Application of the WEPP Model to Surface Mine Reclamation[1]

by

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Abstract. Sediment from mining sources contributes to the pollution of surface waters. Restoration of mined sites can reduce the problems associated with erosion, and one of the most important objectives of surface mine reclamation is the control of surface runoff and erosion from reclaimed areas. Current methods for predicting sediment yield do not suit surface mine sites because non-agricultural soils and vegetation are involved. There is a need for a computer model to aid in identifying improved management systems and reclamation practices with suitable input data files and appropriate hydrologic modeling routines.

The USDA Water Erosion Prediction Project (WEPP) resulted in the development of a computer model based on fundamental erosion mechanics. The WEPP model will be in widespread use by the mid 1990s by the Soil Conservation Service (SCS), and will be the erosion prediction model of choice well into the next century. This paper gives an overview of the WEPP erosion prediction technology and its implications to surface mine reclamation, and reports on a research project that identifies critical watershed parameters unique to surface mining and reclamation through a sensitivity analysis of the WEPP Watershed Model. The study contributes to the validation of the WEPP Watershed Version by comparing estimates generated by the model with observed data from watersheds after surface mining.

Additional Key Words: Erosion simulation

INTRODUCTION

As renewable fossil fuel energy reserves are depleted, the importance of coal as a source of energy will increase. McKetta (1974) predicted that coal usage will have to triple to insure that the energy needs of the USA are met. This inevitable increase in coal usage will result in an increase in surface mining operations, along with associated erosion and water quality problems (Barfield et al., 1983). In the USA, sediment from mining sources contributes to the pollution of surface waters, affecting water used for drinking, swimming, fishing, and other domestic and recreational purposes (Mitchell et al., 1983). In addition, this sediment may affect the productivity of agricultural land and the life of engineering works. Appropriate restoration of mined sites can contribute to the control of surface runoff and erosion from reclaimed areas (Mitchell et al., 1983; Hartley and Schuman, 1984).

In regulating reclamation of surface mine sites, it is necessary for agencies and contractors to have a method for predicting erosion rates before and after mining to aid in identifying improved management systems and reclamation practices. Current methods for predicting soil erosion apply to agricultural soils and vegetation, and so are unsuitable for surface mine sites where the hydrologic conditions can be significantly different. With current process-based computer models, the large input data sets are too complex for technicians and other field users to develop. There is a need for a process-based computer model that can predict erosion and water

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quality problems associated with surface mining with input files from readily available data.

OBJECTIVES

The purpose of this study was to determine the suitability of the WEPP model for surface mining situations, and to contribute to the validation of the WEPP Watershed Version 91.5 by comparing estimates produced by the model with observed data from reclaimed surface mine sites.

The objectives of this paper are to:

1. Give an overview of the WEPP erosion prediction technology and its implications to surface mine reclamation.

2. Report on a research project that identifies critical watershed parameters unique to surface mining and reclamation through a sensitivity analysis of the WEPP Watershed Version.

3. Contribute to the validation of the WEPP Watershed Version by comparing estimates generated by the model with observed data from watersheds after surface mining.

MODELING

Hydrologic computer simulation modeling makes a valuable contribution to agricultural research and practice (Ferreira and Smith, 1988). Research involving data collection from long-term field studies is a time-consuming and expensive process. An alternative approach is to carry out computer simulations to analyze the hydrologic effects of management for given climate conditions.

Scientists are developing process-based erosion prediction models for computers that allow the user to model the individual processes that lead to soil erosion, including rainfall intensity and distribution, infiltration and runoff, and soil detachment, transport, and deposition. Process-based models initially required main frame computer capabilities and large input data sets. However, they can successfully be applied to many more conditions than statistical models as long as the factors affecting the processes can be identified and characterized (Foster and Meyer, 1972).

