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Estimation of erosion model erodibility parameters from media properties

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Abstract

The aim of this research was to enable erodibility values for hillslope-scale erosion prediction models to be determined from easily measured media properties. Simulated rainfall and overland flow experiments were carried out on 34 soils and overburdens from 15 Queensland open-cut coal mines at The University of Queensland Erosion Processes Laboratory. Properties of the 34 media determined included aggregate stability, Atterberg limits, bulk density, cation exchange capacity, dispersion ratios, electrical conductivity, exchangeable sodium percentage, organic carbon content, pH, texture, and water content at field capacity and wilting point. Correlation and stepwise multiple regression procedures were used to determine those media properties that could best be used to predict rill and interill erodibility. Correlations between media properties and sediment delivery at each of 5, 10, 15, 20, and 30% slope revealed that different media properties were correlated with erosion rates at different slopes. A media property could show a strong correlation with erodibility at 30% slope, and a low correlation at 5% slope. Splitting the data set into soils only, and overburdens only, showed that properties that were positively correlated with erosion rates for one group could be negatively correlated for the other group. Therefore, in this study, erodibility could not be explicitly linked to one set of media properties for all medium types and erosive conditions. It was concluded that a single regression equation could not be used to predict erodibility under all conditions. Instead, 4 equations were developed to predict rill and interill erodibility, for soils and overburdens separately. The need for separate regression equations was attributed to the presence of different erosive sub-processes for specific combinations of medium type and slope gradient.

Additional keywords: mine, mine-site, overburden, prediction, soil, spoil.

Introduction

Early studies by Bennett (1926), Middleton (1930), Baver (1933), and Cook (1936) demonstrated that erosion rates were influenced by soil properties. The initially simple relationships reported by those authors have subsequently been shown to be considerably more complex. Since 1926 there are at least 68 published research papers relating soil responses to various forms of erosive stress, to practically every measurable soil property. A number of these studies, and the soil properties shown to affect erodibility, are listed in Table 1.

A significant review of the effect of soil properties on erosion rates is that of Peters (1993). In essence, the significance of soil properties is due to the net impact they have on the processes of infiltration, aggregate breakdown, sediment detachment, and sediment transport.

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Table 1. Some studies in the literature relating erosion to soil properties

OM, organic matter content

Author	Date	Soil property
Bennet	1926	Texture, structure, OM chemical composition
Cook	1936	Texture
Laflen and Beasley	1960	Bulk density
Barnett and Rodgers	1966	9 variables
Wischmeier *et al.*	1971	Silt, sand, OM, structure, permeability
El Swaifey and Dangler	1977	Inorganic constituents
Romkens *et al.*	1977	Texture, exchangeable Fe and Al
Kemper *et al.*	1985	Gravimetric water content
Barfield *et al.*	1988	Bulk density
Elliot *et al.*	1989*b*	Classification, mineralogy
Effendi	1991	Shear strength
Loch and Rosewell	1992	Water-stable particles <0.125 mm, wet sediment density
Ekwue *et al.*	1993	Two types of OM
Poesen *et al.*	1994	Rock content
Shainberg *et al.*	1994	Exchangeable sodium percentage
Balisacan	1996	Electrical conductivity

The soil's susceptibility to erosive processes has been termed its erodibility (Cook 1936). The term initially represented a general summation of the differing behaviours of soils subject to erosion. As erosion research developed, erodibility was used to represent the response of a soil to more specific erosive sub-processes (Foster and Meyer 1972). The utility of the term erodibility is now limited as researchers have used it in diverse contexts without explicitly defining its meaning in each case. Romkens *et al.* (1985) suggest the use of the nomenclature 'soil erodibility coefficients', expressing the susceptibility of a soil to a specifically defined erosive sub-process.

The physical meaning of erodibility coefficients will depend on the equation in which they are used. The universal soil loss equation (USLE) (Wischmeier and Smith 1978) erodibility factor is a lumped parameter representing the average annual net effect of the processes of interill and rill erosion, deposition, and infiltration. The modified USLE (Onstad and Foster 1975) contains a separate term for runoff; hence, its erodibility coefficient represents only rill and interill processes for individual rainfall events. Mechanistic models such as the water erosion prediction project (WEPP) (Lane and Nearing 1989) contain separate erodibility values for rill and interill processes under steady-state conditions of rainfall and runoff. Other models (Hairsine 1988) delineate erosive processes even more explicitly. The erodibility values in each of these models clearly have different physical meanings, and a nomenclature needs to be developed to reduce the confusion now associated with the term erodibility.

Erodibility coefficients can be measured directly by experimentation, or estimated from soil properties often using multiple regression procedures. Direct measurement of rill, interill, and 'lumped' interill/rill coefficients generally involves field rainfall simulation or data from field plots under natural rainfall. These data are costly, inconvenient, and time-consuming to generate. Therefore, this research aims to enable the prediction of rill and interill erodibility from the physical and chemical properties of the media.

Methods and materials

A total of 17 soils and 17 overburdens were collected by back-hoe from 15 open-cut coal mines in Queensland and shipped in 200-L drums to the Erosion Processes Laboratory at The University of Queensland. Each medium was uniformly mixed in a 6-m^3 cement mixer and sieved to remove rocks >5 cm in diameter. The physical and chemical properties of the soils and overburdens were determined from subsamples of the fractions <2 mm of medium used for each laboratory plot. Soil bulk density (g/cm) and air-dry water content (g/g) were determined from core samples 80 mm in diameter and 80 mm deep from the laboratory plot surface. Hand-held probes were used to determine the pH and electrical conductivity (EC) of a 1 : 5 soil/water extract.

The particle size distribution of a chemically and physically dispersed sample of each medium was determined by the sedimentation and pipette technique described by Day (1965). Air-dry, 25-g samples were completely dispersed by the addition of 10 mL of 1 M sodium hydroxide and 10 mL of 10% sodiumhexametaphosphate to 1 L of deionised water, and end-over-end shaking for 16 h. The clay (<2 μm) dispersion ratio was calculated as the ratio of the percentage of clay in suspension after end-over-end shaking for 30 min in deionised water. The dispersed clay content (<2 μm) was calculated as the ratio of the percentage of clay in suspension after end-over-end shaking for 30 min in deionised water, to the percentage of clay following complete chemical and mechanical dispersion. An equivalent methodology was used for the silt and clay dispersion ratio and the dispersed silt and clay content.

