This paper was peer-reviewed for scientific content.
Pages 1053-1058. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Predicting Hillslope Scale Erosion on Disturbed Landscapes from Laboratory Scale Measurements

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ABSTRACT

Open-cut coal mining in Queensland, Australia has resulted in the disturbance of an estimated 50,000 ha of land. The cost of rehabilitation range from an estimated $5000 to $45,000 per hectare, most of which is associated with earthworks to lower the slopes of the steep spoil-piles produced by dragline operations. The extent and cost of earthworks may be minimized, and failures avoided, if erosion from design landforms can be predicted prior to construction.

A method was developed and tested for predicting hillslope scale soil erosion from laboratory scale measurements of erodibility. A laboratory tilting flume and rainfall simulator was used to determine rill and inter-rill erodibility coefficients for 32 soils and overburdens from Central Queensland open-cut coalmines. A simple steady state rainfall event based model, called MINErosion, was developed based on fundamental erosion processes incorporating functions developed from this research. MINErosion is a user-friendly Windows 95 program, to provide a simple method for the rapid assessment of potential erosion from bare unconsolidated post-mining landscapes.

Predicted sediment delivery rates based on the MINErosion model were tested against field measurements of erosion from simulated rainfall events on 12 m x 1.5 m plots at slopes ranging from 5 to 30 %. Regression analysis showed a good agreement (R^2=0.70) between predicted and measured sediment delivery rates. Extrapolation of MINErosion to large field erosion plots established on the outer slopes of waste rock dumps at slopes of 44 % and 75 % shows good agreements with observed erosion rates.

INTRODUCTION

Open-cut mining and associated activities necessitate the disturbance of large areas of land, which must be stabilized and rehabilitated following mining operations. In central Queensland, Australia, the area disturbed by open-cut coal mining operations exceeds 50,000 ha (Welsh et al. 1994). The first step in mine-site rehabilitation is the design of the post-mining landform. This is also the most expensive component of the rehabilitation process as it involves extensive earthworks requiring heavy plant and equipment. Recent estimates of costs may range from $ 5,000 to $ 45,000 per hectare. The primary aim of the earthworks is to produce a post-mining landscape, which is resistant to geo-technical failure and to surface erosion processes from rainfall and runoff. The extent and cost of earthworks may be minimized, and rehabilitation failures avoided, if soil erosion from design landforms can be predicted prior to construction. Soil erosion prediction models have developed almost exclusively to solve erosion problems associated with agricultural land use. The surface media, topography and management practices on mines are very different to those found in agricultural settings, so it is unclear whether agriculturally based models will work under these different conditions.

The inherent soil characteristics affecting its susceptibility to erosion, the erodibility, is generally determined from field rainfall simulation or long term field plots (Middleton, et al. 1934; Barnett and Rogers 1966; Wischmeier and Mannering 1969; Elliot et al. 1989), where data collection are expensive and time consuming.

This research develops a methodology and modeling approach whereby data for the parameterization of hillslope scale, process based, erosion models can be collected at the laboratory scale. These data were used to develop a simple process based erosion model called MINErosion. The prediction of erosion from laboratory scale measurements, using the MINErosion model, will enable post-mining landscapes to be designed more efficiently and effectively, while at the same time reducing the costs of data collection for that purpose.

MATERIALS AND METHODS

Theoretical considerations

MINErosion models erosion as a simple steady-state process on uniform, unconsolidated, bare slopes of low surface roughness, where rill and interrill processes are potentially active. Rills are assumed to flow perpendicular to the contour with equal flow in each rill at a density of 1 rill/m (Gilley et al. 1990). The streampower required to detach sediment is assumed to be greater than the streampower required to transport that sediment. Therefore, rill sediment loads are assumed to be detachment limited (less than transport capacity) and no sediment deposition routines were used in the model.

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The steady-state equation of continuity (Foster et al. 1977) is used to describe sediment movement down a slope profile:

$$\frac{dE_t}{dL} = E_{rt} + E_i \qquad [1]$$

where E_t (kg/m.s) is the total sediment load, L (m) is the distance downslope, E_{rt} (kg/m^2.s) is the rill erosion rate and, E_i (kg/m^2.s) is the interill erosion rate.

Sediment load is therefore given by:

$$E_t = \int_{L1}^{L2} (E_{rt} + E_i)dL + E_{tL1} \qquad [2]$$

where E_{tL1} is the sediment load at L_1.