In 1984, the USDA Agricultural Research Service (ARS) and SCS in cooperation with the Bureau of Land Management (BLM) and the Forest Service (FS) began a cooperative effort known as the Water Erosion Prediction Project (WEPP). Their goal was to develop a user-friendly process-based erosion prediction model that would operate on a portable computer, and could be used by SCS and other field technicians as an aid in erosion prediction and conservation planning for cropland, rangeland, and forests. After five years of field, laboratory, and computer research, the first completed research version of the WEPP program was released in August, 1989, and the first field version in 1991. It is expected that the model will begin receiving wide-spread use by SCS in the mid-1990s, and will be the erosion prediction model of choice well into the next century (Foster and Lane, 1987).

The WEPP model is based on fundamentals of infiltration, surface runoff, plant growth, residue decomposition, hydraulics, tillage management, soil consolidation and erosion mechanics (Nearing et al., 1989). Table 1 summarizes the important input parameters for the model. This model combines a process-based erosion model with a process-based hydrology model and a climate generator to estimate soil loss and deposition, and so facilitate the selection of agricultural management practices for soil conservation.

The WEPP technology includes a Hillslope Profile Version, a Watershed Version, and a Grid Version (Lane and Nearing, 1989). The Hillslope Profile Version predicts when and where soil loss and deposition will occur on a hillslope, taking into account management practices and climate. It is continuous, simulating the processes that impact erosion prediction as a function of time. However, the model may also be used in the single-storm mode (Lane and Nearing, 1989).

The individual processes that lead to soil

Table 1. Input requirements for WEPP Model

Input file	Contents
Slope	Pairs of points indicating distance from top of slope and respective slope.
Soil	For top layer: Albedo, initial saturation, interrill and rill erodibility.
	For all layers: thickness, initial bulk density, initial hydraulic conductivity, field capacity, wilting point; contents of: sand, clay, organic matter, and rock fragments; cation exchange capacity.
Climate	For each day of simulation: precipitation amount, duration, time to peak rainfall, peak rainfall, maximum and minimum temperatures, solar radiation, average wind speed and direction.
Management	Type of vegetation (crop, range, or forest), plant growth parameters, tillage sequences and effects on soil surface and residue, dates of harvesting or grazing; if necessary, description of irrigation, weed control, burning, and contouring.
Structure	Relationships among the hillslope and channel elements of the watershed.

erosion are the same for agricultural and forested lands, and also occur on reclaimed mine sites. The erosion differences are due to plant growth and in the hydrologic response of the soils. On reclaimed surface mine sites, plant growth is slow, and alternative cover crops have been, and continue to be sought.

The growth rates of many cover crops are documented, and by studying the data, the necessary crop growth files for the computer model could be generated. Crop growth parameters measured on reclaimed surface mine sites (Holmberg, 1980) could be formatted for the WEPP model. The WEPP model not only predicts erosion, but also predicts infiltration and runoff, and may be superior to other methods in predicting runoff from a reclaimed watershed (Lane and Nearing, 1989).

One of the common hydrologic features of reclaimed surface mines is greater infiltration (Ward et al., 1983). On steep terrain, interflow, where surface water that infiltrates upslope areas resurfaces further downslope, may occur (Harrold et al., 1986), adding to the erosion rates on downslope areas and potentially causing inferior surface water quality. In the current Watershed Version, interflow may be accounted for by a channel parameter.

VALIDATION

With reference to the operational requirements for the WEPP model, Foster and Lane (1987) stated that one of the major factors important to the users is the validity of the model. They stipulated that (p. 10-11):

> The procedure must be sufficiently accurate to lead to the planning and assessment decision that would be made in the large majority of cases when full information is available. However, more than accuracy is to be considered in establishing the validity of the procedure. The procedure is to be validated, and the validation process and its results are to be documented. The prediction procedure is expected to be composed of a number of modules. Each major module is to be

individually validated and the procedure is to be validated as a package.

