Impact of surface coal mining on soil hydraulic properties

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Abstract

Soil erosion is strongly related to soil hydraulic properties. Understanding how surface coal mining affects these properties is therefore important in developing effective management practices to control erosion during reclamation. To determine the impact of mining activities on soil hydraulic properties, soils from undisturbed areas, areas of roughly graded mine spoil, areas with replaced topsoil before seeding, and revegetated areas at the Rosebud Mine in Eastern Montana were evaluated. Field and laboratory studies were conducted to determine the soil hydraulic properties of the four representative areas, including particle-size distribution, organic matter content and saturated hydraulic conductivity. Using this data, Water Erosion Prediction Project (WEPP) simulations and risk analyses were performed to investigate mining's effects on changes in soil erosion potential. Significant differences were seen in the hydraulic properties of the soils in the representative areas due to the mining and reclamation practices at the mine. The WEPP simulations show that the potential for soil erosion increases as a result of mining activities disturbing the soil. The simulations also indicate that the erosion potential may return to pre-mining levels over time with effective revegetation practices.

Key words: Surface mining, Reclamation, Revegetation, Soil erosion

2015 *Transactions of the Society for Mining, Metallurgy & Exploration,* Vol. 338, pp. 381-392.

Paper number TP-12-036. Original manuscript submitted September 2012. Revised manuscript accepted for publication February 2015. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications Dept. prior to Sep. 30, 2016.

Introduction

Surface coal mining disturbs large areas of land, increasing the potential for surface runoff and soil erosion (Mummey et al., 2002). Surface mining in the western United States operates under noticeably different environmental conditions from those in other regions of the country. Most of the western U.S. coal mining areas are located in arid and semi-arid regions characterized by sparse vegetation, highly erodible soils, frequent flash floods, limited water resources, and complex topography (U.S. Environmental Protection Agency, 2000).

Many factors affect soil erosion, including climate, soil type, topography, land use and management practices (Conrad, 1990). Other than climate, each of these factors can be altered by mining activities. Understanding how surface mining affects soil hydraulic properties can help mine operators and regulatory personnel plan for sound mining activities and develop effective Best Management Practices (BMPs) for erosion control and reduction during reclamation. BMPs may include diverting runoff water away from or establishing vegetative cover on disturbed land to prevent erosion, or installing silt fences or sedimentation ponds to remove suspended sediment from runoff before it leaves disturbed areas (Conrad, 1990).

To evaluate mining's effects on soil erosion, studies had been carried out to assess the changes in soil hydraulic and erosion properties such as texture, bulk density, aggregation, organic matter content and compaction of soil in different areas (Gee and Bauer, 1976; Lusby and Toy, 1976; Hartley and Schuman, 1984; Sanchez and Wood, 1989). Disturbed mine soils typically have different characteristics from natural soils. The structure of soil is often destroyed during stripping and replacement (Morris and Therivel, 2001), and organic matter content is usually lost during stockpiling (Akala and Lal, 2000). Mine soils are also susceptible to compaction during placement (Smith et al., 1971), thus having low infiltration capacity and high potential for erosion.

Attempts have been made to use computer modeling to predict how the changes in soil, especially in soil hydraulic properties, affect soil erosion (Elliot et al., 1993; Hoomehr and Schwartz, 2013). Currently, a commonly used model for developing engineered plans with BMPs for erosion control in the surface coal mining industry is Civil Software Design LLC's SEDCAD – Sediment, Erosion, Discharge by Computer Aided Design – program (Hoomehr and Schwartz, 2013). SEDCAD uses the empirically based curve number and the Revised Universal Soil Loss Equation (RUSLE) to estimate runoff and sediment yields (Warner et al., 1998). However, these empirically based methods cannot properly represent (1) spring snowmelt runoff that can cause significant erosion and sediment detachment in high-elevation areas in the arid and semi-arid western United States, (2) differences in cumulative watershed responses to changes in spatial distribution of BMPs and (3) the spatial variation of soil detachment and deposition associated with complex topography. As such, SEDCAD application is limited to areas whose hydrological conditions are similar to those from which the parameter values of the empirical formula had been derived statistically. For erosion simulation in the arid and semi-arid western U.S. mining areas, the U.S. Office of Surface Mining Reclamation and Enforcement has been investigating physically based modeling tools such as WEPP-MINE (Wu et al., 2012), a management tool for western alkaline surface coal mines based on the physically based Water Erosion Prediction Project (WEPP).

This study is one of the efforts in WEPP-MINE development to examine, using field and laboratory experiments,

Table 1 — Upland planting mixture.

Common name	Scientific name
Cool season	
Thickspike wheatgrass	*Agropyrondasytachyum*
Western wheatgrass	*Agropyronsmithii*
Bluebunch wheatgrass	*Agropyronspicatum*
Prairie Junegrass	*Koeleriacristata*
Indian ricegrass	*Oryzopsishymenoides*
Green needlegrass	*Stipavirdula*
Warm season	
Blue grama	*Boutelouagracilis*
Side-oats grama	*Boutelouacurtipendula*
Prairie sandreed	*Calamovilfalongifolia*
Switchgrass	*Panicumvirgatum*
Sand dropseed	*Sporoboluscryptandrus*
Perennial forb	
Common yarrow	*Achilliamillefolium*
Narrowleaf purple cone-flower	*Echinacea angustifolia*
Perennial flax	*Linumlewisii*
Purple prairie clover	*Daleapurpureum*
Prairie coneflower	*Ratibidacolumnifera*
Munro globemallow	*Sphaeralceamunroana*
Shrub	
Silver sagebrush	*Artemisia cana*
Big sagebrush	*Artemisia tridentata*

Table 2 — Conifer planting mixture.

