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# Use of laboratory-scale rill and interill erodibility measurements for the prediction of hillslope-scale erosion on rehabilitated coal mine soils and overburdens

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*Abstract*

Prediction of hillslope-scale soil erosion traditionally involves extensive data collection from field plots under natural rainfall, or from field rainfall simulation programs. Recognising the high costs and inconvenience associated with field-based studies, 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 were used to determine rill and interill erodibility coefficients for 32 soils and overburdens from Queensland open-cut coal mines. Predicted sediment delivery rates based on laboratory determinations of erodibility were tested against field measurements of erosion from 12-m-long plots under simulated rainfall at 100 mm/h on slopes ranging from 5% to 30%. Regression analysis demonstrated a strong relationship between predicted and measured sediment delivery rates, giving an $r^2$ value of up to 0.74, depending on the particular modeling approach used. These results demonstrate that soil losses due to the combined processes of rill and interill erosion at the hillslope scale can successfully be predicted from laboratory-scale measurements of erodibility, provided a suitable methodology and modelling approach is adopted. The success of this approach will greatly reduce the cost and effort required for prediction of hillslope scale soil erosion.

*Additional keywords*: critical shear, flume, mine-site, rainfall simulation, spoil, WEPP.

## Introduction

In Queensland, the area disturbed by open-cut coal mining exceeds 50 000 ha (Welsh *et al.* 1994), with much of that area required to be rehabilitated. The first step during mine-site rehabilitation is to design a post-mining landform. Costs for rehabilitation range from $AU5000 to $25 000/ha (Bell *et al.* 1993), with the most expensive component of the rehabilitation process being re-shaping of overburden spoildumps to create a suitable landform for rehabilitation. Landform construction typically involves extensive earthworks to produce a post-mining landscape that is resistant to geo-technical failure and surface erosion processes by rainfall and runoff. The extent and cost of earthworks may be minimised, 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 from those found in agricultural settings,

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so it is unclear whether agriculturally based models will work under these different conditions. Rubio-Montoya and Brown (1984) found that the universal soil loss equation (USLE) significantly over-predicted observed erosion rates from strip-mine areas along the Gulf Coast of the USA. However, Wu *et al.* (1996) reported that the ANSWERS model performed on overburdens with about the same accuracy as it did on agricultural lands.

The level of erosion from mined land is frequently reported as lower than that found on similar landforms in agricultural areas. Gilley *et al.* (1977) reported low rates of erosion from overburdens on North Dakota surface mine sites, and Mitchell *et al.* (1983) compared erosion rates on newly reclaimed topsoils with unmined areas and found the reclaimed sites to be less erodible. Evans (1992) found the physical and chemical characteristics of mine overburdens to be different from that of agricultural soils, resulting in significant differences in erodibility.

Of all the factors affecting erosion, erodibility is the most difficult to quantify. Erodibility is generally estimated using soil loss data from either field rainfall simulation or long-term field plots (Middleton *et al.* 1934; Barnett and Rogers 1966; Wischmeier and Mannering 1969; Elliot *et al.* 1989). Hence, data collection is generally expensive and time-consuming. In an effort to simplify this, some researchers have used laboratory rainfall simulation and tilting flumes to determine erodibility (Verhaegen 1987; Evans 1992). The use of laboratory scale measurements for prediction of hillslope-scale erosion offers many technical advantages and considerable cost savings over traditional data collection methods for erosion prediction. However, there has been limited success in the parameterisation of predictive hillslope scale models, usually due to the inadequate representation and separation of the relevant erosion processes (Trieste and Gifford 1980; Foster *et al.* 1981).

A methodology and modelling approach is proposed and tested whereby data for the parameterisation of hillslope-scale, process-based, erosion models can be collected at the laboratory scale. The prediction of erosion from laboratory-scale research will enable post-mining landscapes to be designed more efficiently and effectively, while at the same time reducing research costs.

## Materials and methods

### *Laboratory measurements*

Sixteen soils and 16 overburdens were collected by back-hoe from 15 open-cut coal mines in Queensland (Fig. 1). Each medium was uniformly mixed in a 6-$m^3$ cement mixer and sieved to remove rocks >5 cm diameter. The texture of the soils and overburdens was then determined by the sedimentation and pipette technique described by Day (1965).

Soil erosion experiments were conducted at the Erosion Processes Laboratory, The University of Queensland. Rainfall was applied over a tilting flume at 100 mm/h for 30 min to bare, unconsolidated plots, 3 m long, 0.8 m wide, and 0.15 m deep at 20% slope. A rainfall simulator was set at the same slope, 2.2 m above the soil surface. The rainfall simulator, supplied by de-ionised water, produced rainfall from 4 fan-shaped nozzles (80100 Veejet®) swept intermittently across the plot. A range of estimates of kinetic energy has been given for the Veejet 80100 nozzle, with possibly the most accurate assessment coming from Duncan (1972), who measured drop velocities directly and found that with a fall height of 2.4 m, the smaller drops had velocities greater than the terminal velocities of similar-sized drops in still air, so that rainfall kinetic energy calculated for the Veejet 80100 nozzle on the basis of measured drop size and velocity was 295 kJ/ha.mm.