One of the criteria for validity (Foster and Lane, 1987) was the requirement that the model should provide a reasonable representation of data covering a broad range of conditions, including situations not appropriate for the Universal Soil Loss Equation (USLE), such as deposition in furrows and complex slope shapes and/or farming practices. Judgements on the "goodness of fit" of the estimates from the procedure to observed data were to be based on a large number of data sets as a whole and not on a few specific and isolated data sets. Quantitative measures of the "goodness of fit" were to be calculated and presented, but a quantitative level of accuracy figure was not specified because of the great variation in the experimental data that would be used in validation. However, the results were to be at least as good with respect to observed data and known relationships as those predicted by the USLE.

METHODS

Surface Mine Sites

During the period of 1978 until 1983, a cooperative research project was carried out between the USDA-ARS, the Ohio Agricultural Research and Development Center (OARDC), the USGS, Utah State University, and the SCS (USDA-ARS, OARDC and Bureau of Mines, 1978, 1983a and 1983b). In the project, four surface mine watersheds, and one similar watershed which was not mined, were instrumented to measure precipitation, runoff, and sediment concentration of runoff. Data on groundwater quality was also collected, and an economic analysis was carried out to compare the mining systems.

Analysis of the data collected is ongoing, but two sites had published preliminary results of the runoff flow rates and sediment concentrations. These sites are located in Muskingum County (Site M09) and Jefferson County (Site J11), Ohio. Site M09 is a south facing 20 ha watershed with an average slope of 23%. The soils and bedrock consisted of calcareous material with the original topsoils being mainly silt loams. Site J11 is a northwest facing watershed with 12 ha and a slope of 12%. The soils were formed from mainly shale and sandstone with the topsoils being mainly silt loams. Figure 1 presents contour maps of the two sites.

Only data from the post-mining condition were considered for the analysis because insufficient information of the details of the mining period were available for validation.

Runoff and sediment data were collected at flumes on the outlet of watersheds. Concentration samples were collected during all stages of each runoff event, and used to calculate an average sediment load rate (tons/day) for each month for M09. Analysis of the climate data is not yet complete, so four years of simulated climate were used to drive the model to allow comparisons of predicted erosion rates from the four simulated years to the two years of observed erosion rates. Six years of data relating runoff to rainfall were available for Site J11. Four of those years were compared to four years of simulated climate and runoff predicted by the WEPP model.

WEPP Program

A simulated climate file was generated with climate statistics for Fredricktown, Ohio with the WEPP climate generator. Soil files were developed using the post-mining soil surveys (USDA-ARS, OARCD and Bureau of Mines, 1983a and 1983b). A perennial brome-grass cover crop was used for the management file.

Because of the shape of the watersheds, it was decided that the watershed version would be more representative of the sites than the hillslope version. The WEPP Watershed Version 91.5 was compiled on a supercomputer.

Initially a value of "0" was entered for saturated hydraulic conductivity to allow the model to calculate a default conductivity using algorithms within the model. The model was then run and the output file stated a value for the "effective hydraulic conductivity". An iterative procedure was then begun altering input values for saturated hydraulic conductivity until the output file listed an