Common name	Scientific name
Cool season	
Western wheatgrass	*Agropyronsmithii*
Bluebunch wheatgrass	*Agropyronspicatum*
Indian ricegrass	*Oryzopsishymenoides*
Warm season	
Sand bluestem	*Andropogonhallii*
Little bluestem	*Andropogonscoparius*
Side-oats grama	*Boutelouacurtipendula*
Prairie sandreed	*Calamovilfalongifolia*
Perennial forb	
Narrowleaf purple Coneflower	*Echinacea angustifolia*
Prairie coneflower	*Ratibidacolumnifera*
Winterfat	*Krascheninnikovialanata*
Shrub	
Big sagebrush	*Artemisia tridentata*
Skunkbush sumac	*Rhustrilobata*

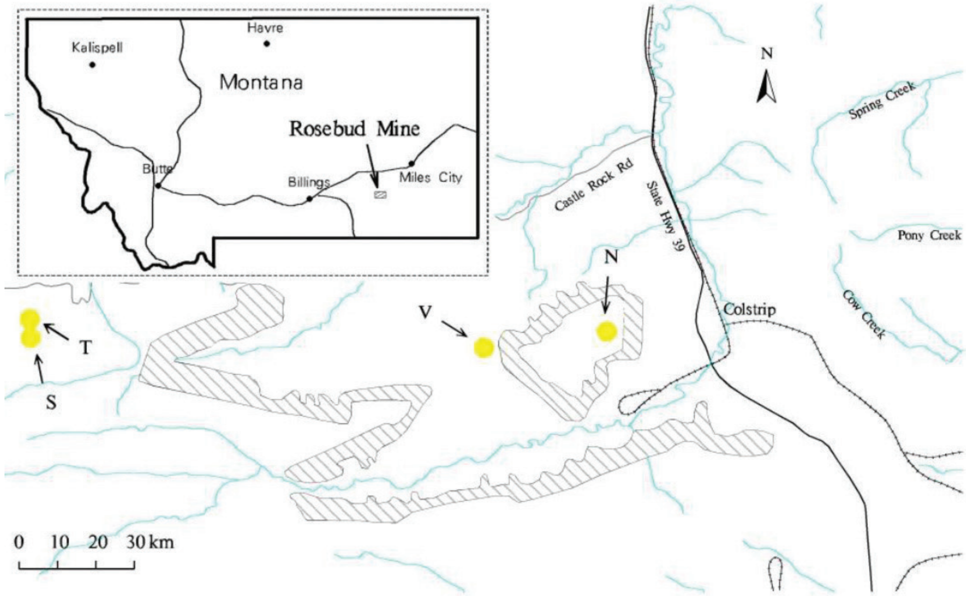

Figure 1 — Sampling sites at the Rosebud Mine.

how mining practices affect soil hydraulic properties and to assess, using a modeling approach, how the altered soil properties affect soil erosion. The primary objectives of this study were to:

1. Determine soil hydraulic properties resulting from reclamation management practices at the Rosebud Mine, a typical surface coal mine in the western United States.
2. Assess the hydrological and water erosion potential of different reclamation conditions using the WEPP model.

Background

The Rosebud Mine is located in the northern Powder River Coal Basin near Colstrip, Montana. It is a typical surface coal mine in the western United States, with mining and reclamation operating conditions that are similar to those encountered at other surface coal mining operations located in the Powder River Coal Basin. Landscape at the mine can be categorized into four representative areas based on mining and reclamation activities:

1. Undisturbed natural area (N).
2. Roughly graded mine spoil (S).
3. Replaced topsoil before seeding (T).
4. Revegetated area (V).

Undisturbed natural area (N) represents areas that contain native vegetation growth and have not been mined. The native vegetation consists primarily of prairie grasses with interspersed trees and sagebrush. Roughly graded mine spoil (S) represents areas where the coal had been removed and the overburden that was removed to uncover the coal had been placed back into the pit and graded to shape the final topography at the site. Replaced topsoil before seeding (T) refers to areas where at least six inches of soil had been placed on top of the graded spoil to serve as a growing medium but no seeding or mulching had been applied to its surface. Revegetated area (V) refers to areas where at least one year of vegetation growth had occurred on the replaced topsoil. Topsoil and subsoil are stockpiled separately before mining and reapplied to the roughly graded spoil, and vegetation is then planted in the replaced topsoil. An upland planting mixture (Table 1) and a conifer planting mixture (Table 2) are used for revegetation at the mine (Martin, 2013).

WEPP is a physically based, continuous-simulation, distributed-parameter, hydrological and erosion prediction model developed by the U.S. Department of Agriculture's Agricultural Research Service (ARS) as a new-generation prediction technology (Flanagan et al., 2007). WEPP's advantages include its capabilities for estimating spatial and temporal distributions of soil detachment and deposition for a single event or on a continuous basis. WEPP can be used to evaluate land use and management practices for erosion control and to estimate erosion from both small areas, such as hillslopes, roads and small parcels, and large watersheds.

WEPP has been parameterized for various benchmark soils across the United States and was applied to two surface mines in a 1993 study in Ohio (Elliot et al., 1993). The authors of that study investigated the suitability of the then newly developed watershed version of the WEPP model for use in mining areas and to identify critical watershed parameters unique to surface mining and reclamation. Through comparing WEPP-simulated and observed runoff and sediment yield, Elliot et al. (1993) concluded that the WEPP model is capable of modeling the hydrologic and erosion processes on surface mining sites with inputs that are suitable for the mining conditions. They also concluded that saturated hydraulic conductivity was the most critical parameter affecting soil erosion from reclaimed soils.

In this study, field and laboratory experiments were conducted to investigate how mining activities affect soil texture and hydraulic properties. In addition, the hillslope version of WEPP was used to examine the first-year erosion risk of the four representative mining areas at the Rosebud Mine and to examine the reclamation effectiveness of the revegetated areas.

Table 3 — Major soil inputs for WEPP simulation.