The gravimetric rock content (>2 mm) was determined by dispersion of a 15-kg sample by agitation in a portable cement mixer for 1 h with a 0.1% calgon solution followed by wet sieving. The gravimetric rock content was converted to a volumetric rock content assuming the rock and soil bulk densities to be 2.65 and 1.65 g/cm^3, respectively. Organic carbon content (%) was determined by the Heanes (1984) wet oxidation technique. The 0.01 M silver-thiourea (AgTU)$^+$ method as documented by Raymond and Higginson (1992) was used to determine cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) of all media. Slight modifications to the procedure were made to allow for inductively coupled plasma-atomic emission spectroscopy rather than the recommended atomic adsorption spectroscopy.

The water characteristic curves of the soils and overburdens were determined using the filter paper method described by Fawcett and Collis-George (1967). The specific surface area of the soil was calculated from the water content at –0.01 kPa assuming a 4-molecular layer of water on the soil surface at this suction (Taylor 1958). The liquid and plastic limits of the media were determined using the Casagrande cup and frosted glass plate method described by Sowers (1965). The plastic index was calculated as the difference between the water content at the plastic and liquid limits. The instability index was calculated as the percentage by weight of particles and aggregates <125 μm on the soil surface following 30 min of 100 mm/h rainfall. Soil surface samples (<3 mm depth) were removed immediately following rainfall using a spatula and stored on a tension table at 5-cm suction before having the particle size distribution determined by wet sieving. This method was recommended by Loch (1994) for estimation of the size distribution of particles and aggregates at the soil surface under rainfall.

A tilting flume and rainfall simulator were used to simulate the processes of raindrop impact and overland flow. Rainfall was applied over the tilting flume at 100 mm/h to bare, unconsolidated plots, 3 m long, 0.8 m wide, and 0.15 m deep at 20, 5, 10, 15, and 30% slopes in that order. The rainfall simulator was calibrated regularly to maintain application rates close to the design intensity of 100 mm/h.

For the initially dry 20% slope, timed runoff samples were collected at 8 intervals during the 30-min rainfall event, weighed, oven-dried at 105°C, and re-weighed to determine the runoff rate and sediment concentration of the runoff. The mean of the last 4 runoff and sediment concentration measurements was used to calculate the steady-state sediment delivery rate and runoff rate for a given replicate. The slope gradient was then set to 5, 10, 15, and 30% slope, respectively, with 4 runoff samples collected during 12 min of simulated rainfall at each slope.

Immediately following rainfall, the flume was tilted to 20% slope and flow was added at increasing rates ranging from 0.1 to 1.8 L/s via a rotameter to the top of the plot. The range of flow rates selected depended on the apparent erodibility of the media. Rills were allowed to develop naturally over the plot surface to replicate natural field processes of rill meander, head-cutting, side-wall collapse, and scour. 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 sediment delivery at a given flow rate. Flow rates were increased until the maximum possible flow was attained, or until flow-lines cut to the base of the flume. Where possible, 3 replicates of the above experiments were carried out for each of the 34 media types collected for this study.

Results

General

The design intensity for the rainfall simulation experiments was 100 mm/h. Calibrations of the rainfall simulator showed the rainfall intensity varied between plots from 93 to 112 mm/h. Runoff and soil loss rates were adjusted for these small variations from the design storm using Eqns 1 and 2 (Meyer 1994):

$$\text{Adj. runoff rate} = \text{measured runoff} + (\text{design intens.} - \text{measured intens.}) \qquad (1)$$

$$\text{Adj. soil loss rate} = (\text{design intens./measured intens.})^2 \times \text{measured soil loss rate} \qquad (2)$$

Eqn 2 assumes that erosion is approximately proportional to the rainfall intensity squared, which is supported by Watson and Laflen (1986).

The flume was initially fitted with a flow-through, grid-type end gate that prevented the deposition of sediment on the plot prior to the flume outlet. This gate was used for the first two media to be tested in the flume, a soil and an overburden from Tarong mine. The flow-through gate was found to give highly variable results, as different media required different grid sizes to find an adequate balance between providing sufficient support for the media, while still allowing free movement of sediment from the plot. The flow-through gate was replaced with a conventional solid gate at the flume outlet for the other 32 media tested. Data collected from the first two media were not used in subsequent analysis.

The rainfall simulation experiments were intended to investigate interill processes only; however, the transition from interill to rill processes occurs on some media at very low/short slopes. The dataset resulting from the rainfall simulation experiments therefore represents some media where only interill processes were active, and others where both rill and interill processes were occurring. In most cases, rilling did not occur on the overburdens at any slope. Rilling was observed at the 20% slope on 12 of the 16 soils in this data set, although was not generally active at the 5% or 10% slope.

Data from an initial set of replicates for a soil from Curragh mine were found to differ significantly from data collected from field rainfall simulation plots undertaken (as part of a separate study) on the same media. Sediment delivery rates in the laboratory were approximately one-third of those measured in the field. Analysis of the laboratory sample showed it consists of highly compacted clods, possibly as a result of being incorrectly collected from the field when wet. These replicates were repeated using media that had been collected dry in the field and the measured sediment delivery rates increased by about a factor of 3, giving similar results to the field rainfall simulation. Results from the second dry sample were used in all subsequent analyses. Similarly, Evans (1992) found runoff and erosion from a cracking clay soil under simulated rainfall were drastically reduced if samples used were taken from material that had been rained on and then oven-dried at 40ºC. He noted that such samples had a high percentage of coarse aggregates resistant to breakdown when wet relative to air-dry samples taken from the field.

Rilling could not be initiated on 5 of the overburden plots (Curragh, Goonyella Norwich Pk tertiary, Wandoan, and Blackwater overburdens) at the maximum flow rates used in the laboratory (1.8 L/s). Rill erodibility coefficients could therefore not be calculated for these media. To enable these media to be retained in the dataset, rill erodibility values were determined from field rill plot data from the same media types (collected as part of a separate study) and combined with the laboratory data set.

Interill erodibility was determined from Eqn 3 (Kinnell 1993) using the steady state sediment delivery data from the rainfall simulation experiments at 10% slope. Rilling was not observed during rainfall simulation for most media at this slope:

$$E_i = K_i * I * Q * S_f * C_f \qquad (3)$$

where E_i (kg/m^2.s) is the interill erosion rate, K_i (kg.s/m^4) is an interill erodibility coefficient related to soil properties, I (m/s) is the steady-state rainfall rate, Q (m/s) is the steady-state runoff rate, and S_f and C_f are non-dimensional slope and cover adjustment factors, respectively, and may be calculated from (NSERL 1995):

$$S_f = 1.05 - 0.85 \exp(-4 \sin (S_2)) \qquad (4)$$

$$C_f = e^{-2.5C} \qquad (5)$$

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.