Timed runoff samples were collected at 8 intervals during the rainfall event, weighed, oven-dried at 105°C, and re-weighed to determine runoff rate, sediment concentration, and sediment yield. The mean of the last 4 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.

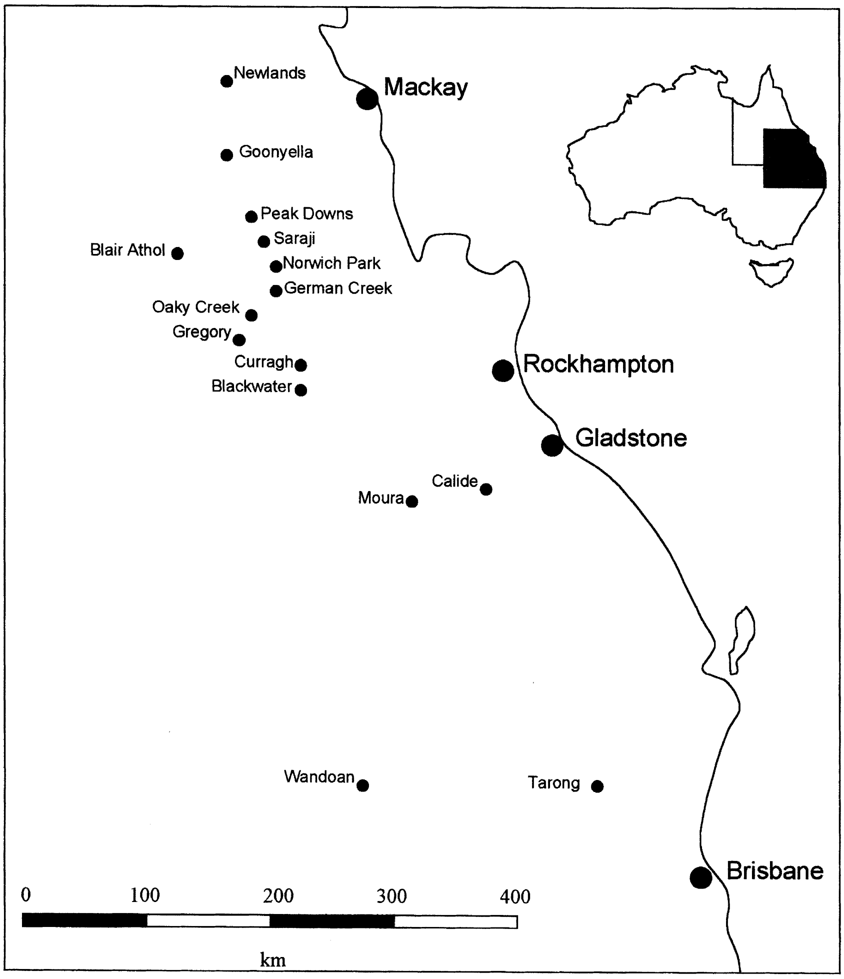


**Fig. 1.** Map showing the location of the Queensland open-cut minesites involved in this research.

Slope gradient was then set to 5, 10, 15, and 30%, respectively, with 4 runoff samples collected during 12 min of simulated rainfall at 100 mm/h being applied at each slope. The mean of the last two runoff samples from each slope was used to calculate the steady-state erosion rate for that slope. Following the final 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 3 min and the sediment concentration of 3 runoff samples taken at 1-min intervals 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, 3 replicates of the above experiments were carried out for each media, giving a total of 91 replicates. Data from rainfall simulation at 10% slope were used to estimate interill erodibility, and data from the overland flow experiments at 20% slope were used to estimate rill erodibility coefficients.

*Field measurements*

Rainfall simulation experiments were carried out at 15 Queensland open-cut coal mines on the same soils and overburdens as were used for the laboratory research. Rainfall was applied at 100 mm/h for 30 min, using a simulator of the same design as the laboratory simulator. Bare field plots measured 12 m long and 1.5 m wide, with the average slope gradient ranging from 5% to 30%. Plots were lightly tilled by hand raking prior to rainfall to produce a loose surface of low surface roughness and an approximately even slope gradient. The number of replicates on each medium varied depending on the variability of the plot and availability of appropriate rainfall simulation sites, resulting in a total of 113 field simulation plots. Runoff rates were measured using computer-logged tipping buckets. Sediment concentrations were measured as described for the laboratory procedure. The texture of the media was determined to confirm that the field erosion events were carried out on the same media as the laboratory experiments.

*Soil erosion equations*

Two modelling approaches were tested to allow laboratory measurements of rill and interill soil erosion to be used for prediction of soil erosion rates observed at the hillslope scale. For both approaches, erosion is modelled as a time-invariant steady-state process on a uniform, unconsolidated, bare slope of low surface roughness. Only rill and interill 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. As a result of this, and the simple linear slope shapes being modelled, rill sediment loads are assumed always to be detachment-limited (less than transport capacity) and no sediment transport routines were used for either model. The two modelling approaches tested differ with respect to the way rill erosion is modelled. The relevant equations are presented below.