Undisturbed natural (N) area				
Effective hydraulic conductivity (mm/hr)			28.3	
Interrill erodibility (kg-s/m^4)			6.69 x 10^5	
Rill erodibility (s/m)			9.04 x 10^{-4}	
Critical shear stress (Pa)			1.07	
Soil albedo			0.05	
Soil texture			Clay loam	
Depth (mm)	*Sand (%)*	*Clay (%)*	*Organic matter (%)*	*Gravel (%)*
0-100	31	33	6.0	1.5
100-200	46	27	4.0	3.5
200-750	38	27	0.75	5
Restrictive layer saturated hydraulic conductivity (mm/hr)				3.6
Roughly graded mine spoil (S)				
Effective hydraulic conductivity (mm/hr)			29.8	
Interrill erodibility (kg-s/m^4)			4.13 x 10^5	
Rill erodibility (s/m)			8.45 x 10^{-4}	
Critical shear stress (Pa)			0.47	
Soil albedo			0.15	
Soil texture			Sandy loam	
Depth (mm)	*Sand (%)*	*Clay (%)*	*Organic matter (%)*	*Gravel (%)*
0-100	53	19	3.4	4.9
100-1,500	50	27	2.4	3.8
Topsoil replaced before seeding (T)				
Effective hydraulic conductivity (mm/hr)			21.0	
Interrill erodibility (kg-s/m^4)			4.96 x 10^5	
Rill erodibility (s/m)			7.36 x 10^{-4}	
Critical shear stress (Pa)			0.73	
Soil albedo			0.18	
Soil texture			Loam	
Depth (mm)	*Sand (%)*	*Clay (%)*	*Organic matter (%)*	*Gravel (%)*
0-100	50	13	3.0	1.6
100-200	60	19	3.7	2.0
200-300	53	19	3.4	4.9
300-1,500	50	27	2.4	3.8
Revegetated (V) area				
Effective hydraulic conductivity (mm/hr)			37.5	
Interrill erodibility (kg-s/m^4)			5.73 x 10^5	
Rill erodibility (s/m)			6.57 x 10^{-4}	
Critical shear stress (Pa)			0.91	
Soil albedo			0.12	
Soil texture			Loam	
Depth (mm)	*Sand (%)*	*Clay (%)*	*Organic matter (%)*	*Gravel (%)*
0-100	43	15	3.9	0.8
100-200	38	24	4.2	6.6
200-300	53	19	3.4	4.9
300-1,500	50	27	2.4	3.8

Note: Based on wet bulk density, available water capacity and rangeland productivity of the Delpoint-Cabbart loams in the SSURGO database, assumed dry bulk density and field capacity of the soils to be 1.15 g/cm^3 and 0.2 m^3/m^3, respectively, and root biomass within 10 cm of soils of the revegetated and undisturbed natural areas to be 0.1 kg/m^2 in estimating the erosion parameters.

Research methodology

A series of soil sampling and field infiltration tests were conducted at the four representative areas at the Rosebud Mine (Fig. 1) during 2009-2010. Laboratory experiments to measure soil texture and hydraulic properties were carried out on the soil samples in Washington State University's Soil Physics Laboratory. WEPP simulations were performed using the data collected from the field and laboratory experiments.

Field sampling and laboratory work. Field soil sampling was replicated three times at randomly chosen locations in each of the four representative areas. For each sample location, two disturbed soil samples were collected, one each from the 0-10 cm and 10-20 cm soil depths, giving a total of six disturbed samples from each representative area. The samples were analyzed for particle-size distribution and organic matter content. Undisturbed soil samples were also collected, cored from four different depths of 0-5 cm, 5-10 cm, 10-15 cm and 15-20 cm, resulting in a total of 12 undisturbed core samples from each representative area. These core samples were tested in the Soil Physics Laboratory to determine the mine soil's hydraulic conductivity (K_s).

In situ K_s was measured using a Guelph Permeameter at the same area where soil core samples were taken and two replications were conducted at each of the four representative areas. At each site of the in situ K_s test, a borehole with diameter of 6 cm and depth of 15 cm was drilled with the soil bucket auger and sizing auger of the Guelph Permeameter kit. Two constant heads, 5 cm and 10 cm, were applied successively in each borehole. The rate of water flow out of the reservoir of the Guelph Permeameter was recorded in two-minute intervals until a steady state was reached. A steady state was considered to have been reached when two or three consecutive flow rates were the same. The two-head method (Soil Moisture Equipment Corp., 2008) was first applied to determine K_s, soil matric potential (Φ_m), and the alpha parameter (α^*, the slope of the line relating the natural log of K_s to the soil matric potential). If either K_s or Φ_m had a negative value, or when α^* values were not in a realistic range of $0.01 \leq \alpha^* \leq 0.5$ cm^{-1}, then the average of the K_s or Φ_m determined by the single-head method (Soil Moisture Equipment Corp., 2008) using the two constant heads was used.

Groundcover was measured in the N and V areas following a step-point method (Evans and Love, 1957). Groundcover was measured with randomly chosen transects with 20 equally spaced points in each transect. The percentage of groundcover along each transect was calculated by dividing the number of points covered by plants, litter, rocks or gravel by the total number of points in the transect. Five transects were surveyed in the N area and 10 in the V area. Five additional transects were taken in the V area because it had greater average groundcover than the N area, which was unexpected. Overall, groundcover consisted primarily of plants and litter, with gravel and rock combined ranging 1.5-6.9 percent.

Soil particle-size distributions were determined using a hydrometer following the procedures outlined in ASTM–D422-63 (ASTM International, 1963). Sand content, with particle diameter less than 50 microns, was independently measured using a No. 270 sieve (53-micron opening) to corroborate the hydrometer test results. Particles with size of 50-100 microns were designated as very fine sand, or VFS (Brown, 1990). Organic matter content was determined by burning the samples at 375°C for 24 hours using a muffle furnace following the procedures outlined in ASTM-D2974-07a (ASTM International, 2007). Saturated hydraulic conductivity was determined using the constant-head method following the American Society of Agronomy (ASA) standard procedure (Klute and Dirksen, 1986).