Rill erodibility (K_{r3}) was determined from Eqn 6 (Sheridan *et al.* 2000) using the overland flow experimental data:

$$K_{r3} = \frac{E_r}{q_r^{1.60} S_3^{2.40}} \qquad (6)$$

where E_r (g/s) is the sediment delivery rate *per rill*, q_r (L/min) is the flow rate per rill, and S_3 (fraction) is the rill slope (Kemper 1985; Gilley *et al.* 1992). Correlations and stepwise multiple regression procedures were used to determine relationships between erodibility and media properties.

Media properties

Physical and chemical properties of the soils and overburdens are listed in Table 2. The range of textures of the laboratory soils and overburdens is plotted on a texture triangle in Fig. 1. It can be seen that the range of soils and overburdens found in this region are relatively low in silt (all media <30% silt). Most large-scale erosion research programs have been carried out on agricultural soils with a range of textures different from the media used for this study. For example, most of the soils tested for the development of the WEPP model (Lane and Nearing 1989) contain >20% silt, and some have silt levels as high as 80% (Elliot *et al*. 1989*a*). Media (soil and overburden) texture in this study ranged from a heavy clay soil (57% clay) from Curragh mine to a sandy loam soil (16% clay) at Norwich Park.

Soils were generally more 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 (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 interill erodibilities (e.g. Norwich Park overburden and Wandoan soil).

The soils from the Blackwater and nearby Curragh mines were notably different from all of the other soils tested in this study. These soils had the highest clay content (57% clay), were almost identical in texture, and had the highest CECs of all the soils (40 and 60 cmol(+)/kg, respectively). These soils were strongly aggregated and swelled upon

Table 2. Physical and chemical properties of 32 soils and overburdens from Queensland open-cut coal mines

O, overburden; S, soil; EC and pH, electrical conductivity (dS/m) and pH of 1 : 5 soil/water suspension; CEC, cation exchange capacity (cmol/kg); ESP, exchangeable sodium percentage; GWC, gravimetric water content at given pressure (kPa); SS, specific surface area of soil (m^2/g); D_2, dispersion ratio—clay; D_{20}, dispersion ratio—silt and clay; BD, bulk density (g/cm^3); LL, liquid limit; PL, plastic limit; PI, plasticity index; OC, organic carbon content; II, instability index—% by weight particles and aggregates <125 μm on the soil surface following rainfall; texture is of the <2 mm portion following dispersion and wet sieving of rock (clay <0.002 mm, 0.002 mm <silt < 0.020 mm, 0.020 mm <sand <2.0 mm); rock, % by volume >2 mm following physical and chemical dispersion; n.d., not determined

Index no.	Media	EC	pH	CEC	ESP	GWC –1.5	GWC –0.01	SS	D_2	D_{20} (%)	BD	Atterberg limits LL	PL	PI	OC (%)	II	Texture %Clay	%Silt	%Sand	Rock (%)
											Blair Athol									
1	O	0.284	7.66	7.6	11.8	0.07	0.16	52.1	6.8	20.7	1.62	17.4	9.0	8.4	n.d.	25.6	17.72	10.48	71.80	8.55
2	S	0.106	7.06	8.6	4.0	0.06	0.15	46.1	2.6	20.5	1.36	17.7	14.6	3.1	1.33	32.2	23.69	15.31	61.00	6.04
											Blackwater									
3	O	0.471	8.62	23.0	15.9	0.10	0.23	77.3	8.7	24.4	1.65	37.3	19.9	17.4	n.d.	21.5	20.65	29.26	50.08	8.28
4	S	0.306	8.69	40.2	10.6	0.21	0.44	155.6	4.9	17.2	1.40	63.2	32.4	30.8	2.35	25.2	57.65	14.20	28.15	2.45
											Calide									
5	O	0.228	6.68	12.7	5.5	0.08	0.15	60.0	6.9	23.6	1.59	n.d.	n.d.	n.d.	n.d.	28.1	18.48	11.91	69.61	12.77
6	S	0.040	5.19	1.4	22.8	0.05	0.13	34.3	1.2	6.2	1.59	n.d.	n.d.	n.d.	2.30	18.9	19.02	4.31	76.68	3.59
											Curragh									
7	O	0.690	8.89	26.9	26.1	0.12	0.29	88.9	14.0	34.7	1.59	n.d.	n.d.	n.d.	n.d.	33.6	22.56	25.24	52.20	1.56
8	S	0.750	7.67	60.2	6.5	0.17	0.37	130.9	9.4	37.0	1.36	50.1	23.5	26.6	1.60	n.d.	57.13	17.26	25.62	0.90
											German Ck									
9	O	1.430	7.57	24.6	10.1	0.08	0.17	59.2	0.8	23.4	1.73	n.d.	n.d.	n.d.	n.d.	25.3	4.63	28.49	66.88	16.16
10	S	0.710	7.57	13.2	13.9	0.06	0.17	44.1	4.0	16.3	1.59	23.5	14.2	9.3	0.79	21.4	22.58	7.92	69.50	4.25
											Goonyella									
11	O	1.373	8.82	36.5	39.8	0.16	0.31	117.1	21.8	41.9	1.48	n.d.	n.d.	n.d.	n.d.	30.6	26.85	22.17	50.98	1.31
12	S	0.207	6.30	10.1	7.9	0.11	0.18	78.9	6.7	18.0	1.58	29.2	15.9	13.2	1.44	n.d.	44.23	7.23	48.54	1.58
											Gregory									
13	O	1.051	7.80	16.2	6.5	0.07	0.15	49.8	0.6	17.7	1.79	n.d.	n.d.	n.d.	n.d.	25.1	9.76	18.16	72.08	6.66
14	S	0.078	6.33	13.6	0.5	0.09	0.21	65.4	3.9	13.7	1.56	29.3	14.2	15.7	0.78	17.9	30.33	5.51	64.16	2.80

(Continued)

