of adequate data for model parameterization, as discussed in Section 4.2. Even with these uncertainties, however, the SIBERIA sediment-yield predictions were in line with long-term values cited in the literature as well as with data from Mesita del Buey, as discussed in Section 4.3.

4.1 Model Limitations

The SIBERIA model was chosen because it was the only landscape evolution model that had been applied to and validated for critical environmental problems constrained by regulations such as mine reclamation and tailing pile remediation. The model version used for this study, however, had four potential drawbacks. First, it did not automatically modify material properties in cells when erosion cut into a new layer. Second, the sediment-transport-capacity equation may cause spurious deposition to occur when there was a change in material type along a flow path from a material with higher transport capacity (e.g., the cover) to one with lower transport capacity (e.g., bedrock). In addition, the model does not allow particle tracking or sediment-packet tracking through the landscape, hence it is impossible to determine if the sediment that eroded from the cover over a given pit was trapped permanently in the rock armor, or eventually made its way to the stream bottom. Third, it is likely that a dynamic climate will give a different result than the steady-state climate the user is forced to adopt by the SIBERIA model. And fourth, the model did not include an explicit cliff-retreat algorithm. A new version of SIBERIA is currently being tested that addresses all but the fourth of these issues.

Each of the model limitations noted above introduces uncertainty in the model results. The fact that the version of SIBERIA used for this study did not automatically update material properties as erosion progressed to a new layer was not a major problem since this study modeled only two materials, a homogeneous cover material and bedrock. Even so, an effort was made to minimize the effect that this limitation had on modeling results. During the simulations performed for this study, the model was manually stopped every 20 years to determine if the amount of erosion or the change in elevation in a given grid cell had caused the cell to move below the cover layer boundary. If it had, the cell type was changed from "cover" to "bedrock" and the model was restarted. Because there was no way of knowing when the boundary between the cover and bedrock had been reached during the 20-year interval, the affected cell was also reassigned a cell elevation of the original bedrock surface. This approach is not expected to introduce much error into the model projections because rates of erosion within the bedrock are small.

A seemingly more difficult problem arises from the use of the sediment-transport-capacity equation to predict both erosion and transport. The amount of eroded sediment transported out of a grid cell depends on the gradient of the cell, its material composition, and the size of the upslope area contributing to the cell. A problem may arise when a grid cell with a material type of "cover" is upslope from a cell with material type "bedrock"; because of the rock armor, this situation occurs around the entire edge of the cover. Under natural conditions, sediment undergoing transport from a more erodible upslope area would stay in suspension and travel across the downslope bedrock area. In the model, however, if the two cells have the same gradient and the same approximate upslope area, the dramatic change in erodibility between the upslope cover cell and downslope bedrock cell causes the sediment transport capacity to drop significantly. This results in sediment deposition at the transition between the cells and could pose a nonquantifiable error in the results, since the deposition around the edge of the cover suppresses erosion at the edge of the cover. For the cover design at MDA G, however, the proposed placement of rock armor at the MDA G cover edge would, in fact, cause deposition of sediment due to frictional resistance and water loss between boulders. Because the rock armor is assigned a material type of "bedrock," the model behavior in this situation is expected to be similar to the actual conditions that will occur at MDA G. Thus, the model limitation noted above probably does not strongly affect the predicted cover performance.

The other aspect of the second model limitation mentioned above is that the model does not allow particle tracking or sediment-packet tracking. This means the model cannot determine if contaminated particles will remain trapped in the rock armor or migrate to a downhill location. Application of the new version of SIBERIA, which replaces the sediment-transport-capacity equation with grain-size-explicit-erosion and sediment-transport equations, would enable particle tracking through the landscape and thus increase understanding of how contaminants will redistribute through the landscape over time. It would also solve the issue of sediment dropping out of suspension at boundaries between upslope cover and lower bedrock cells.

The third model limitation, the fact that SIBERIA uses a steady-state landscape-forming event to drive erosion, is likely to have a significant impact on the predicted cover performance. In nature, many storms of different durations and intensities occur throughout a single year; over a period of 1,000 years the climate may become significantly wetter or drier. Even if the mean annual precipitation remains the same, rain may come in fewer but larger events that would result in more erosion per event. In this analysis, the uncertainty introduced by climate variability over the 1,000-year simulation period is only partially addressed. An attempt was made to bracket the impact of climate on cover performance by using both a 2- and 5-year runoff event, with the 5-year event representing a wet and highly erosive condition over the 1,000 year time frame and the 2-year event representing a more moderate climate over that same period. The choice of the 2- and 5-year landscape-forming events was based on data from the Santa Rita Experimental Watershed in southern Arizona and is supported by analyses for climates as diverse as Australia and England (Willgoose and Riley, 1998; Willgoose et al., 1991b). However, the impacts of climate variability and extreme events on long-term cover performance should probably be considered in greater detail. The new version of SIBERIA allows consideration of an event-based climate series; the application of this version to MDA G may be appropriate.

The fourth limitation of the model used in this analysis is that it does not include the process of cliff retreat. While including a stochastic rockfall algorithm in SIBERIA would not be difficult, calibrating such a model would be difficult without better quantification of the actual processes. Data limitation issues related to modeling cliff retreat are discussed below.

4.2 Data Limitations

In some cases, uncertainties were introduced because of the lack of adequate data for model parameterization. Areas of particular concern include the characterization of the hydraulic and erosional properties of the proposed cover, the role of climate variability and extreme events in cover performance, and the impact of various ongoing geomorphic processes on cover performance at MDA G.