Statistical analysis. Two-way analysis of variance (two-way ANOVA) *F*-tests were performed on the soil hydraulic property data using the SAS statistical analysis software package (SAS Institute, 2004). A two-way ANOVA test was conducted to determine significance for the factors of representative area, with levels N, S, T and V, and soil depth, with levels 0-10 cm and 10-20 cm, as well as testing for significant interaction, denoted by area*depth. This analysis was performed with the dependent variables *OM* content, K_s and particle-size distributions, that is, clay, sand and VFS content. If significance was found at the $\alpha = 0.1$ level, a Tukey multiple comparison procedure was employed to determine specifically where significant differences reside.

WEPP applications. WEPP simulations were carried out to analyze erosion risk after mining reclamation. Data collected in this study, consisting of groundcover, soil texture and soil hydraulic property, and 30 years of climate data observed at the weather station in Colstrip near the study site were used for WEPP simulations. WEPP simulations without vegetation cover (fallow conditions) for all the representative areas were performed to examine the impact of the soil conditions on erosion and sediment yield.

To assess revegetation effects during the canopy cover and groundcover growth period, 30 simulation scenarios were constructed for the V area by rotating 30 years of climate data on a yearly basis, which was achieved by cutting out the data for the first year and pasting them to the end of the data sequence. WEPP simulation results from these 30 scenarios were used for erosion risk analysis for the V area where vegetation reestablishment renders yearly variance of the groundcover. For the N area, with vegetation well established, and the areas in fallow condition, with no vegetation, groundcover conditions were assumed to be relatively stable, and one WEPP simulation scenario was used to study erosion risk for those areas.

All simulations were made using WEPP v2012.8. A simple uniform slope with slope length of 150 m and slope steepness of 0.10, typical of the reclamation areas, were used as WEPP topographical inputs for the four representative areas. WEPP soil as well as land-use and management inputs were parameterized to reflect soil and groundcover conditions specific to each of the four representative areas as detailed below.

WEPP climate inputs. Observed climate data from the Colstrip weather station located at the Rosebud Mine (U.S. National Oceanic and Atmospheric Administration, 2013) were obtained. The observed climate data included daily precipitation and daily maximum and minimum temperatures for 30 years (1983-2013). The remaining climate parameters used in the WEPP simulations, namely, duration of precipitation, precipitation peak intensity and time to peak, daily solar radiation, dew-point temperature, and wind velocity and direction, were estimated using CLIGEN, an auxiliary stochastic weather generator (Nicks et al., 1995), based on the long-term climate statistical parameters from the Rosebud weather station.

WEPP soil inputs. Major WEPP soil inputs included soil texture, effective hydraulic conductivity for infiltration, erosion parameters – rill erodibility (K_r), interrill erodibility (K_i) and critical shear (τ_c) – and soil albedo for estimating the net solar radiation reaching the soil surface (Table 3). For the N area, soil texture inputs for the top 20 cm of soil were the laboratory-measured soil texture data from the samples collected at the representative area, while for the soils below 20 cm, data from the SSURGO database (U.S. Department of Agriculture, 2009) were used. The laboratory-measured soil texture data were similar to those of the Delpoint-Cabbart loams, one of the dominant soils of the sampling area. The Delpoint-Cabbart loams data were thus used for the deeper soils of the N area. As the SSURGO data indicate a less permeable layer at the 75-cm depth of the natural soil in the area, the soil profile for the N area in this study was set to 75 cm with a restrictive layer that has a much lower saturated hydraulic conductivity based on the SSURGO database.

For the three disturbed areas (S, T and V), a typical soil profile depth of 1.5 m was used in this study. For the S area, the measured soil texture data were used for the whole soil profile from 0 to 150 cm. For the T area and the V area where topsoil had been spread over the graded spoil, the texture data measured in this study were used for the top 20 cm and measured data from the mine spoil areas were used for the remaining 20-150 cm depth. Since regraded mine spoil is much deeper than 1.5 m and without structures as those in the natural soil, no restrictive layer was set in the WEPP soil inputs for the three disturbed areas.

K_i, K_r and τ_c are used in WEPP for simulating erosion caused by raindrop impacts and sheet flow (interrill erosion) as well as by concentrated water flow (rill erosion). All three parameters are sensitive inputs and all are closely related to soil texture (Lal and Elliot, 1994). In this study, baseline K_i, K_r and τ_c were estimated based on the laboratory-measured soil texture data near the soil surface using the empirical equations for rangeland soils presented in the WEPP User Manual (Flanagan and Livingston, 1995).

Effective hydraulic conductivity is a sensitive infiltration parameter for simulating runoff generation (Flanagan and Nearing, 1995). The hydraulic conductivity values estimated from the in situ hydraulic conductivity test were used as the inputs for the baseline effective hydraulic conductivity. It is noted that the baseline values for the infiltration and erosion parameters are adjusted daily within the WEPP model throughout the simulation for cropping, tillage and consolidation; changes in canopy and groundcover; sealing and crusting; and freeze and thaw (Flanagan and Nearing, 1995).

Soil albedo is an important parameter in simulating soil freeze and thaw, a major winter hydrological process that has an impact on soil erosion (Flanagan and Nearing, 1995). In this study, soil albedo was estimated based on the measured organic matter content using the empirical formula in the WEPP documentation (Alberts et al., 1995).

WEPP land-use and management inputs. The management inputs for the N area were based on the default "tall grass prairie" file in the WEPP database under "Forest Disturbed WEPP Management." The simulated groundcover, a highly sensitive parameter for erosion prediction, was calibrated to maintain the observed value of 82 percent for the N area.