Figure 1.a. Watershed M09

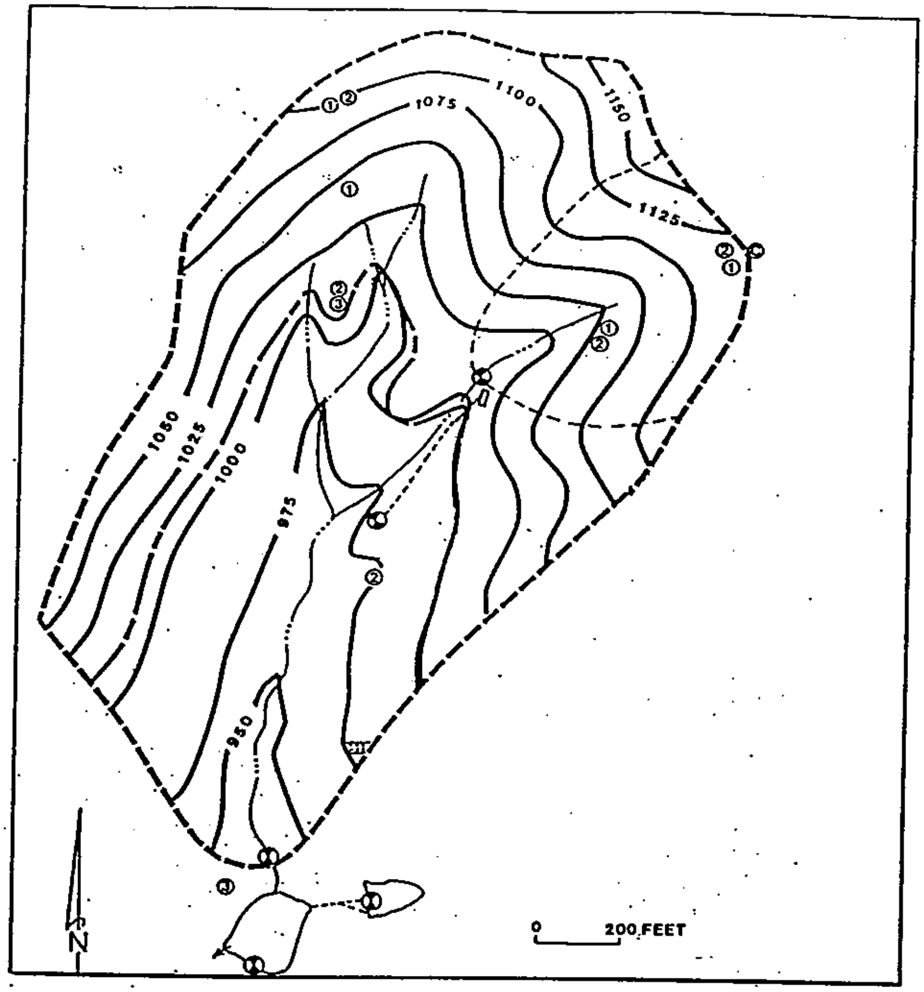

Figure 1.b. Watershed J11

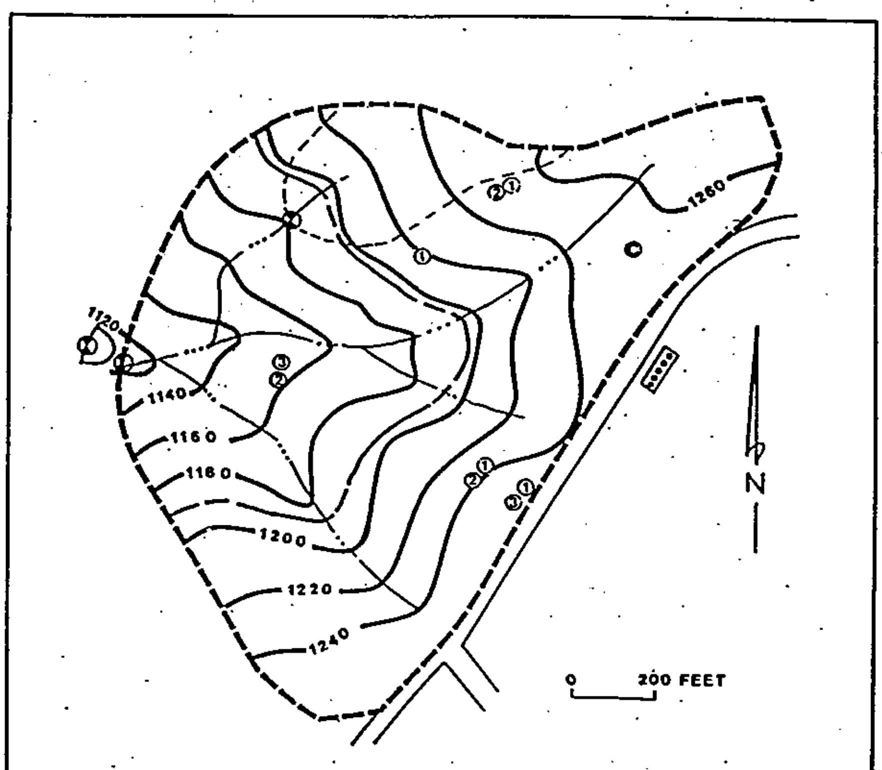

Figure 1. Contour maps of watersheds.

effective hydraulic conductivity similar to that stated for the default condition. The saturated hydraulic conductivities were found to be 1.075 mm/hr for Site J11 and 0.13 mm/hr for site M09.

The erodibility values were calculated from nomographs based on the WEPP cropland field erodibility studies data set (Elliot and Brown, 1993). The estimated erodibility values for each site are included in Table 2, which also includes other selected soil properties from the sites.

Table 2. Selected soil properties from the sites

Property	Value		Units
	Site J11	Site MO9	
Series	Gilpin	Morristown	
Texture	Silt loam	Silty clay loam	
Number of layers	3	3	
Interrill erodibility	3,100,000	2,100,000	$kg\text{-}s/m^4$
Rill erodibility	0.008	0.0085	s/m
Critical shear	3.8	2.6	Pa
Top layer thickness	280	305	mm
Initial hydraulic conductivity	1.075	1300	mm/hr
Sand content	35.8	6	percent
Silt content	20.65	33.3	percent
Organic matter	1.0	1.0	percent
Cation exchange capacity	15.9	29.1	meq/l
Rock fragments	15	12.5	percent

DISCUSSION AND RESULTS

The results comparing cumulative runoff vs. cumulative rainfall for site J11 are presented in Figure 2. There are four years of observed runoff compared to the predicted runoff from a generated climate. It appears that the observed variation is similar to the simulated variation. The predicted curve slightly over-predicts the runoff. An earlier study of the climate generator using data for Fredricktown found that the generated climate had slightly greater intensities and shorter durations than the observed climate (Elliot et al., 1993). Such an overprediction of intensity could lead to an overprediction of runoff from major events, and an overall greater prediction of runoff from the same total rainfall.

The average monthly sediment yields are presented in Table 3, along with seasonal and annual means. An analysis of variance was carried out to determine if there were any differences between years or seasons, or among months. There was no difference between the two years. The difference between months was significant at P=0.006, and the difference between seasons at P=0.002. A contrast within the analysis of variance was carried out to see if there were any differences between the observed and simulated results, and they were not significantly different. It appears that, if considering the combination of the climate generator and the WEPP model, the predicted sediment yields are not different from observed yields on the average. This result indicates that the WEPP model is capable of producing reasonable results, which was one of the stated user requirements for the model (Foster and Lane, 1987).

By using simulated climate, the ability of the entire WEPP system including the climate