Table 2. *(Continued)*

Index no.	Media	EC	pH	CEC	ESP	GWC –1.5	GWC –0.01	SS	D_2	D_{20} (%)	BD	Atterberg limits LL	PL	PI	OC (%)	II	Texture %Clay	%Silt	%Sand	Rock (%)
											Moura									
15	O	0.439	7.88	25.1	19.2	0.14	0.29	101.5	10.8	28.6	1.44	n.d.	n.d.	n.d.	n.d.	14.0	24.13	25.38	50.49	28.01
16	O	0.755	8.57	32.6	31.3	0.12	0.26	88.3	9.5	29.9	1.48	40.2	17.9	22.3	n.d.	32.8	31.06	16.66	52.28	4.93
17	S	0.269	7.81	34.6	9.0	0.20	0.47	147.7	6.9	18.8	1.18	52.0	21.7	30.3	1.67	18.6	48.85	15.73	35.42	4.37
											Norwich Pk									
18	O	0.711	8.34	14.6	27.7	0.07	0.12	50.6	7.4	20.7	1.77	n.d.	n.d.	n.d.	n.d.	18.6	17.22	25.19	57.59	33.14
19	O	0.485	7.29	15.4	35.4	0.11	0.20	79.0	12.4	30.0	1.61	n.d.	n.d.	n.d.	n.d.	43.8	31.91	13.04	55.05	4.47
20	S	0.142	6.56	3.5	29.2	0.04	0.11	26.6	4.7	10.6	1.73	15.0	10.0	5.0	0.56	26.6	15.72	2.71	81.57	1.22
											Newland									
21	O	0.303	8.16	14.8	3.1	0.07	0.14	56.3	4.7	17.0	1.53	n.d.	n.d.	n.d.	n.d.	37.9	13.82	18.30	67.88	9.93
22	S	0.574	8.93	24.7	36.8	0.10	0.22	71.6	16.5	29.3	1.52	31.5	15.2	16.4	0.68	41.6	28.58	10.40	61.02	1.49
											Oaky Ck									
23	O	1.600	7.60	30.0	6.9	0.06	0.16	48.7	1.2	21.1	1.67	n.d.	n.d.	n.d.	n.d.	26.6	0.72	24.18	75.10	7.34
24	S	0.257	7.10	10.2	9.8	0.07	0.17	49.6	4.4	17.6	1.61	25.8	17.7	8.1	1.39	49.1	22.88	8.47	68.65	0.97
											Peak Downs									
25	O	1.552	8.55	25.1	52.7	0.12	0.27	89.3	19.5	50.4	1.29	n.d.	n.d.	n.d.	n.d.	26.9	27.45	42.91	29.64	6.96
26	S	0.227	7.53	9.5	17.1	0.05	0.14	38.5	6.6	15.5	1.44	16.9	12.0	5.0	0.80	53.2	20.17	7.03	72.80	2.63
											Saraj									
27	O	0.447	9.44	26.5	28.5	0.13	0.30	100.9	15.4	29.5	1.50	n.d.	n.d.	n.d.	n.d.	54.1	34.00	9.08	56.92	0.98
28	S	0.144	8.67	5.8	5.5	0.04	0.13	33.5	3.3	14.7	1.71	n.d.	n.d.	n.d.	1.04	44.7	14.01	9.00	76.99	1.26
											Tarong									
29	S	0.351	4.99	4.9	14.4	0.09	0.19	68.1	5.4	21.9	1.47	24.5	17.0	7.4	3.49	22.0	30.06	12.13	57.82	16.77
30	S	0.096	4.75	2.7	3.3	0.13	0.22	96.4	3.3	10.1	1.21	31.2	20.4	10.8	2.63	16.9	37.84	6.92	55.24	8.86
											Wandoan									
31	O	0.856	8.17	25.9	31.3	0.13	0.30	98.6	17.0	48.4	1.41	44.2	22.5	21.7	n.d.	50.2	26.57	36.62	36.81	6.05
32	S	0.113	8.07	23.9	3.0	0.11	0.23	85.4	2.6	19.6	1.48	38.8	20.7	18.1	2.43	27.7	33.54	17.94	48.52	0.72

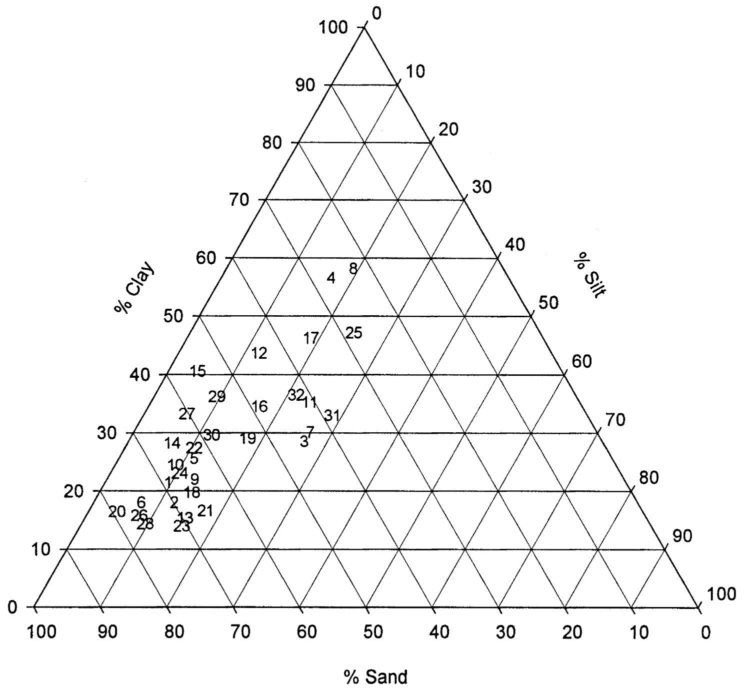

Fig. 1. Texture triangle showing the texture of the portion of the soils and overburdens <2 mm used in the laboratory research. Plotted numbers correspond to the media index numbers listed in Table 2.

wetting. During rainfall, the soils were observed to erode as aggregates of apparent low density. The soils from Norwich Park, Saraji, and Peak Downs are very similar to each other in texture and may indicate a single soil type across these mines. These soils were high in sand and low in clay, poorly structured, and showed relatively low cohesion.

The physical properties of the overburdens varied considerably, although they were generally characterised by high ESP values and/or high rock contents. Overburdens from Blackwater, Callide, German Creek, Moura, Norwich Park, Newlands, and Oaky Creek all had high rock contents. Many of the overburdens were extremely sodic, with ESP >20% being common, and one overburden from Peak Downs mine recording an ESP >50%. The high ESP media generally formed strong surface seals under rainfall.