To calibrate the observed groundcover, the initial groundcover for the N area was adjusted to reflect the observed initial condition. The observed groundcover of 82 percent was used as the initial cover value in the study. The biomass energy ratio, a sensitive parameter for plant growth simulation, was adjusted to reproduce the rangeland productivity value (the maximum living biomass) of 0.10 kg/m^2 as reported in the SSURGO database. The residue decomposition rate was then adjusted to produce the observed groundcover value of 82 percent. Major management inputs for the WEPP simulation are presented in Table 4.

Typical reclamation revegetation practices at the Rosebud Mine are that easy-growing short grass is grown first, until the soil becomes fertile enough to plant native tall grass. For modeling the current reclamation practices, the revegetated area was described with a combination of short grass prairie and tall grass prairie. The default "short grass prairie" file in the WEPP database under "Forest Disturbed WEPP Management" was adapted, with the groundcover calibrated to 92 percent as observed in the V area, and the modified "short grass prairie" input parameters were used for the first five years of the revegetation. The "tall grass prairie" input parameters calibrated for the N area were used for the remaining 25 years.

The initial groundcover value for the "short grass prairie" was set to zero as grass was planted on bare soil after disturbance. Residue decomposition rate was set to the same value as for the N area, and the biomass energy ratio was adjusted to produce a long-term groundcover of 92 percent, the field-observed value for the V area. The simulated annual rangeland productivity values were around 0.15 kg/m^2, higher than those for the N area.

A "fallow" condition, with no plant cover, was used as the management condition for all four representative areas so that differences in simulated erosion would be attributed solely to the differences in soil properties. The default "fallow" file in the WEPP database was used for fallow-condition WEPP simulations.

Erosion risk analysis. Two sets of erosion risk analyses were carried out in the study. First, erosion risk analyses for the S area and for the T area were conducted and the results compared with those under bare-soil conditions for the N area and the V area to examine the impact of different soil conditions on erosion and sediment yield. Second, the erosion risk of the V area was compared with that of the N area to examine the effectiveness of the revegetation and the duration of recovery and reestablishment.

WEPP results obtained from the 30 years of climate data were analyzed for each of the four representative areas. The return period of the runoff events that result in sediment delivery were determined using the Weibull method (Ward and Trimble, 2004):

$$T = \frac{n+1}{m} \tag{1}$$

where T = return period in years, n = number of simulation years and m = rank of the annual maximum events in de-

Table 4 — Major management inputs for WEPP simulations.

Parameters	Tall grass prairie	Short grass prairie
Initial groundcover (%)	82	0
Biomass energy ratio (kg/MJ)	4	11
Fraction of biomass remaining after senescence (%)	25	25
Above-ground biomass decomposition constant	0.0027	0.0027

Table 5 — Laboratory-measured soil organic matter and particle-size distribution.

Area	Depth (cm)	Percentage by weight mean/standard deviation (%)						
		Gravel[1]	Organic matter[2]	USDA soil texture classification[3]				
				VFS	Sand	Silt	Clay	Soil texture
N	0-10	1.5/1.4	6.04/0.92	6.7/1.5	31/10	36/7	33/4	Clay loam
	10-20	3.5/3.5	4.02/1.98	8.3/0.6	46/10	27/4	27/6	Clay loam
V	0-10	0.8/0.7	3.85/1.10	8.7/1.2	43/5	42/13	15/9	Loam
	10-20	6.6/3.6	4.15/0.81	7.7/3.1	38/20	39/7	24/18	Loam
T	0-10	1.6/1.1	3.02/0.56	8.3/2.1	50/21	36/6	13/16	Loam
	10-20	2.0/1.7	3.70/0.27	10.0/2.6	60/19	21/15	19/15	Sandy loam
S	0-10	4.9/2.6	3.43/1.19	11.0/0.0	53/12	29/4	19/9	Sandy loam
	10-20	3.8/2.5	2.39/0.66	9.7/0.6	50/11	29/4	21/7	Sandy loam

Note: N, S, T and V refer to the undisturbed natural area, roughly graded mine spoil, replaced topsoil before seeding, and revegetated area, respectively. [1]Percentage of the whole soil sample. [2]Percentage of the soil after removal of gravel. [3]Percentage of the soil after removal of gravel and organic matter.

Table 6 — Soil hydraulic conductivity (mm/hr) mean/standard deviation determined in laboratory and in situ experiments.

Area	Lab constant head method				In situ infiltration test
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	
N	171/136	235/175	253/65.2	181/132	28.3/10.0
V	77.2/32.0	63.7/44.8	26.7/26.1	12.7/7.8	37.5/5.0
T	74.4/27.7	32.0/9.8	28.9/18.2	24.6/9.3	21.0/9.9
S	20.1/15.9	20.2/17.3	19.2/10.1	29.4/26.0	29.8/22.7

Note: N, S, T and V refer to the undisturbed natural area, roughly graded mine spoil, replaced topsoil before seeding, and revegetated area, respectively.

scending order.

The sediment delivery exceedance probability was calculated as (Barfield et al., 1981):

$$P(T,n) = 1 - \left(1 - \frac{1}{T}\right)^n \quad (2)$$

where $P(T, n)$ = probability that an event with a T return period will occur at least once during n years.

For this study, n was set to 1, since it was desired to determine the sediment delivery exceedance probability in a single year.

Results and discussion

Particle-size distribution. The particle-size distributions determined from the laboratory experiments are presented in Table 5. The measured saturated hydraulic conductivities are presented in Table 6. The samples collected from the N area contain more clay and less VFS than those collected from the disturbed areas. At $\alpha = 0.1$, the ANOVA results (Table 7) for sand, clay and VFS indicate no significant interaction between soil depth and representative area, no significant differences in soil texture at different depths, and no significant differences in mean sand content among different representative areas, but significant differences in mean clay and VFS contents in the different representative areas.