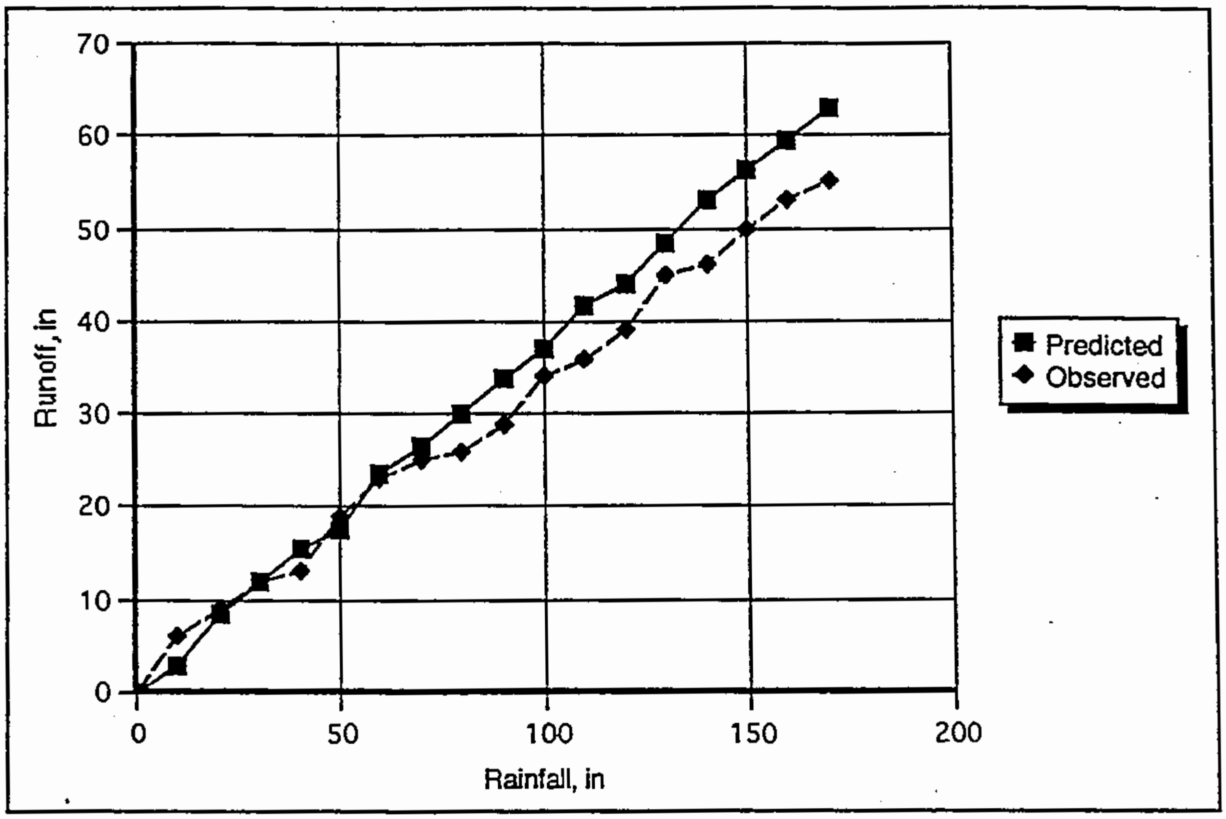

Figure 2. Cumulative runoff vs. cumulative rainfall for four years of generated climate with predicted runoff, and four years of observed climate and runoff

Table 3. Average daily sediment yields for each month, tons per rainy day.

Month	Obs Load	Simul 1 Load	Simul 2 Load	Monthly Means:
1	2.5	0	0	0.60
2	2.06	0.03	0	0.35
3	4.38	2.54	0.29	4.85
4	5.38	4.48	8.27	5.42
5	5.82	9.59	1.45	13.42
6	21.3	0.15	1.82	14.27
7	0.84	4.32	0.06	3.02
8	2.02	8.09	6.05	4.67
9	1.14	0.06	0.06	0.29
10	0.26	2	0.48	0.48
11	1	1.84	0.11	2.11
12	0.76	3.29	0.01	1.35
1	1.1	0	0	
2	0	0	0	
3	7.34	5.68	8.88	
4	2.03	12.26	0.08	
5	2.43	40.4	20.84	
6	5.05	35.25	22.06	
7	4.47	3.05	5.36	
8	3.24	1.53	7.11	
9	0	0.2	0.3	
10	0	0.03	0.09	
11	0.4	3.87	5.42	
12	0.05	0.01	0.03	
Mean:	3.07	5.78	3.70	4.18
Seasonal Mean			Aut, Win:	1.51
			Spr, Sum:	6.85
Annual Mean			1:	2.85
			2:	5.52

simulator can be evaluated. This practice, however, may make it difficult to determine sources of variation when comparing the predicted results to the observed results. Further validation studies where climatic data from the site can be used to generate the climate input file are necessary before a final evaluation of the WEPP model can be made.