Determinations for organic carbon were not carried out on the overburdens as these media have been sourced from depths of up to 100 m and were therefore assumed to have no, or negligible, organic carbon. The measurements for the instability index may sometimes be misleading as some media developed strong surface seals, which did not breakdown during wet sieving, yielding data that gave the impression of a high proportion of stable aggregates or particles at the surface.

The findings from this study concur with the well-established concept that texture plays a dominant role in determining many of the other properties of a soil or overburden. Very high correlations were found between texture, especially clay content, and other media properties, including the plastic limit, liquid limit, specific surface area, and water contents at field capacity and wilting point. Given that texture is a relatively simple and routine measurement to make, the measurement of other, more difficult to quantify, properties is probably of less importance for studies of this type in the future.

Media properties and erodibility

Variations in sediment delivery rates (from the rainfall simulation plots at 30% slope) due to media properties alone were in the order of 200 times and the value of the rill erodibility coefficient varied by about 290 times. The magnitude of these variations indicates the importance of the erodibility parameter for successful erosion prediction modelling.

An initial qualitative assessment of rill and interill data indicated some clear trends in terms of the types of soils and overburdens associated with high and low levels of

Table 3. Soils and overburdens ranked in order from highest to lowest for rill and interill erodibility coefficients

Field rill plot erodibility values used where rilling could not be initiated on the laboratory plot. Values determined from Eqn 6. Interill erodibility determined at 10% slope from Eqn 3

Mine & media	Rill erodibility K_{r3}	Mine & media	Interill erodibility $10^{-6} \times K_i$ (kg.s/m^4)
Norwich Pk sandy clay loam soil	37.92	Curragh medium heavy clay soil	6.01
Peak Downs loamy sand soil	33.15	Blackwater heavy clay soil	5.78
Calide Sandy clay loam soil	22.76	Saraji obn	4.20
Blackwater heavy clay soil	21.90	German Ck clay loam soil	4.04
Blackwater rocky obn	17.78	Gregory clay loam soil	3.97
Gregory clay loam soil	12.72	Norwich Pk sandy clay loam soil	3.58
Saraji sandy loam soil	12.43	Moura Permian obn	3.30
Curragh medium heavy clay soil	11.07	Newlands sandy clay loam soil	3.23
Tarong Krasnozem soil	9.30	Wandoan shale obn	3.12
Oaky Ck clay loam soil	9.24	Goonyella Permian obn	3.05
Wandoan light clay soil	8.94	Oaky Ck clay loam soil	2.94
Blair Athol obn	8.69	Norwich Pk tertiary obn	2.87
Moura medium clay soil	8.24	Goonyella light clay soil	2.57
German Ck clay loam soil	8.12	Blair Athol sandy loam soil	2.31
Gregory rocky obn	8.06	Moura medium clay soil	2.28
Newlands rocky obn	7.53	Saraji sandy loam soil	2.25
Goonyella light clay soil	7.24	Curragh obn	2.13
Blair Athol sandy loam soil	7.09	Wandoan light clay soil	1.86
Tarong Lithosol soil	6.81	Calide sandy clay loam soil	1.68
Oaky Ck shale obn	6.14	Gregory rocky obn	1.63
German Ck rocky obn	5.76	Blair Athol obn	1.38
Calide obn	5.04	Peak Downs obn	1.22
Goonyella Permian obn	5.00	Peak Downs loamy sand soil	1.22
Moura Permian obn	4.82	Tarong Krasnozem	1.05
Curragh obn	4.33	Calide obn	1.04
Wandoan shale obn	3.09	Moura rocky obn	0.98
Newlands sandy clay loam soil	2.26	Newlands rocky obn	0.88
Saraji obn	2.12	German Ck rocky obn	0.87
Moura rocky obn	1.74	Oaky Ck shale obn	0.80
Peak downs obn	1.02	Tarong Lithosol soil	0.76
Norwich Pk tertiary obn	0.29	Blackwater rocky obn	0.54
Norwich Pk rocky obn	0.13	Norwich Pk rocky obn	0.09

Table 4. Correlation between media physical and chemical properties and measured soil loss rates under rainfall at a range of slopes (%) for soils, overburdens, and soils and overburdens together

See Table 2 for property definitions. Soils from Curragh and Blackwater mines not included in analysis

Media property	Soil data only					Overburden data only					Soil and overburden data				
	Slope:					Slope:					Slope:				
	5	10	15	20	30	5	10	15	20	30	5	10	15	20	30
EC	0.45	0.33	0.08	–0.25	–0.20	–0.05	–0.04	–0.19	–0.35	–0.33	0.03	–0.17	–0.40	0.51**	–0.47**
PH	0.67**	0.47	0.47	0.16	0.06	0.51*	0.48*	0.40	0.19	0.26	0.44*	0.19	0.01	–0.22	–0.24
CEC	0.25	0.28	–0.18	–0.44	–0.48	0.44	0.45	0.30	0.07	0.08	0.29	0.12	–0.30	–0.52**	–0.53**
ESP	0.53*	0.25	0.52*	0.42	0.49	0.47	0.48*	0.39	0.31	0.21	0.45*	0.24	0.12	0.01	0.03
GWC															
–1.5 kPa	–0.31	–0.22	–0.67**	–0.69**	–0.72**	0.62**	0.65**	0.54*	0.42	0.38	0.17	0.11	–0.33	–0.47**	–0.51**
–0.01 kPa	–0.18	–0.07	–0.50	–0.58*	–0.57*	0.62**	0.63**	0.51*	0.40	0.36	0.25	0.22	–0.19	–0.34	–0.36*
SS (m^2/g)	–0.31	–0.22	–0.67**	–0.69**	–0.72**	0.62**	0.65**	0.54*	0.42	0.37	0.17	0.11	–0.33	–0.47**	–0.51**
D2	0.63*	0.26	0.16	–0.12	–0.19	0.54*	0.57	0.48	0.43	0.35	0.50**	0.28	–0.01	–0.19	–0.23
D20	0.4	0.14	–0.15	–0.44	–0.57*	0.45	0.46	0.32	0.27	0.18	0.34	0.08	–0.27	–0.44*	–0.48**
OC	–0.75**	–0.77***	–0.76***	–0.54*	–0.46	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Instab.	0.50	0.09	0.57*	0.36	0.22	0.73***	0.81***	0.80***	0.71**	0.73***	0.61***	0.45*	0.50**	0.30	0.23
Clay	–0.23	–0.17	–0.65**	–0.67**	–0.70**	0.81***	0.81***	0.82***	0.78***	0.72***	0.31	0.41*	0.13	0.02	–0.03
Silt	–0.09	–0.21	–0.45	–0.57*	–0.62*	–0.06	–0.06	–0.23	–0.32	–0.36	–0.07	–0.25	–0.51	–0.57***	–0.58***
Sand	0.52*	0.48	0.90***	0.85***	0.84**	–0.08	0.09	0.08	0.07	0.12	0.25	0.24	0.46**	0.46**	0.48**
Rock	–0.53*	–0.64*	–0.62*	–0.50	–0.42	–0.66**	–0.67**	–0.66**	–0.64**	–0.63**	–0.59***	–0.68***	–0.63***	–0.53**	–0.49**
BD	0.49	0.55*	0.67**	0.66**	0.64**	–0.46	–0.41	–0.35	–0.36	–0.29	–0.07	–0.04	0.08	0.13	0.16
LL	–0.19	–0.07	–0.53	–0.59*	–0.61*	0.42	0.56	0.28	–0.17	–0.20	0.08	0.06	–0.45	–0.57*	–0.58*
PL	–0.49	–0.42	–0.73***	–0.72**	–0.76**	0.2	0.39	0.06	–0.37	–0.40	–0.16	–0.15	–0.52	–0.58*	–0.61**
PI	–0.03	0.11	–0.37	–0.47	–0.47	0.59	0.69	0.47	0.03	0.00	0.20	0.16	–0.36	–0.49*	–0.49*