The material properties of the cover and bedrock are critical data for determining the predicted performance of the cover in relation to both erosion processes and infiltration (Newman and Schofield, 2005). A critical parameter for both processes is saturated hydraulic conductivity. The SIBERIA analysis was performed before the results of hydraulic conductivity measurements performed on samples of the proposed cover material were available. In the absence of a measured value, Newman and Schofield (2005) estimated a saturated hydraulic conductivity of 0.039 mm/hr (1.3×10^{-4} in./hr) for the proposed cover material. This value is almost 300 times less than the value of 11 mm/hr (4.3×10^{-1} in./hr) used in ISR9 to compute runoff for the 2- and 5-year events used in SIBERIA.

The hydraulic conductivity values used in the ISR9 modeling were taken from literature values (Nyhan et al., 1993; Charman and Murphy, 1992) for actual soils with the same texture (i.e., the same proportions of sand, silt and clay) as that for the proposed cover. The Newman and Schofield (2005) infiltration calculations used estimated hydraulic conductivities for a 6 percent bentonite/crushed tuff mixture. These estimates were based on a linear regression fit between the measured hydraulic conductivity of pure crushed tuff and the value reported in Nyhan et al. (1997) for a 10 percent bentonite/tuff mixture. Both sets of values have limitations. The values representing actual soils reflect the fact that these soils have developed, over a long period of time, a structure with a hierarchy of pores and water pathways. The samples of crushed tuff/bentonite used for the Newman and Schofield estimate were homogeneous with none of the characteristics that will develop as a result of biotic activities such as root growth or the burrowing activities of insects or animals. In all likelihood, the actual value for the saturated hydraulic conductivity of the cover lies somewhere between the Newman and Schofield value and the value used for the SIBERIA modeling.

The uncertainty in the saturated hydraulic conductivity of the cover material is a potentially significant source of error in the surface erosion modeling. If the actual hydraulic conductivity values are lower than the values adopted for the modeling, the SIBERIA runoff rates, and subsequent erosion, will be higher than predicted. As mentioned, samples of the proposed cover material have been submitted for analysis; the results of this testing should provide additional insight into this critical property of the cover.

Rainfall simulator experiments carried out on test plots at a hillslope scale (including flow in drainage lines) would help to fully characterize the infiltration, runoff, erosion, and transport characteristics of the cover over a wide range of event intensities. Such experiments would significantly reduce the main source of uncertainty in the performance assessment — the hydraulic properties of the cover. They would also provide data about the amount of runoff and erosion associated with the wide range of rainfall events expected under actual variable climate conditions, which is critical to running SIBERIA with a climate series rather than a steady-state landscape-forming event. The development of a set of potential future climate series to be used as input to the new version of SIBERIA would help to lower uncertainty related to climate and provide a better understanding of the uncertainty associated with the timing and size of extreme events.

Currently, it is not known which of the ongoing geomorphic processes at MDA G pose the greatest risk to the long-term integrity of the waste disposal units. Although rough estimates exist for fluvial and wind erosion, no data are available to assess rates of cliff retreat or sediment-diffusion processes. Studies to determine the rates of cliff retreat, fluvial erosion, wind erosion, soil development, and diffusion at Mesita del Buey would improve knowledge in this area. The development of cliff retreat rates requires the collection and processing of a statistically meaningful set of samples to determine the distribution of cliff face ages at Mesita del Buey using cosmogenic radionuclides. Similar techniques can be used to assess diffusion and soil development rates. Observations suggest that the cliff faces at Mesita del Buey are eroding through mass wasting (block falls), wind erosion, and fluvial erosion but no useful data exist about the erosion rates. A thorough investigation of cliff retreat rates and processes, including time for collecting and processing enough samples to be statistically meaningful, would help to lower uncertainty in this area.

4.3 Comparison of SIBERIA Results to Field-Collected Data

In spite of the sources of error and uncertainty in the parameterization of the model and the model structure, a comparison of annual sediment yield predicted by SIBERIA and that estimated from mean sediment concentrations collected at experimental plots and gauging stations on Mesita del Buey suggest that SIBERIA performed well. Table 5 shows sediment yield values derived from these sites range from 0.2 to 1 T/ha (0.089 to 0.45 t/ac) per landscape-forming event; this is close to the range of predicted values of 0.4 to 3.2 T/ha (0.16 to 1.3 t/ac) per event. The fact that the values derived for Mesita del Buey are lower than the SIBERIA values could be a result of the relatively short data-collection periods, which did not include large events. In contrast, the SIBERIA analysis was based on 16 years of data from the Santa Rita Experimental Watershed which included several large erosional events.

Table 5
Estimated Sediment Yield for Mesita del Buey Sites from Events with 2- and 5-Year Return Periods [a]

Observation Site	Drainage Area (m^2)	Return Period Runoff Volumes [b] (m^3)		Mean Sediment Concentration (mg/L)	Sediment Yield [c] (T/ha)	
		2-Year Event	5-Year Event		2-Year Event	5-Year Event
TA-51 Runoff Plots	3.3E+01	3.0E-01	5.0E-01	2.3E+03	1.9E-01	3.6E-01
Small catchments draining TA-54						
E221	4.1E+03	5.2E+01	8.3E+01	4.1E+03	5.2E-01	8.3E-01
E227	1.7E+04	2.1E+02	3.4E+02	5.0E+03	6.3E-01	1.0E+00
E247	5.0E+04	3.2E+02	5.4E+02	4.1E+03	2.7E-01	4.4E-01

[a] All values from actual site data, except as noted

[b] Calculated using the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model

[c] Calculated by multiplying the mean concentration from observed events by the calculated runoff volume. These yields compare favorably with those predicted by SIBERIA for the annual landscape-forming event, as shown in Table 3.

5.0 References

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