Tukey multiple comparison on clay and VFS for the representative areas showed that the samples from the T area had significantly less clay, on average, than those from the N area

Table 7 — ANOVA results for soil organic matter, hydraulic conductivity (K_s), and particle-size distribution (sand, clay and very fine sand).

Parameter	Factor	Degrees of freedom	P-value
Organic matter	Area[1]	3	0.017
	Depth[2]	1	0.25
	Area*depth	3	0.14
Log(K_s), lab	Area	3	< 0.0001
	Depth	1	0.024
	Area*depth	3	0.18
Log(K_s), in situ	Area	3	0.73
Clay	Area	3	0.099
	Depth	1	0.86
	Area*depth	3	0.73
Sand	Area	3	0.17
	Depth	1	0.48
	Area*depth	3	0.60
Very fine sand	Area	3	0.070
	Depth	1	0.73
	Area*depth	3	0.31

[1]Area refers to the undisturbed natural area, roughly graded mine spoil, replaced topsoil before seeding, and revegetated area.
[2]Depth refers to soil depths of 0-10 cm and 10-20 cm.

(at $\alpha = 0.1$, Tables 8 and 9) and the S area had significantly greater VFS, on average, than the N area (at $\alpha = 0.1$, Tables 8 and 9). Previous studies (Lal and Elliot, 1994; Romero et al., 2006) showed that soil erodiblity increases with decreasing clay and increasing silt and VFS contents. The soils at the disturbed areas contained less clay and more VFS suggesting that the disturbed areas (S, T and V) have a higher risk of erosion than the natural areas (N).

Organic matter content. Organic matter content in the top 0-20 cm of soil in the N area was greater than in the top 0-20 cm of soils in the disturbed areas (Table 5). At $\alpha = 0.1$, two-way ANOVA for organic matter content shows no significant interaction between soil depth and representative area, no significant differences in soil organic matter content at different depths, and significant differences among the four representative areas (Table 7). Tukey multiple comparison indicates significantly more organic matter content in the soil of the N area than in both the S and T areas (at $\alpha = 0.1$, Tables 8 and 9).

Loss of organic matter content is an outcome associated with surface mining during the stripping and stockpiling of soil (Stahl et al., 2003). Organic matter content may increase in reclaimed areas some years later (Gilewska et al., 2001). Observations in this study (Table 5) corroborate these findings. The natural topsoil at the Rosebud Mine contains high organic matter content, but after the soil is stripped and stockpiled, it loses organic matter content. Organic matter content levels then increase in the top 10 cm of the V area. However, the organic matter content remains lower than it was in the pre-mining soil. The roughly graded spoil comes from deeper layers, and, as expected, has the lowest organic matter content.

Organic matter content is crucial for plant productivity (Bauer and Black, 1994) while plant cover reduces soil erosion. Organic matter content also helps to ameliorate erosion by increasing soil aggregation stability and infiltration capacity, which helps to reduce runoff (Lal et al., 1998). Thus, the N and V areas, with their higher organic matter contents, will have lower risk of soil erosion than the S and T areas at the Rosebud Mine.

Table 8 — Least-square means for organic matter, laboratory-measured hydraulic conductivity (K_s), and clay and VFS contents of the different areas.

Area	Organic matter (%)	Log(K_s), lab Log (mm/hr)	Clay (%)	Very fine sand (%)
S	2.91	1.23	19.83	10.3
N	5.03	2.20	30.33	7.5
T	3.36	1.52	12.50	9.2
V	4.00	1.47	19.33	8.2

Note: N, S, T and V refer to the undisturbed natural area, roughly graded mine spoil, replaced topsoil before seeding, and revegetated area, respectively.

Table 9 — *P*-values from the Tukey multiple comparison procedure for the representative areas.

Parameter	Area	S	N	T
Organic matter	N	0.015		
	T	0.88	0.063	
	V	0.32	0.36	0.73
Log(K_s), lab	N	< 0.0001		
	T	0.36	0.0023	
	V	0.54	0.0009	0.99
Clay	N	0.42		
	T	0.70	0.069	
	V	1.0	0.38	0.74
Very fine sand	N	0.059		
	T	0.67	0.39	
	V	0.19	0.92	0.77

Note: N, S, T and V refer to the undisturbed natural area, roughly graded mine spoil, replaced topsoil before seeding, and revegetated area, respectively.

Saturated hydraulic conductivity. Table 6 shows a substantial discrepancy between the laboratory and the in situ measurement results for average K_s for the soil in the N area, with in situ average K_s value of 28 mm/hr and laboratory-measured K_s value of 210 mm/hr. From the SSURGO soil database, dominant soils at the sampling areas for the natural area and revegetated area were Cambeth-Cabbert silt loam and Delpoint-Cabbart loam with K_s of 15-50 mm/hr for the top 20 cm of both soils. The high K_s value from laboratory testing of the soil samples from the N area may be a result of preferential flow along the root channels caused by their changes after the soil samples were taken from the ground. Boundary effects of the standard 2-in. brass soil sampling ring may also be greater for the N area soil than for soils from other areas as the presence of living grass and grass roots in the N area makes it difficult to collect an undisturbed sample. In the S and T areas, the dominant soil before mining was Busby fine sandy loam, with K_s of 50-150 mm/hr for the top soils based on the SSURGO soil database. These values are about three times greater than those of Cambeth-Cabbert silt loam and Delpoint-Cabbart loam soils for the N and V areas.

The *F*-test results for K_s, with a $\log_{10}$ transformation made to K_s to assure normally distributed residuals following Dieleman and Trafford (1976), indicate no significant difference for the in situ K_s values (Table 7). For laboratory-measured K_s, there was no significant interaction between soil depth and representative areas, while significant differences were detected for in situ K_s due to both soil depth and representative areas (Table 7). Additionally, the laboratory-measured K_s for the N area was significantly greater than those for other areas (at $\alpha = 0.1$, Tables 8, 9 and 10), and for soils at the 0-10 cm depth than those at the 10-20 cm depth (Table 7).