The steady-state runoff rate $Q$ (m/s) may be calculated as the difference between the steady-state rainfall rate, $I$ (m/s), and the steady-state infiltration rate, $I_r$ (m/s):

$$Q = I - I_r \tag{1}$$

where the steady-state infiltration rate is estimated from laboratory rainfall simulation data. The steady-state continuity equation (Foster *et al.* 1977) may be used to describe sediment movement down a slope profile:

$$\frac{\partial Et}{\partial L} = E_{rt} + E_i \tag{2}$$

where $E_t$ (kg/m.s) is the 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:

$$E_t = \int_{L1}^{L2} (E_{rt} + E_i)\,dL + E_{tL1} \tag{3}$$

where $E_{tL1}$ is the sediment load at $L$ =1. The interill erosion rate ($E_i$) may be calculated from (Kinnell 1993):

$$E_i = K_i{*}I{*}Q{*}S_f{*}C_f \tag{4}$$

where $K_i$ (kg.s/m$^4$) is an interill erodibility coefficient related to soil properties, and $S_f$ and $C_f$ are non-dimensional slope and cover adjustment factors, respectively, and may be calculated from (NSERL 1995):

$$S_f = 1.05 - 0.85 \exp(-4 \sin (S_2)) \tag{5}$$

$$C_f = e^{-2.5C} \tag{6}$$

where $S_2$ is the slope in radians, and $C$ is assigned a value equal to the rock content (fraction by volume >2 mm) of the media.

The rill erosion rate ($E_{rt}$) per plot may be calculated from the erosion rate *per rill*, multiplied by the number of rills, and divided by the plot area. In this study, the erosion rate per rill is estimated using two contrasting approaches.

Firstly, the erosion rate *per rill* may be estimated using the critical-shear based approach (as taken in the Water Erosion Prediction Project, or WEPP model). The WEPP model is fully described by Nearing *et al.* (1989); however, under the simple conditions used for this study, detachment capacity of rill flow may be estimated by the shear-based equation:

$$D_c = K_r(\tau - \tau_c) \quad (7)$$

where $D_c$ (kg/m$^2$.s) is the detachment capacity of the flow, $K_r$ (s/m) is the rill erodibility of the soil, $\tau_c$ (Pa) is the shear below which there is no detachment, and $\tau$ (Pa) is the hydraulic shear of the flowing water. Rill erodibility parameters $K_r$ and $\tau_c$ are determined experimentally from the measured erosion rates at a range of flow shear values. The rill erosion rate is plotted against the calculated shear for each of the flow rates. The slope of the regression line is the rill erodibility, $K_r$ and the intercept with the horizontal axis is the critical shear, $\tau_c$. Flow hydraulic shear is calculated as per the WEPP Technical Documentation (NSERL 1995).

Alternatively to Eqn 7, the sediment delivery rate *per rill*, $E_r$ (g/s), may be calculated as a power function of flow rate per rill, $q_r$ (L/min), and rill slope, $S_3$ (fraction):

$$E_r = K_{r2} * q_r^{a} * S_3^{1.5a} \quad (8)$$

where $K_{r2}$ and $a$ are empirically determined non-linear regression coefficients representing soil properties, calculated (SAS Institute Inc. 1988) from the measured erosion rates at a range of flow rates (Kemper *et al*. 1985; Gilley *et al.* 1992).

## Results

### *Media properties*

The range of textures of the laboratory soils and overburdens is shown in Fig. 2. Media (soil and overburden) texture ranged from a heavy clay soil (58% clay) from Curragh mine to a sandy loam soil (16% clay) at Norwich Park. Soils were generally more

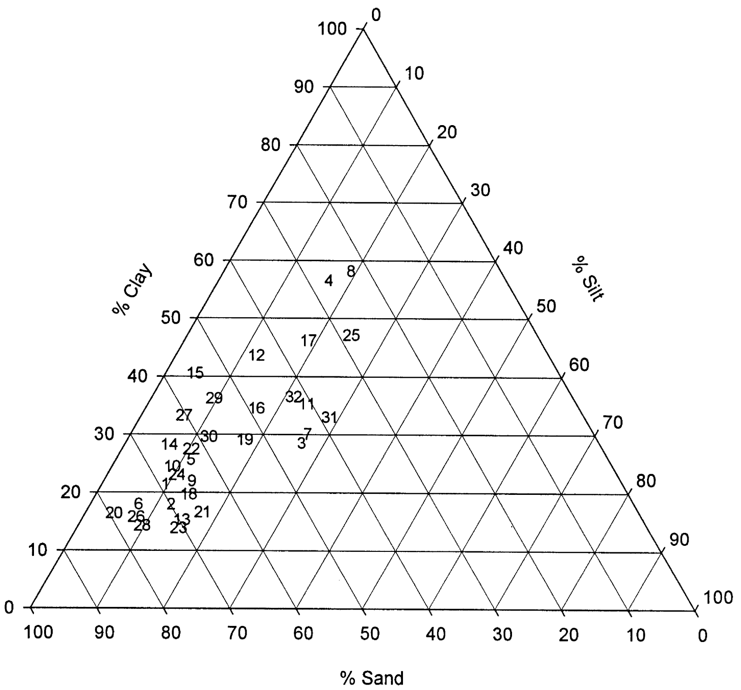


**Fig. 2.** Texture triangle showing the texture of the <2 mm portion of the laboratory media. Plotted numbers correspond to the numbered media in Table 1.