The interrill erosion rate (E_i) is then calculated following Kinnell, (1993);

$$Ei = Ki*I*Q*Sf*Cf \qquad [3]$$

where K_i (kg.s/m^4) is an interrill erodibility coefficient related to soil properties, and S_f and C_f are non-dimensional slope and cover adjustment factors respectively. S_f was calculated using a sigmoid function fitted to laboratory data:

$$Sf = c1+(c2/(1+exp(-(S2-c3)/c4))) \qquad [4]$$

where c_1, c_2, c_3, c_4 are constants and S_2 is the slope in radians. C_f was calculated from (NSERL, 1995);

$$C_f = e^{-2.5C} \qquad [5]$$

where C is assigned a value equal to the rock content, C_k (fraction by volume > 2mm) of the media.

The steady-state runoff rate *Q* (m/s) is calculated as the difference between the steady state rainfall rate, *I* (m/s) and the steady-state infiltration rate, I_r, (m/s);

$$Q = I - Ir \qquad [6]$$

where the steady-state infiltration rate is estimated from laboratory rainfall simulation data.

The rill erosion rate (E_{rt}) per plot is calculated as the erosion rate per rill (g/s), multiplied by the number of rills, and divided by the plot area. The erosion rate per rill is calculated as a power function of flow rate per rill, q_r (l/min), and rill slope *S* (fraction):

$$Er = Kr2*qra*S1.5a \qquad [7]$$

where K_{r2} and *a* are empirically determined coefficients representing rill erodibility (Kemper et al. 1985; Gilley et al. 1992). As the range of values for *a* turns out to be rather narrow for the materials examined, a mean value was calculated (1.60 ± 0.78) and a single value for rill erodibility was derived as:

$$K_{r3} = \frac{E_r}{q_r^{1.60} S^{2.40}} \qquad [8]$$

Equations 1 to 8 were used to calculate the potential soil loss from a combination of slope gradient and slope length for each soil or overburden material. These calculations were combined with relationships between erodibility and soil physico-chemical properties derived for the range of materials investigated, and incorporated into a user friendly Windows based application called “MINErosion”. This application provides a rapid estimation of the potential rates of soil loss from bare, unconsolidated material on a range of slope gradients and length.

Laboratory measurements

Sixteen soils and sixteen overburdens were collected by backhoe from 15 open-cut coalmines in Queensland and shipped in 200-liter drums to the Erosion Processes Laboratory at the University of Queensland. Each media was uniformly mixed in a 6 m^3 cement mixer and sieved to remove rocks greater than 5 cm diameter. Texture ranged from a heavy clay soil (58% clay) to a sandy loam soil (16% clay). Soil erosion experiments were conducted in this laboratory.

Rainfall with energy of 29.5 J m^{-2} mm^{-1} (Duncan, 1972) was applied over a tilting flume at 100 mm h^{-1} for 30 minutes to bare, unconsolidated plots (3m long, 0.8 m wide, and 0.15m deep) set at 20% slope. A rainfall simulator was set at the same slope, 2.2 m above the soil surface. Timed runoff samples were collected at eight intervals during the rainfall event, to determine runoff rate, sediment concentration, and sediment yield. The mean of the last four runoff measurements was used to calculate the steady-state sediment delivery rate and runoff rate for a given replicate. The steady-state infiltration rate was calculated as the difference between the rainfall rate and the steady-state runoff rate.

Slope gradient was then set to 5, 10, 15 and 30%, respectively, with four runoff samples collected during 12 minutes of simulated rainfall at each slope. The mean of the last two measurements was used to calculate the erosion rate for a given slope. The first run at 20° was conducted for 30 mins to ensure steady state was achieved. All other runs were steady state runs for 15 minutes and 4 measurements were considered adequate.

Following the last rainfall application, overland flow was added to the top of the plots at 20% slope at increasing rates ranging from 0.1 to 1.8 l/s. Rills were allowed to develop naturally over the plot surface. Each flow rate was held constant for three minutes and the sediment concentration of three runoff samples averaged to determine the sediment delivery at a given flow rate. Flow rates were increased until the maximum possible flow was attained, or until the flow-lines cut to the base of the flume.

Where possible, three replicates of the above experiments were carried out for each media giving a total of 91 replicates. The rainfall simulation data from the 10% rainfall experiments was used to estimate interrill erodibility, while the overland flow data from the 20% experiments was used to estimate rill erodibility coefficients.