The laboratory-measured K_s results are consistent with those for organic matter content for the four representative areas. A higher degree of aggregation due to the presence of relatively high organic matter content (Piccolo and Mbagwu,

Table 10 — Least-square means for laboratory-measured hydraulic conductivity (K_s), and *F*-test *P*-value for soil depth.

Soil depth (cm)	Log(K_s), lab Log (mm/hr)	*P*-value
0-10	1.75	0.024
10-20	1.46	

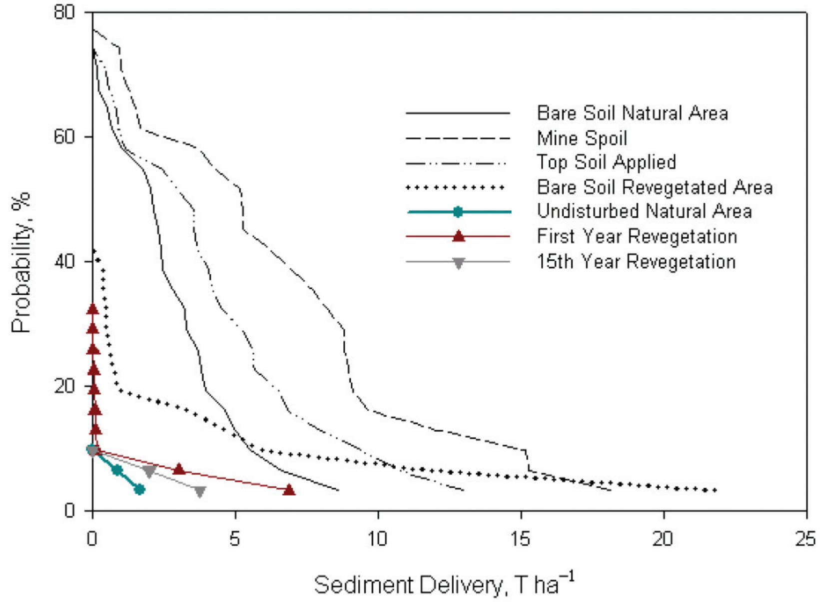

Figure 2 — Annual exceedance probability of sediment delivery.

1999) in the natural soil should result in relatively larger macro-porosity, and thus higher K_s. The structure of the topsoil is often destroyed during replacement of the soil, especially since there is no vegetation growing in it (Fulton and Wells, 2005). Once revegetated, the structure of the soil should start to recover and K_s should increase over time. Roughly graded spoil is derived from deeper soil layers and subject to natural settling and compaction as well as additional compaction from heavy machinery movement during grading. It had the lowest K_s in this study. Akala and Lal (2000) reported that soil compaction can be relieved by plant rooting action. Soil K_s is a key factor affecting infiltration and surface runoff (Jadczyszyn and Niedzwiecki, 2005) and ultimately soil erosion by water. The K_s test results in this study also suggest that there are higher erosion risks in the areas of roughly graded spoils and replaced topsoil before seeding.

Erosion risk analyses. Figure 2 shows WEPP-simulated exceedance probability of sediment delivery from bare soils (under fallow condition) of the four representative areas. The simulation results demonstrate that soils from the N and V areas have lower erosion risk than those from the S and T areas. For events of the same return period, sediment delivery occurs in decreasing amount from the S area to the T area to the N area to the V area. It is noted that the V area has a lower erosion potential from the WEPP-simulation results for the events with exceedance probability greater than 10 percent, though it has higher sediment yield from the extreme events. The lower erosion potential of the V area might be due to the higher hydraulic conductivity of the soils measured in this area and the removal of the restrictive layer during mining activities. The WEPP simulation results are consistent with the implications of the soil hydraulic property analyses that showed that the S and T areas are more prone to soil erosion than the N and V areas.

Figure 2 also shows the effect of vegetation cover on reducing erosion risk and sediment yield from the extreme events. WEPP simulations suggest that the N area has the lowest erosion risk and the erosion risk of the V area would decrease with time.

Tables 11 and 12 present the results of the return-period analyses of the sediment delivery events of the bare soils under fallow conditions. The results indicate that most of the large sediment delivery events at the site would occur during the nonwinter period. The simulated sediment yield generally increases with increasing runoff and precipitation, though the relationship is not a simple, linear one.

Table 13 presents the averages of the 30-year WEPP simulations for runoff and sediment delivery. The results show that the largest amount of runoff is generated during the win-

Table 11 — Return-period analyses of sediment delivery events: runoff and sediment yield.

Return period (year)	Bare soil natural area			Mine spoil			Top soil applied			Bare soil revegetated		
	P (mm)	RF (mm)	Sed (t/ha)	P (mm)	RF (mm)	Sed (t/ha)	P (mm)	RF (mm)	Sed (t/ha)	P (mm)	RF (mm)	Sed (t/ha)
30	68	40	8.6	68	41	18.1	68	39	13.0	68	47	21.8
10	32	19	5.5	67	21	15.2	67	18	9.4	66	9	5.9
5	50	16	3.9	45	19	9.1	50	16	6.5	0	23.3	0.9
2	32	7	2.0	32	9	5.2	31	7	3.0	0	0	0

Note: P, RF and Sed refer to precipitation, runoff and sediment yield during an event.

ter (November-March) months. However, nonwinter runoff results in greater sediment delivery than winter runoff. While the results indicate that snowmelt in winter can be a dominant process for runoff generation in the study area, summer storms can generate more intense overland flow, which tends to cause more severe erosion than the snowmelt events in winter. Frozen soil conditions during the winter at the site may also help mitigate runoff-generated erosion.