erodible than overburdens, as many of the overburdens either contained considerable amounts of rock, or tended to seal strongly. The strongly aggregated high clay soils (e.g. Blackwater and Curragh) tended to be the most erodible, followed by the lighter textured sandy loams and loamy sands (e.g. 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 (e.g. Norwich Park overburden and Wandoan soil).

*Critical-shear based model*

The values for interill erodibility ($K_i$), rill erodibility ($K_r$), critical shear ($\tau_c$), and steady state infiltration rate ($I_r$), estimated from laboratory flume and rainfall simulator experiments, are shown in Table 1. The standard error is shown to the right of each estimated parameter value. The $r^2$ value represents the fit of the regression of soil loss against shear for the estimation of the $K_r$ and $\tau_c$ parameters.

Interill erodibility was found to vary by approximately an order of magnitude from $0.54 \times 10^6$ kg.s/m$^4$ for an overburden from Blackwater to $6.01 \times 10^6$ kg.s/m$^4$ for a soil from Curragh. The tertiary overburden from Norwich Park (media No. 18 in Table 1) recorded an interill erodibility of only $0.09 \times 10^6$ kg.s/m$^4$; however, this is due to the

**Table 1. Infiltration rates, interill erodibilities, and critical-shear based erosion model parameters determined from laboratory rainfall simulation experiments**
S, soil; O, overburden

| Mine site | Media No. | Media | Infiltration (mm/h) | s.e. | $10^{-6} \times K_i$ (kg.s/m$^4$) | s.e. | $10^3 \times K_r$ (s/m) | s.e. | $\tau_c$ (Pa) | s.e. | $r^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Blair Athol | 1 | O | 4.5 | 1.52 | 1.38 | 0.20 | 21.1 | 3.0 | 12.5 | 0.82 | 0.61*** |
| | 2 | S | 2.72 | 1.10 | 2.31 | 1.10 | 16.3 | 2.2 | 11.3 | 0.92 | 0.65*** |
| Blackwater | 3 | O | 8.86 | 1.69 | 0.54 | 0.05 | 4.7 | 2.5 | 16.7 | 1.15 | 0.12n.s. |
| | 4 | S | 7.58 | 1.33 | 5.78 | 0.35 | 34.8 | 3.0 | 9.7 | 0.55 | 0.83*** |
| Calide | 5 | O | 8.94 | 1.86 | 1.04 | 0.07 | 17.9 | 2.3 | 14.6 | 1.08 | 0.77*** |
| | 6 | S | 14.24 | 4.04 | 1.68 | 0.55 | 30.6 | 2.2 | 14.0 | 0.44 | 0.88*** |
| Curragh | 7 | O | 22.61 | 5.66 | 2.13 | 0.31 | n.d. | n.d. | n.d. | n.d. | n.d. |
| | 8 | S | 16.84 | 3.34 | 6.01 | 0.33 | 46.5 | 6.5 | 19.3 | 1.16 | 0.76*** |
| German Ck | 9 | O | 21.98 | 2.73 | 0.87 | 0.24 | 7.2 | 3.4 | 1.6 | 1.43 | 0.11* |
| | 10 | S | 20.41 | 1.03 | 4.04 | 0.80 | 5.1 | 4.6 | 18.0 | 1.82 | 0.05n.s. |
| Goonyella | 11 | O | 15.64 | 4.06 | 3.05 | 0.06 | n.d. | n.d. | n.d. | n.d. | n.d. |
| | 12 | S | 19.36 | 3.15 | 2.57 | 0.23 | 25.1 | 6.4 | 13.6 | 1.39 | 0.79* |
| Gregory | 13 | O | 18.21 | 1.67 | 1.63 | 0.20 | 4.6 | 3.2 | 9.4 | 2.08 | 0.09n.s. |
| | 14 | S | 20.05 | 0.76 | 3.97 | 0.24 | 44.3 | 8.8 | 13.8 | 0.60 | 0.57*** |
| Moura1 | 15 | O | 5.46 | 4.20 | 0.98 | 0.21 | 8.6 | 3.1 | 20.9 | 1.74 | 0.28* |
| | 16 | O | 0.14 | 1.03 | 3.30 | 0.33 | 28.3 | 4.1 | 23.0 | 0.66 | 0.65*** |
| Moura2 | 17 | S | 8.03 | 1.74 | 2.28 | 0.20 | 19.2 | 3.6 | 13.6 | 1.06 | 0.66*** |
| Norwich Pk1 | 18 | O | 70.97 | 8.38 | 0.09 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| | 19 | O | 14.10 | 0.30 | 2.87 | 0.22 | n.d. | n.d. | n.d. | n.d. | n.d. |
| Norwich Pk2 | 20 | S | 12.03 | 2.45 | 3.58 | 0.98 | 85.4 | 15.3 | 11.7 | 0.64 | 0.76*** |
| Newlands | 21 | O | 13.01 | 1.99 | 0.88 | 0.13 | 39.5 | 5.7 | 21.1 | 0.81 | 0.67*** |
| | 22 | S | 4.66 | 2.75 | 3.23 | 0.39 | 10.7 | 1.3 | 20.1 | 1.04 | 0.77*** |
| Oakey Ck | 23 | O | 21.03 | 2.71 | 0.80 | 0.09 | 17.1 | 4.9 | 10.6 | 1.29 | 0.33** |
| | 24 | S | 10.06 | 0.64 | 2.94 | 0.94 | 20.9 | 2.5 | 12.0 | 0.55 | 0.77*** |
| Peak Downs | 25 | O | 6.22 | 3.18 | 1.22 | 0.05 | 11.5 | 2.8 | 28.9 | 1.07 | 0.63** |
| | 26 | S | 6.86 | 2.88 | 1.22 | 0.10 | 45.9 | 3.9 | 9.6 | 0.60 | 0.81*** |
| Saraji | 27 | O | 12.74 | 1.82 | 4.20 | 0.40 | 14.2 | 4.2 | 23.1 | 1.27 | 0.36** |
| | 28 | S | 5.84 | 1.63 | 2.25 | 0.21 | 12.9 | 1.4 | 4.7 | 0.97 | 0.70*** |
| Tarong | 29 | S | 8.51 | 0.33 | 0.76 | 0.04 | 14.4 | 2.0 | 8.9 | 0.92 | 0.71*** |
| | 30 | S | 7.06 | 2.48 | 1.05 | 0.21 | 21.3 | 2.5 | 14.4 | 0.94 | 0.74*** |
| Wandoan | 31 | O | 8.15 | 3.73 | 3.12 | 0.32 | n.d. | n.d. | n.d. | n.d. | n.d. |
| | 32 | S | 8.38 | 4.28 | 1.86 | 0.40 | 1.3 | 0.6 | 7.1 | 1.88 | 0.15n.s. |