Validation against field erosion measurements:

The model MINErosion was validated against results from field rainfall simulation experiments carried out on 15 Queensland open-cut coal mines on the same soils and overburdens as were used for the laboratory research (Loch et all, 1998). Rainfall was applied at 100 mm h^{-1} for 30 minutes, from a simulator of the same design as the laboratory simulator

Large replicate field erosion plots were set up to compare erosion rates from two slope gradients (37° and 20°) on the outer slopes of waste rock dumps at Kidston Gold Mine in Central Queensland. Plots were 20 m x 70 m long on the 37° slopes and 20 m x 130 m long on the 20° slopes, and covered with approximately 500 mm of soil material. Erosion was compared on plots with and without vegetation. Erosion was monitored with a combination of Gehrlach troughs, Parshal flumes, and sediment samplers on some plots, and large erosion collection pits on others. Data for selected erosion events from bare plots of the first and second years of monitoring were compared to predictions made using MINErosion.

RESULTS

The values for interrill erodibility (K_i), rill erodibility (K_{r3}), and steady state infiltration rate (I_r), estimated from laboratory flume and rainfall simulator experiments, are shown in Table 1. The standard errors for I_r and K_i are shown to the right of each estimated parameter value. Soils were generally more erodible to inter-rill erosion than overburdens, as many of the overburdens either contained considerable amounts of rock, or tended to seal strongly. The strongly aggregated high clay soils (eg. Blackwater, Curragh) tended to be the most erodible, followed by the lighter textured sandy loams and loamy sands (eg. Norwich Park and Peak Downs soils). Soils or overburdens with 20-30% silt tended to form strong, raindrop impact seals under rainfall and consequently had very low erodibilities (eg. Norwich Park overburden and Wandoan soil).

Inter-rill erodibility was found to vary by an order of magnitude from 0.54 x 10^6 kg s m^{-4} for an overburden from Blackwater to 6.01 x 10^6 kg s m^{-4} for a soil from Curragh. The tertiary overburden from Norwich Park recorded an inter-rill erodibility of only 0.09 x 10^6 kg s m^{-4} due to very high infiltration rate on this media (71 mm h^{-1}).

Table 1. Erosion model parameters determined from laboratory rainfall simulation experiments.

Mine site	Media No.	Media[a]	Infiltration I_r (mm/h)	s.e.	K_I (10^{-6} kg s m^{-4})	s.e.	K_{r3} ($a=1.6$)
Blair Athol	1	O	4.5	1.52	1.38	0.20	8.69
	2	S	2.72	1.10	2.31	1.10	7.09
Blackwater	3	O	8.86	1.69	0.54	0.05	0.88
	4	S	7.58	1.33	5.78	0.35	21.90
Calide	5	O	8.94	1.86	1.04	0.07	5.04
	6	S	14.24	4.04	1.68	0.55	22.76
Curragh	7	O	22.61	5.66	2.13	0.31	0.05
	8	S	16.84	3.34	6.01	0.33	11.07
German Ck	9	O	21.98	2.73	0.87	0.24	5.76
	10	S	20.41	1.03	4.04	0.80	8.19
Goonyella	11	O	15.64	4.06	3.05	0.06	0.07
	12	S	19.36	3.15	2.57	0.23	7.24
Gregory	13	O	18.21	1.67	1.63	0.20	3.75
	14	S	20.05	0.76	3.97	0.24	12.72
Moura1	15	O	5.46	4.20	0.98	0.21	1.74
	16	O	0.14	1.03	3.30	0.33	4.82
Moura2	17	S	8.03	1.74	2.28	0.20	8.24
Norwich Pk1	18	O	70.97	8.38	0.09	-	0.04
	19	O	14.10	0.30	2.87	0.22	0.21
Norwich Pk2	20	S	12.03	2.45	3.58	0.98	37.92
Newlands	21	O	13.01	1.99	0.88	0.13	7.53
	22	S	4.66	2.75	3.23	0.39	2.26
Oakey Ck	23	O	21.03	2.71	0.80	0.09	6.14
	24	S	10.06	0.64	2.94	0.94	9.24
Peak Downs	25	O	6.22	3.18	1.22	0.05	1.02
	26	S	6.86	2.88	1.22	0.10	33.15
Saraji	27	O	12.74	1.82	4.20	0.40	2.12
	28	S	5.84	1.63	2.25	0.21	12.43
Tarong	29	S	8.51	0.33	0.76	0.04	6.81
	30	S	7.06	2.48	1.05	0.21	9.30
Wandoan	31	O	8.15	3.73	3.12	0.32	0.18
	32	S	8.38	4.28	1.86	0.40	0.43

[a]S= soil and O = overburden.