Figure 3 shows WEPP-simulated sediment delivery from events of different exceedance probabilities for the N and V areas during the groundcover establishment period. The 30-year WEPP simulation results indicate that little or no erosion would occur for the N and V areas. For the V area, erosion risk would decrease with time and then approach a stable status at a higher erosion rate than for the N area with the same exceedance probability. WEPP-simulated events of 3 and 6 percent exceedance probabilities for the V area approach a stable erosion rate around Year 5 after seeding. For the events of 10 percent exceedance probability, however, there is an increase in the erosion rate, possibly caused by a combination of factors of plant growth, soil water dynamics and winter processes. Overall, WEPP simulation suggests that revegetation is an effective reclamation practice for erosion reduction and control at the Rosebud Mine and likely at other sites in the western United States with similar geographic and climatic conditions.

Conclusions

In this study, field soil sampling and experimentation were conducted, and hydraulic properties, consisting of K_s, organic matter content and particle-size distributions, were measured for four representative areas at the Rosebud Mine in eastern Montana, representing undisturbed natural area (N), roughly graded mine spoil (S), replaced topsoil before seeding (T) and revegetated area (V). The WEPP model was used to simulate runoff and erosion from the four representative areas using field-measured hydraulic properties and groundcover conditions. Based on the results of this study, the following were concluded for the study area:

- Organic matter content is lost in stockpiled topsoil, but may recover in revegetated soil.
- Sand contents were higher in the S and T areas than in the N and V areas.
- Saturated hydraulic conductivity was higher in the N and V areas than in the S and T areas.
- Both the spoil and stockpiled topsoil have higher potential for soil erosion than the natural and revegetated soils, as indicated by WEPP simulation results.
- For the N and V areas, WEPP-simulated long-term runoff and soil erosion are both low and not significantly different.
- The highest sediment deliveries occur from the T and S areas, which were not revegetated.

Surface mining tends to change soil hydraulic properties, as reported in numerous studies. The differences in soil hydraulic properties observed in this study may not be entirely attributed to the mining activities conducted at the site. The findings and results from this study should be viewed with caution. The natural saturated soil hydraulic conductivity values determined during laboratory testing may be unreasonably large as the K_s value in the undisturbed soils is already large.

Future research efforts should be devoted to corroborating the impact of altered soil hydraulic properties and surface conditions on soil erosion and establishing management strategies to mitigate such impacts in other western alkaline surface coal mines. Research should also be conducted to develop a more comprehensive and pertinent mining soil database for western alkaline coal mining areas in the United States.

Table 12 — Return-period analyses of sediment delivery events: precipitation event date.

Return period (year)	Bare soil natural area		Mine spoil		Top soil applied		Bare soil revegetated	
	P (mm)	Event Date	P (mm)	Event Date	P (mm)	Event Date	P (mm)	Event Date
30	68	5/28/2013	68	5/28/2013	68	5/28/2013	68	5/28/2013
10	32	5/18/2011	67	5/6/2005	67	5/62005	66	6/4/2007
5	50	6/5/1993	45	7/14/2002	50	6/5/1993	0	3/23/1990
2	32	6/14/1990	32	8/8/2000	31	10/13/1995	0	

Note: P refers to precipitation.

Table 13 — WEPP-simulated annual average runoff and sediment delivery from bare soils under fallow condition.

Representative area	Precipitation (mm)	Runoff (mm)	Runoff winter (mm)	Sediment yield (t/ha)	Sediment yield winter (t/ha)
N	368	20	11	2.52	0.17
S	368	23	13	7.03	0.71
T	368	21	12	4.07	0.27
V	368	14	12	1.67	0.14

Note: N, S, T and V refer to the bare soil natural area, roughly graded mine spoil, replaced topsoil before seeding, and bare soil revegetated area, respectively.

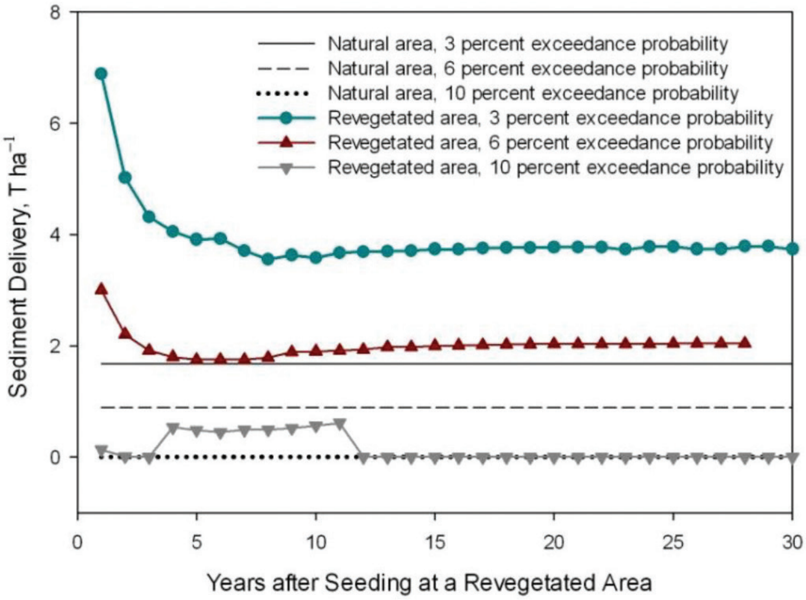

Figure 3 — Chance of erosion risk after seeding at the revegetated area.

Acknowledgments

The authors thank the U.S. Office of Surface Mining Reclamation and Enforcement for funding this research project, especially the efforts of Dr. Duane Matt, to make this project possible. The authors also thank the Montana Department of Environmental Quality for assisting in developing the scope of work for this research project and for providing valuable insight to soil conditions and potential erosion and sedimentation conditions at western U.S. alkaline mining operations. Finally, the authors are grateful to Western Fuels Company for granting access to the Rosebud Mine for conducting field studies and collecting soil samples for this study.

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