The results of the sensitivity analysis are summarized in Table 4. The values presented are the ratios as defined by equation 1:

$$\text{Sensitivity} = \frac{\dfrac{\text{Change in Output Value}}{\text{Output Value}}}{\dfrac{\text{Change in Input Value}}{\text{Input Value}}} \quad (1)$$

As would be expected, a reduction in the hydraulic conductivity results in a corresponding increase in runoff, and an increase in peak flow rate of 1.7 times. The increase in sediment concentration of 25x and the increase in sediment yield of 64x with a 50 percent decrease in hydraulic conductivity on Site J11 is, however, of concern. Apparently, within the range of input variables considered, the change in hydraulic conductivity, resulting in greater runoff, has dramatic effects on the ability of overland and concentrated rill flow to detach and transport sediment from the watershed. Less dramatic but still major results were obtained using the topography on site M09. The calculated runoff rates were similar for M09 and J11, but the hydraulic conductivity of J11 was much lower than M09, so the increase in both total and peak runoff was less dramatic on the more permeable soils of M09. An earlier sensitivity analysis for the cropland version of the hillslope model had found the sensitivity of sediment delivery to hydraulic conductivity to be -0.83 (Lane and Nearing, 1989).

It appears that, within the range of the parameter values that were being used, the entire source of sediment was from interrill erosion, and that no rill erosion was occurring.

Table 4. **Sensitivity analysis of the effects of varying WEPP input parameters on output values.**

Input Parameter	Change in Output Value			
			Sediment	
	Total Runoff	Peak Flow Rate	Concentration	Yield
For J11				
Hydraulic Cond	-1.0	-1.7	-25	64
Interrill Erod	--	--	1.0	1.0
Rill Erod	--	--	--	--
Critical Shear	--	--	--	--
For M09				
Hydraulic Cond	0.2	-0.2	-5.2	11
Interrill Erod	--	--	1.0	1.0
Rill Erod	--	--	--	--
Critical Shear	--	--	3.0	3.0

Experience has shown that eroded rills are a common feature of reclaimed sites, and the fact that the WEPP model is not sensitive to rill erodibility requires further investigation. The transport capacity of the overland flow was sufficient to remove all of the detached sediment, so any increase in interrill erodibility was followed by a matching increase in sediment yield. Only on the lowest critical shear value for Site M09 was any rill erosion occurring, which resulted in the increase in erosion that led to the sensitivity of -3 for critical shear. In all other cases, there was no effect of altering rill erodibility on sediment yield. It appears that the interrill erodibility component of the WEPP model is adequately predicting the observed erosion on this site. A validation of an earlier version of the WEPP hillslope model for cropland had found a sensitivity for sediment delivery of about 0.1 to 0.2 for interrill erodibility and 0.6 for rill erodibility (Lane and Nearing, 1989).

CONCLUSIONS

From an initial attempt to predict the sediment from a reclaimed surface mine using the WEPP watershed version, the following conclusions were reached:

1) Suitable WEPP input files can be developed for surface mine conditions.

2) Additional work with more detailed field data is necessary to evaluate runoff and sediment load rates, although sediment yields predicted from a simulated climate by the WEPP model were not significantly different from those measured in the field when considering multiple storms.

3) The most critical parameter affecting sediment yield from the reclaimed surface mined sites in this analysis is hydraulic conductivity.

4) Interrill erosion may be the dominant source of sediment on reclaimed surface mined sites, but this result requires further investigation.

From this study, it appears that the WEPP model may well be capable of modeling the hydrologic and erosion processes on surface mine sites, but further study is necessary with more detailed watershed data than were available for this study. The climate generator appears to be predicting rainfall patterns of duration and amount with sufficient accuracy for use in predicting sediment yields with the WEPP model.

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