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; n.s., not significant. n.d., not determined.

extremely high infiltration rate on this medium (71 mm/h). Only 1 replicate of this medium produced runoff during the rainfall event. 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 interill erosion. Rocky overburdens tended to have very low interill erodibilities, even though the effect of rocks >2 mm was accounted for in the cover factor (Eqn 6) of the interill equation (Eqn 4).

The range of interill erodibility values recorded during this study is similar to the range of values reported in the WEPP Compendium (NSERL 1989) ($0.87 \times 10^6$ kg.s/m$^4$ for a Bonifay soil to $4.32 \times 10^6$ kg.s/m$^4$ for a Palouse soil), although does not approach the lower range of expected rangeland values ($0.01 \times 10^6$ kg.s/m$^4$) reported in the WEPP User Summary (NSERL 1994). This suggests that the degree of variability in the interill erodibility parameter found in this study is similar to that found by other researchers working with agricultural soils.

Rill erodibility could not be determined for 5 of the overburdens, as these media formed strong surface seals that resisted rill initiation even at the highest overland flow rate possible (2.5 L/s) with the laboratory equipment. A further 9 media produced results where the $r^2$ for the estimation of $K_r$ and $\tau_c$ was not significant or was low ($r^2 <$ 0.60). For the remaining 18 media, rill erodibility was found to vary by approximately a factor of 8, from $10.7 \times 10^{-3}$ s/m for a soil from Newlands, to $85.4 \times 10^{-3}$ s/m for a soil from Norwich Park. However, the Norwich Park soil was a highly erodible outlier, with the next highest $K_r$ value being $46.5 \times 10^{-3}$ s/m for a soil from Curragh. The Norwich Park soil aside, these values are similar in range to those reported in the WEPP compendium ($1.18 \times 10^{-3}$ s/m to $45.30 \times 10^{-3}$ s/m), although the mean value for $K_r$ from this study is somewhat higher, suggesting that, on average, the mine site media are more susceptible to rill erosion than the soils recorded in the WEPP compendium (NSERL 1989).

Measured critical shear ($\tau_c$) values for rill detachment varied from 4.7 Pa for a soil from Saraji to 28.9 Pa for an overburden from Peak Downs. Detachment could not be initiated on 5 media at shear values of 40 Pa. WEPP compendium values range from 0.7 to 6.6 Pa. The critical shear values for the media studied are very high compared with the WEPP compendium (NSERL 1989) values, reflecting the sealing and hardsetting nature of the media.

Sediment delivery rates based on laboratory determinations of erodibility and the critical-shear based erosion equations were tested against field data from a total of 113 rainfall simulation events carried out on 15 mine-sites. The relationship between predicted and measured sediment delivery rates is shown in Fig. 3*a* and *b*. Regression analysis demonstrated a reasonable relationship ($r^2 = 0.64$) and a slope of 0.6 between predicted and measured sediment delivery rates. Hence, the critical-shear based model generally under-predicted erosion rates under these experimental conditions.