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

erodibility. Table 3 ranks all media from highest to lowest in order of the calculated rill and interill erodibility values. The media most susceptible to rill erosion were the sandy soils from Norwich Park, Peak Downs, and Callide mines. These soils were low in clay, had very low cohesion, and provided little resistance to detachment by overland flow. The least susceptible to rill erosion were the sodic, dispersive overburdens that form strong surface seals that resist detachment. Of the 10 least erodible materials, 9 had an ESP >25. An ESP >15 is considered highly sodic under Australian agricultural conditions (Northcote and Skene 1972).

The most susceptible media to interill erosion were the well-aggregated clay soils from Curragh and Blackwater, presumably due to the presence of easily detached, low-density aggregates. Interill erosion at low slopes is often limited by the transport capacity of the interill flow. Low-density aggregates are carried more easily by the flow, which explains the high erodibility of these soils under these transport-limited conditions. It is interesting to note that at 30% slope, where detachment limited conditions are more likely to prevail, it was not the well-aggregated soils that were the most erodible, but the sandy non-cohesive soils. These results highlight the process-specific nature of erodibility, and indicate some of the difficulties associated with attempting to predict erodibility from a single set of properties under a range of erosive regimes. The media least susceptible to interill erosion were the rocky overburdens, due to the protection from raindrop impact provided by the rock armour. Of the 7 least erodible media, all contained significant amounts of rock.

The process-specific nature of erodibility shown by the interill data suggested that erodibility prediction equations developed at one slope may not be valid at other slopes or under other erosive conditions. This concept was further explored by correlating the media properties with the sediment delivery rates at each slope. For all correlations, the soils from Blackwater and Curragh were excluded. These soils, from adjacent mines, behaved differently from all the other soils, and when included in the analysis were consistent outliers and tended to mask relationships for all of the other soils.

Table 4 indicates that physical and chemical properties best correlated with erosion rates are different at different slopes, or when the data are grouped into soils or overburdens only. Texture class was found to be an excellent predictor of interill erodibility for soils at 20–30% slope, with correlation coefficients as high as 0.90 with sand content. However, at 5% slope, texture was poorly correlated with erosion rates for the soils. The trend for lower correlations with texture as slope gradient decreases is clear (for soils) and is reinforced by the correlations with other, independently measured, but texture-related, properties, such as the Atterberg limits, the water contents at wilting point and field capacity, and the specific surface area of the soil.

At lower slopes, erosion rates show increasingly significant correlations with organic carbon content, pH, ESP, dispersible clay, EC, and the stability index. In general it appears that the factors that affect surface stability are better correlated with erosion rates at low slopes, while at high slopes the matrix properties (i.e. texture) are more important. These differences may be due to transport-limited conditions at low slopes, and detachment-limited conditions at high slopes. They may also reflect the change from interill to rill processes as slope gradient increases, as rilling was observed for many of the soils at the higher slopes.

Data for the overburdens showed very different correlations with media properties than data for the soils. The strong negative correlation between clay content and erosion rate for the soils is completely reversed for the overburden. Thus, increasing clay is associated with reduced erosion for the soils, while being related to increased erosion for the overburdens. This positive relationship with clay is very uncommon in the literature (except when aggregation is strong), although it has been reported previously by Levy *et al.* (1994), who showed that for 3 soils with ESP >5 , soil loss increased linearly with an increase in clay content. Of the 16 overburdens in this study, 14 have an ESP >10, perhaps suggesting an interaction between ESP, clay content, and erodibility.

The variation in correlation coefficients at different slopes found for the soils was not repeated for the overburdens. For example, the correlations with clay content at 5% and 30% slope for the overburdens are similar, at 0.81 and 0.72, respectively. This may be due to a change in erosion process on the soil plots as the plots began to rill at higher slopes. As no rilling was observed on the overburden plots, erosion at all slopes is due to interill processes alone.

Increasing rock content was consistently correlated with decreasing erosion rates, at all slopes and for both soils and overburdens. This reflects the significant effect of rock on surface processes (Poesen *et al.* 1990, 1994), protecting the soil from raindrop impact and overland flow energy.

The correlations between erosion rates and media properties at each slope gradient and for subsets of the data show that a single set of media properties for the estimation of erodibility does not exist. Different properties are best correlated with erosion rates at different points along the continuum from transport-limited to detachment-limited conditions, and from interill-dominated to rill-dominated conditions.

Rill erodibility values, determined from the overland flow experimental data, were correlated against the media properties listed in Table 2. The correlations with properties for soils, overburdens, and soils and overburdens together are listed in Table 5. Correlations between rill erodibility and media properties were generally low and insignificant. Separating or grouping the data based on media type made little difference to the results. Only silt content and the silt and clay dispersion ratio were significantly correlated (negatively) with rill erodibility for the soils.