Consequently the value does not reflect the physical nature of the erodibility parameter, which should primarily represent the detachability and transportability of the soil particles and aggregates. There was a clear trend for the fine sandy soils (e.g. Norwich Park) and the well-aggregated clay soils (e.g. Blackwater) to be the most susceptible to inter-rill erosion. Rocky overburdens tended to have very low inter-rill erodibilities, even though the effect of rocks >2mm was accounted for in the cover factor (Eq. 5). The range of inter-rill erodibility values recorded during this study are similar to the range of values reported in the WEPP Compendium for agricultural soils (NSERL, 1989) (0.87×10^6 kg s m^{-4} for a Bonifay soil to 4.32×10^6 kg s m^{-4} for a Palouse soil).

Rill erodibility could not be determined for five of the overburdens, as these media formed strong surface seals which resisted rill initiation even at the highest overland flow rate possible (2.5 l s^{-1}) with the laboratory equipment. Rill erodibility values varied by approximately 3 orders of magnitude, from 0.04 for the overburden from Norwich Park mine to 37.92 for a soil, also from Norwich Park.

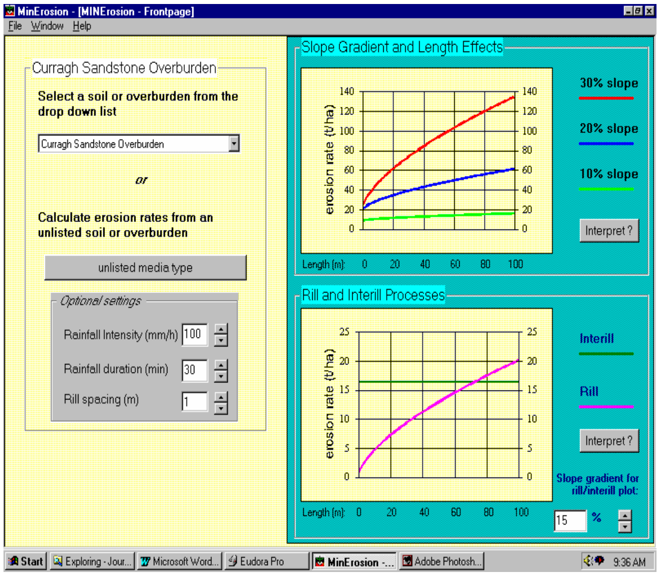
The MINErosion model

The output from the MINErosion model are displayed as graphs showing (a) erosion rates as affected by slope gradient and slope length, and (b) rill and inter-rill erosion rates as affected by slope gradient and slope length. With these outputs, environmental officers can readily select the combination of slope gradients and lengths that can limit erosion rates to acceptable values. An example of the output is shown in Fig. 1.

Comparison to field rainfall simulator plots and field erosion plots

Sediment delivery rates predicted using MINErosion was compared to data collected from field rainfall simulation experiments on the same materials (Loch et all, 1998). Fig. 2 shows a highly significant relationship (r^2=0.70) between predicted and measured sediment delivery rates. Although MINErosion underestimate field erosion rates by 20%, the high value of the coefficient of determination allows this model to be used for predictive purposes.

The model was also used to predict erosion rates from very steep outer slopes of waste rock dumps at Kidston Gold mine in central Queensland. As the slopes and slope lengths on this experiment were greater than the range of values used in the MINErosion, the model was used to derive sediment delivery rates or erosion rates from a fixed slope length as a function of slope gradient (data points in Figure 3). An appropriate curve was fitted to these points and was used to derive erosion rates at the angle of repose (75% slope). Figure 3 shows that the model predicts erosion rates on the 70 m, 37° slopes accurately in the first year, but underestimated the erosion rate from the 130 m, 20° slope by approximately 100%. The high rate of erosion from the latter appears to be caused by mass flow associated with the large volume of run-off water accumulated at the lower parts of the slope, which was unconsolidated at that time. This was not observed on the shorter and steeper slopes. In the second year, the surfaces were significantly consolidated from the wetting and drying cycles during the year and mass flow did not occur to any significant extend. Hence the prediction for the second year matched the observed erosion rates very well. The greater loss of erodible materials during the first year from the shorter and steeper slopes and consolidation during the year resulted in no observable changes on these slopes in the second year. Erosion was limited to inter-rill processes only and no significant soil loss occurred.