### *Flow-rate based model*

Laboratory and field results were also compared using a flow-rate based power function to model rill detachment (Eqn 8) instead of the shear based approach (Eqn 7). All other model parameters were calculated as described previously. The coefficents $a$ and $K_{r2}$ in Eqn 8 were calculated for each media from laboratory overland flow data at 20% slope

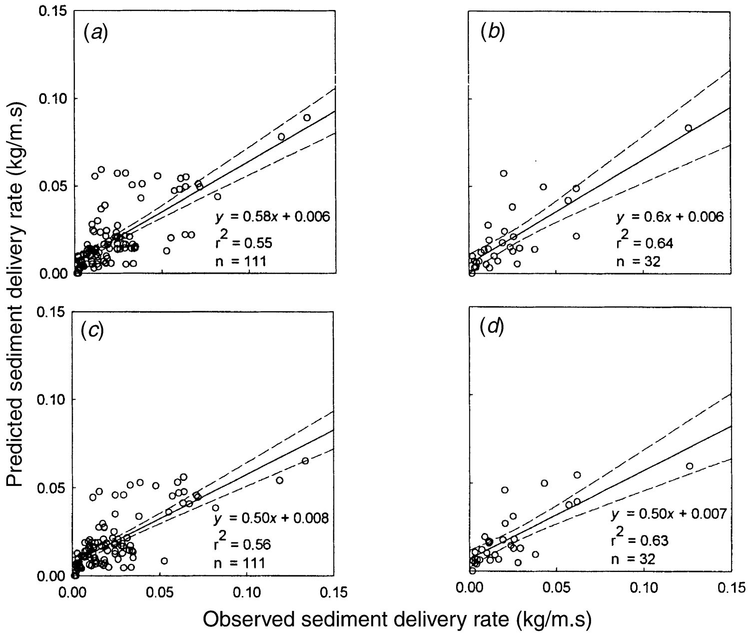


**Fig. 3.** Plots of observed and predicted field sediment delivery rates for the critical shear-based rill model (*a*,*b*) and the flow-rate based rill model (*c*,*d*). Plots on the right have been averaged (mean) by media type. The regression line and the 95% confidence lines are also shown.

(Table 2). An average value for $a$ of 1.60 (s.d. = 0.78) was determined and rill erodibility ($K_{r3}$) was subsequently calculated from:

$$K_{r3} = \frac{E_r}{q_r^{1.60} S_3^{2.40}} \tag{9}$$

The simplifcation of Eqn 8 to Eqn 9 allows rill erodibility to be represented by a single coefficent, $K_{r3}$. The reduction in the predictive ability ($r^2$ value) of the non-linear rill model due to this simplification is shown in Table 2.

Flow-rate based 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. These findings compare with analysis by Gilley *et al.* (1992) of the WEPP data set using a value of 1.18 for $a$ giving a range of the $K_{r2}$ parameter from 6.9 to 220. The higher $K_{r2}$ values found by Gilley partially reflect the compensating effect of the lower exponents used on flow and slope in that study.

Predicted sediment delivery rates based on laboratory determinations of erodibility and the flow-rate based erosion equations were tested against the data collected using the field rainfall simulator. The relationship between predicted and measured sediment delivery rates is shown in Fig. 3*c* and *d*. Regression analysis demonstrated a similar relationship ($r^2$ = 0.63 and a slope of 0.50) to that found using the shear-based model, resulting in an under-prediction of field erosion rates.

**Table 2. Rill erodibility parameters for the non-linear flowrate based rill model (Eqns 8 and 9)**

S, soil; O, overburden; the coefficents $a$ and $K_{r2}$ (Eqn 8) were calculated for each media and an average value for $a$ of 1.60 was used to calculate rill erodibility $K_{r3}$ for Eqn 9. The simplifcation of Eqn 8 to Eqn 9 allows rill erodibility to be represented by a single coefficent, $K_{r3}$. The reduction in the predictive ability ($r^2$ value) of the non-linear rill model due to this simplification is shown below