The literature suggests that silt content is usually positively correlated with erodibility (Wischmeier and Mannering 1969), although this is not always the case (Verhaegen 1987; Wood *et al.* 1987). One reason for the different result here may be that silt in this study is classed as the 2–20 μm component, whereas in most studies from the United States silt is considered to be the 2–50 μm component. Thus, the US silt fraction contains a greater proportion of particles in the non-cohesive, yet easily transportable size range. Another reason may be that most of the other major erodibility studies (Lane and Nearing 1989) have been carried out on soils with much higher levels of silt, up to 80% in some cases (Elliot *et al.* 1989*a*). Soils with these levels of silt are known to be low in cohesion and therefore highly erodible. The upper range of silt contents found in the soils used in this study is often associated with hardsetting and surface sealing, conditions associated with low erodibility. The significant negative correlation with the silt and clay dispersion ratio also supports this hypothesis.

The generally low correlations between media properties and rill erodibility prompted inspection of the data for possible non-linear trends. Only rock content was found to display such a trend, as shown in Fig. 2.

Rock content affects rill erosion by protecting the soil surface from the energy of overland flow. The data shown in Fig. 2 suggest that rill erodibility was related to rock

Table 5. Correlation coefficients between media properties and rill erodibility calculated from Eqn 6 for soils, overburdens, and soils and overburdens together

For property definitions see headnote of Table 2

Media properties	Soils[A]	Overburdens[B]	Soils and overburdens[C]
EC	–0.30	–0.13	–0.41*
PH	–0.07	0.00	–0.27
CEC	–0.18	–0.09	–0.25
ESP	0.34	–0.52*	–0.18
GWC			
–1.5 (kPa)	–0.27	–0.27	–0.26
–0.01 (kPa)	–0.22	–0.20	–0.17
SS (m^2/g)	–0.27	–0.27	–0.28
D2	–0.24	–0.38	–0.39
D20	–0.47*	–0.39	–0.54***
OC	–0.23	n.d.	0.29
WSA	0.08	–0.28	0.20
Clay	–0.27	–0.36	–0.01
Silt	–0.47*	–0.04	–0.46
Sand	0.35	0.30	0.30
Rock	–0.24	–0.22	–0.34
BD	0.30	0.33	0.10
LL	–0.20	–0.21	–0.21
PL	–0.20	–0.07	–0.17
PI	–0.18	–0.32	–0.22

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

[A] $n = 16$ for all correlations.

[B] $n = 16$ for all correlations except for Atterberg limits where $n = 5$.

[C] $n = 32$ for all correlations except for Atterberg limits where $n = 21$.

content by an exponential decay function. At low levels of rock content, erodibility may be high or low, but at rock contents greater than about 30%, erodibility is low. Overburdens containing >30% of competent rock can therefore be considered to be relatively stable with respect to rill erosion—at least for the flow conditions tested in this study. Rock content is the percent by volume >2 mm following agitation and dispersion of a 15-kg sample in a portable cement mixer. Dry sieving yields significantly higher rock contents than the method described above.

It was found that the moisture status of the sample when collected could significantly affect the measured erodibility of the media in the laboratory. A heavy clay soil from Curragh mine was collected following rainfall, causing significant compaction during excavation and transport. This soil recorded a significantly lower erodibility in the laboratory than was recorded from similar field rainfall simulation events. Fig. 3 shows that the sediment concentration of the runoff was approximately 3 times greater for the sample collected air-dry compared with the sample collected following rainfall.

Visual inspection of the samples shown in Fig. 3 indicated that the sample collected following rainfall consisted of compacted high density clods, while the sample collected air-dry possessed a friable, well-aggregated structure common to self-mulching clay soils. It was concluded that field samples should be collected as dry as possible to prevent compaction, especially for high clay soils.

The data suggest that rill erodibility cannot be simply linked to the media properties listed in Table 2. Further analysis was undertaken to determine whether the standard

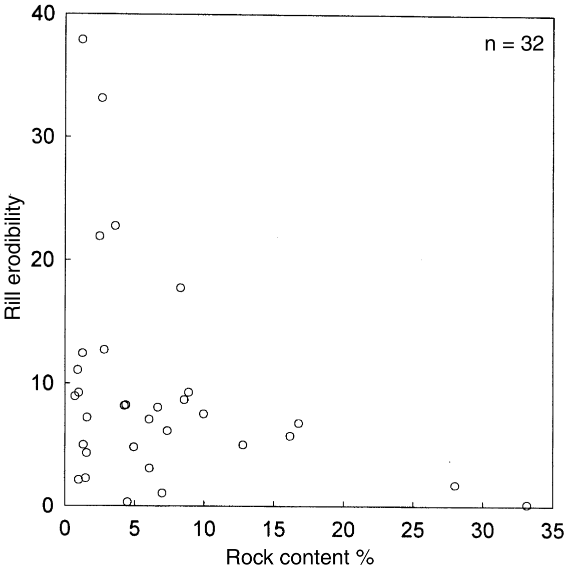

Fig. 2. Relationship between the percent rock content by volume and rill erodibility for all 32 soils and overburdens.

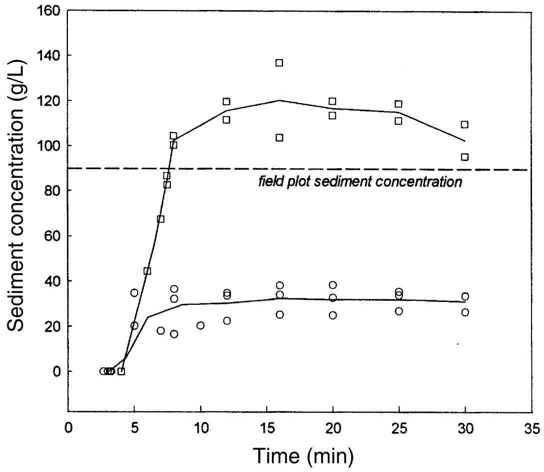

Fig. 3. Sediment concentration of runoff from laboratory rainfall simulation plot for a heavy clay soil from Curragh mine collected following rainfall (○) and air dry (□). Dashed line indicates the sediment concentration recorded from field rainfall simulation on the medium type.

texture size classes were appropriate for correlation against rill erodibility. The hypothesis was that possibly groupings, or sub-groupings, of texture classes could be better correlated with rill erodibility than the standard clay, silt, and sand texture classes. This approach was taken by Wischmeier and Smith (1978) who developed the ‘m’ texture parameter, which was defined as: (percent by mass in the 2–100 μm range × 100) – percent clay. This size class was found to be strongly correlated with the erodibility parameter in the USLE.