Select a soil or overburden from the drop down list

Curragh Sandstone Overburden

Calculate erosion rates from an unlisted soil or overburden

Rainfall Intensity (mm/h) 100

Rainfall duration (min) 30

Rill spacing (m) 1

Slope gradient for rill/interill plot: 15 %

Figure 1: The graphical user interface for the MINErosion model, showing the drop down list for selection of mine site and media type.

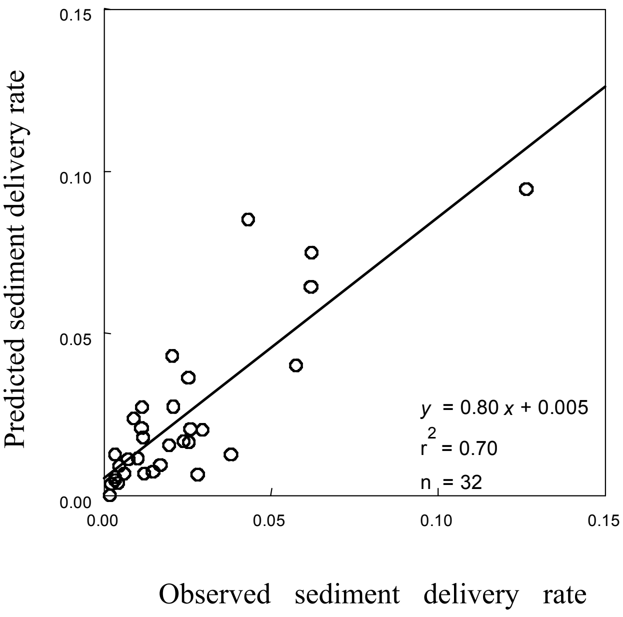


Figure 2: Plot of predicted and observed field sediment delivery rates.

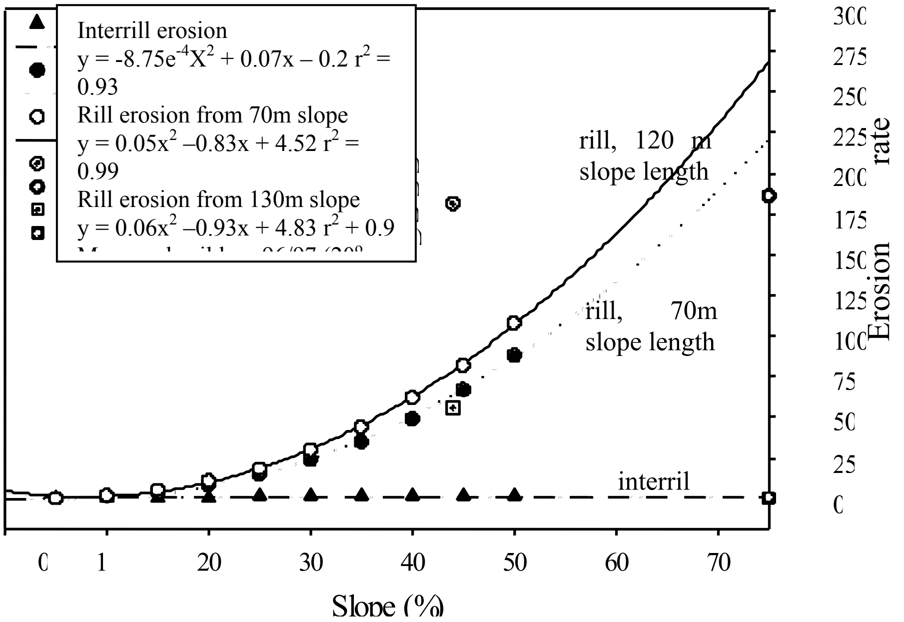


Figure 3: Predicted rill and inter-rill erosion rates from the outer slopes of waste rock dumps at Kidston Gold Mine, Queensland, Australia.

CONCLUSION

In conclusion, the simple steady state erosion model MINErosion, developed in this paper proves adequate to predict hillslope scale erosion from laboratory-based measurements, on the highly disturbed materials associated with open cut mining activities.

ACKNOWLEDGEMENTS

Support for this work was received from the Australian Coal Association Research Program, BHP Coal Pty Ltd, MIM Holdings Ltd, Pacific Coal Pty Ltd, Curragh Queensland Mining Ltd, Callide Coalfields Pty Ltd, Capricorn Coal Management Pty, and Kidston Gold Mine Ltd.

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