| Mine site | Media | $K_{r2}$ | $a$ | $r^2$ | $K_{r3}$ ($a$ = 1.6) | $r^2$ | Reduction in $r^2$ |
|---|---|---|---|---|---|---|---|
| Blair Athol | O | 8.76 | 1.67 | 0.73 | 8.69 | 0.73 | 0.00 |
| | S | 8.71 | 1.55 | 0.82 | 7.09 | 0.81 | 0.00 |
| Blackwater | O | 0.88 | 1.68 | 0.21 | 0.88 | 0.21 | 0.00 |
| | S | 27.12 | 1.48 | 0.89 | 21.90 | 0.89 | 0.01 |
| Calide | O | 1.60 | 2.27 | 0.94 | 5.04 | 0.91 | 0.02 |
| | S | 32.12 | 1.33 | 0.94 | 22.76 | 0.90 | 0.04 |
| Curragh | O | 0.53 | 0.41 | 0.12 | 0.05 | –0.37[A] | 0.50 |
| | S | 6.71 | 1.94 | 0.85 | 11.07 | 0.84 | 0.01 |
| German Ck | O | 12.96 | 1.21 | 0.57 | 5.76 | 0.54 | 0.04 |
| | S | 34.60 | 0.57 | 0.29 | 8.19 | –0.50[A] | 0.80 |
| Goonyella | O | 0.59 | 0.12 | 0.02 | 0.07 | –1.70[A] | 1.72 |
| | S | 1.85 | 2.59 | 0.90 | 7.24 | 0.85 | 0.05 |
| Gregory | O | 28.26 | 0.50 | 0.23 | 3.75 | –0.31[A] | 0.55 |
| | S | 6.28 | 2.27 | 0.61 | 12.72 | 0.58 | 0.03 |
| Moura1 | O | 0.13 | 2.88 | 0.56 | 1.74 | 0.52 | 0.04 |
| | O | 0.32 | 3.22 | 0.77 | 4.82 | 0.68 | 0.09 |
| Moura2 | S | 8.87 | 1.62 | 0.74 | 8.24 | 0.74 | 0.00 |
| Norwich Pk1 | O | 0.06 | 1.48 | 0.61 | 0.04 | 0.60 | 0.00 |
| | O | 2.10 | 0.10 | 0.00 | 0.21 | –0.15[A] | 0.15 |
| Norwich Pk2 | S | 26.67 | 2.07 | 0.88 | 37.92 | 0.85 | 0.03 |
| Newlands | O | 2.61 | 2.25 | 0.79 | 7.53 | 0.75 | 0.03 |
| | S | 1.12 | 2.04 | 0.90 | 2.26 | 0.89 | 0.01 |
| Oakey Ck | O | 19.76 | 0.98 | 0.41 | 6.14 | 0.30 | 0.10 |
| | S | 8.97 | 1.71 | 0.82 | 9.24 | 0.82 | 0.00 |
| Peak Downs | O | 0.05 | 3.10 | 0.83 | 1.02 | 0.78 | 0.06 |
| | S | 51.54 | 1.27 | 0.84 | 33.15 | 0.81 | 0.04 |
| Saraji | O | 0.82 | 2.12 | 0.55 | 2.12 | 0.54 | 0.01 |
| | S | 30.18 | 0.84 | 0.79 | 12.43 | 0.46 | 0.33 |
| Tarong | S | 6.23 | 1.73 | 0.83 | 6.81 | 0.83 | 0.00 |
| | S | 16.17 | 1.23 | 0.83 | 9.30 | 0.77 | 0.06 |
| Wandoan | O | 0.48 | 1.09 | 0.35 | 0.18 | 0.31 | 0.04 |
| | S | 0.48 | 1.62 | 0.60 | 0.43 | 0.60 | 0.00 |

[A] $r^2$ value may be negative as non-linear model is not necessarily nested within data.

### *Interill slope adjustment function*

The interill slope adjustment factor $S_f$ (Eqn 5) used in the calculation of interill erodibility was replaced with a sigmoid interill slope adjustment function $S_{f2}$; fitted to laboratory data:

$$S_{f2} = c_1+\{c_2/[1+\exp(-(S_2-c_3)/c_4)]\} \quad (10)$$

where $c_1$, $c_2$, $c_3$, and $c_4$ are empirically derived coefficients fitted to the laboratory data from the 5, 10, 15, 20, and 30% slope experiments. Thus, interill sediment delivery rate was predicted from:

$$E_i = K_i{*}I{*}Q{*}S_{f2}{*}C_f \quad (11)$$

Fig. 4*a* and *b* compares observed and predicted erosion rates as a result of the replacement of Eqn 4 with Eqn 11 for both models. The $r^2$ increases to 0.74 and the slope of the regression line is not significantly different from 1, and the intercept not significantly different from zero, at $P = 0.05$.

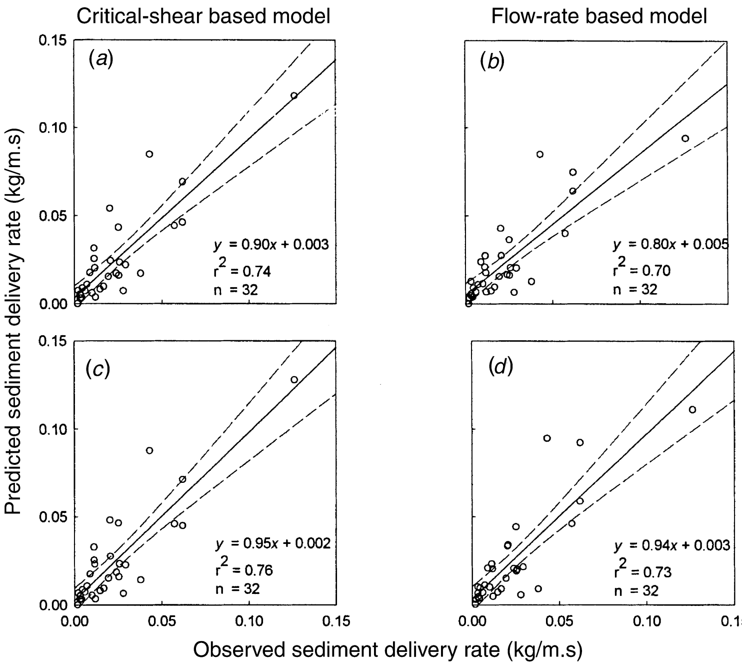


**Fig. 4.** Plot of the predicted and observed field sediment delivery rates for the critical-shear based (*a*,*c*) and flow-rate based (*b*,*d*) erosion models. Predicted values plotted in *a* and *b* incorporated a sigmoid interill slope adjustment function, and in *c* and *d*, laboratory estimates of runoff have been replaced with field runoff rates. The regression line and the 95% confidence lines are also shown.

Fig. 4*c* and *d* compares the observed and predicted rates when the fitted slope function is used and *Q* in Eqn 1 is replaced with measured field runoff rates. Regression analysis demonstrated a slight improvement in prediction ($r^2 = 0.76$) over the use of laboratory estimates of infiltration rate.

## Discussion

The results show that the critical-shear based model (Fig. 3*a* and *b*) and the non-linear flow based model (Fig. 3*c* and *d*) produced similar predictions of sediment delivery rates from field rainfall simulation plots. This result suggests that rill erosion can effectively be modelled as either a linear (with a non-zero intercept) or a non-linear process. Rill erosion is commonly modelled as a linear function of shear stress (Nearing *et al.* 1989), although empirical evidence (Gilley *et al.* 1992) and theoretical investigations (Kemper *et al.* 1985) suggest this relationship is often non-linear. Nearing (1994) stresses that the parameters $\tau_c$ and $K_r$ (Eqn 7) are mathematical entities resulting from a linearisation of the commonly non-linear relationship between detachment and shear stress, and warns against a physical linear interpretation. A comparison of the $r^2$ values for the estimation of the rill erodibility parameters from the laboratory overland flow data (Tables 1 and 2) reveals the non-linear equation fits better for 30 of the 32 media tested. However, this did not result in better field predictions from the non-linear model.

A significant improvement in the predictive ability of both models was achieved by the replacement of the interill slope adjustment function (Eqn 5) with an alternative function (Eqn 10) calibrated for each soil or overburden with data from the 5, 10, 15, 20, and 30% slope experiments (Fig. 4*a* and *b*). The extremely variable and media-dependent effect of slope gradient on the interill erosion rate found in this study has also been reported by Kinnell and Cummings (1993). These authors concluded that a common relationship between interill erosion and slope gradient does not exist. Consequently, a range of functions containing coefficients to represent individual media responses were fitted to the slope data, and a sigmoid function (Eqn 10) was selected and incorporated into the interill prediction equation (Eqn 11). The improved predictive ability of the models using this function must be weighed against the additional data required for estimation of the media-dependent coefficients within the sigmoid function. Fortunately, these data can readily be collected using the laboratory flume and rainfall simulator.

The use of laboratory estimates of infiltration rate (Table 1) in both erosion models produced predictions of field erosion (Fig. 4*a* and *b*) similar to when runoff rates measured in the field were used (Fig. 4*c* and *d*). The results suggest that the runoff rates predicted from laboratory rainfall simulation provide suitable estimates of field runoff rates. Some authors (Mutchler *et al.* 1994) have reported laboratory simulations to be unsuitable in this regard as plots either become saturated due to lack of drainage or fail to replicate field matric potential when perforated flume floors are used. In this study, however, most of the overburdens and many of the soils developed surface seals and infiltration was limited to the top few centimeters. As a result, the effects of the shallow flume plot on surface hydrology were probably negligible.

Predictions of field-scale erosion from laboratory-scale measurements using the methodology described in this paper are subject to a number of limitations. Only rill and interill erosive processes are represented in this approach. In cases where other processes are significant (such as gullying and tunnel erosion), erosion rates will be significantly underestimated. Predictions are currently only valid for bare (non-vegetated) unconsolidated slopes as the effects of consolidation and vegetation on infiltration, rill, or interill detachment have not been investigated in this work. A sediment transport routine is not included; therefore, the approach should only be used to estimate erosion rates from steep linear slopes of low surface roughness where on-site deposition of sediment will be minimal. Where there is significant surface storage of runoff water, such as in ponds and cross-rips, the approach will probably overestimate the interill component and underestimate the rill component. These limitations should be carefully considered when interpreting predictive results using the approach described in this paper. Future development of this work should focus on the incorporation of the above factors into the predictive equations using laboratory-determined parameter values.

In summary, this research demonstrates that soil losses due to the combined processes of rill and interill erosion at the hillslope scale can successfully be predicted from laboratory-scale measurements of erodibility, provided a suitable methodology and modelling approach is adopted. The success of this approach can greatly reduce the cost and effort required for the prediction of hillslope scale soil erosion during the design of the post-mining landform.

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