Table 6 shows the correlations between erodibility (rill and interill) and texture size classes for soils and overburdens. For rill erodibility, correlations are increasingly negative for size classes approaching the 0–20 μm class and increasingly positive approaching the 20 μm–10 mm size class. Thus, the size range of silt and below is

Table 6. Correlations of particle size classes with rill and interill erodibility

Tabulated values represent the correlation coefficient between erodibility and the particle size interval for overburdens (above diagonal) and soils (below diagonal) given by the column and row headings. High correlation values are highlighted in **bold**

Blackwater and Curragh soils not included in analysis; interill erodibility calculated from Eqn 3 assuming a cover adjustment factor of 1, i.e. rock not included in cover factor

Size (mm)	0	0.002	0.005	0.020	0.050	0.10	0.20	0.50	1.0	2.0	5.0	10.0	20.0	50.0
Rill erodibility														
0		–0.56	–0.65	–0.64	–0.63	–0.55	–0.30	–0.20	–0.04	–0.01	–0.03	–0.05	–0.09	0.56
0.002	–0.54			–0.36	–0.37	–0.25	0.04	0.18	0.41	0.47	0.54	0.61	0.65	0.65
0.005	–0.57			–0.24	–0.28	–0.15	0.16	0.31	0.53	0.59	0.66	**0.73**	**0.74**	0.64
0.020	–0.63	–0.67	–0.57		–0.30	–0.05	0.31	0.44	0.62	0.66	**0.72**	**0.76**	**0.73**	0.63
0.050	–0.61	–0.48	–0.40	–0.25		0.20	0.47	0.53	0.66	0.68	**0.73**	**0.74**	**0.71**	0.55
0.10	–0.50	–0.21	–0.14	0.00	0.18		0.54	0.55	0.65	0.65	0.67	0.67	0.63	0.30
0.20	–0.23	0.18	0.25	0.37	0.53	0.71		0.35	0.48	0.47	0.44	0.40	0.35	0.20
0.50	0.07	0.47	0.51	0.60	0.66	0.68	0.47		0.50	0.47	0.36	0.30	0.22	0.04
1.0	0.13	0.54	0.58	0.65	**0.68**	0.66	0.43	0.10		0.29	0.06	0.02	0.01	0.01
2.0	0.14	0.58	0.61	**0.67**	**0.69**	0.64	0.39	0.06	–0.02		–0.08	–0.07	–0.04	0.03
5.0	0.19	0.61	0.64	**0.69**	**0.69**	0.63	0.37	0.04	0.00	0.00		–0.05	–0.02	0.05
10.0	0.21	0.60	0.63	**0.68**	**0.68**	0.61	0.35	0.02	–0.03	–0.04	–0.11		–0.01	0.08
20.0	0.22	0.59	0.63	**0.67**	**0.67**	0.58	0.31	–0.01	–0.01	–0.01	–0.15	–0.18		
50.0		0.54	0.57	0.62	0.61	0.50	0.23	–0.07	–0.13	–0.14	–0.20	–0.21	–0.23	
Interill erodibility														
0		**0.79**	0.62	0.38	0.22	0.18	0.24	0.46	0.62	0.67	0.7	0.71	0.67	n.a.
0.002	–0.65			–0.32	–0.36	–0.36	–0.26	–0.05	0.07	0.11	0.02	–0.12	–0.51	**–0.79**
0.005	–0.68			–0.29	–0.35	–0.33	–0.2	0.03	0.15	0.19	0.12	0	–0.33	–0.62
0.020	–0.70	0.61	0.49		–0.35	–0.28	–0.1	0.16	0.28	0.31	0.26	0.16	–0.12	–0.38
0.050	–0.62	0.50	0.25	0.08		–0.41	0.04	0.29	0.37	0.39	0.34	0.26	0.03	–0.22
0.10	–0.36	0.08	0.17	0.32	0.51		0.13	0.4	0.44	0.45	0.39	0.3	0.07	–0.18
0.20	–0.02	0.49	0.55	0.66	0.78	0.78		0.62	0.53	0.5	0.39	0.26	–0.01	–0.24
0.50	0.37	0.79	0.82	**0.87**	**0.87**	0.73	0.50		0.3	0.3	0.11	–0.04	–0.29	–0.46
1.0	0.42	0.82	**0.84**	**0.88**	**0.84**	0.65	0.36	0.19		0.25	–0.18	–0.33	–0.52	–0.62
2.0	0.41	0.84	**0.86**	**0.87**	**0.82**	0.60	0.29	–0.23	–0.22		–0.37	–0.46	**–0.6**	**–0.67**
5.0	0.42	0.82	**0.84**	**0.84**	0.77	0.54	0.21	–0.28	–0.34	–0.36		–0.55	**–0.67**	**–0.7**
10.0	0.44	0.80	0.82	0.83	0.75	0.51	0.18	–0.30	–0.35	–0.36	–0.33		**–0.71**	**–0.71**
20.0	0.45	0.77	0.79	0.80	0.71	0.37	0.13	–0.33	–0.38	–0.38	–0.37	–0.40		**–0.67**
50.0	1.00	0.65	0.68	0.70	0.62	0.36	0.02	–0.37	–0.42	–0.41	–0.42	–0.44	–0.45	

associated with low rill erodibilities, while the size class greater than silt but <10 mm is associated with high rill erodibility. The data could be explained if we consider that the particles <20 μm are contributing to cohesion and low erodibility, while the particles >20 μm are easily detached and transported and associated with higher erodibility. At sizes greater than about 5–10 mm, erodibility is reduced as the greater mass to surface area ratio of the rocks makes them difficult to transport at this range of flow rates.

For interill erodibility the soils and overburdens are related to texture in very different ways. For soils, correlations are increasingly positive for sizes approaching the 20 μm–1 mm class and become increasingly *negative* for sizes approaching the 0–20 μm class. This pattern is not repeated for the overburdens. These differences may be due to the different processes of genesis of fine particles for soils and overburdens, leading to particles with very different behavioral properties. Soil particles have been derived from chemical and physical weathering over geological time periods, while overburden particles have been derived through physical crushing and pulverising of rock, usually followed by only a few years of weathering. For overburdens, strong negative correlations were found for the size classes >2 mm, reflecting the influence of the high rock content on erodibility

In summarising the texture and erodibility data, it appears that rill erodibility is negatively correlated with particle classes <20 μm and higher than about 5–10 mm for both soils and overburdens. Interill erodibility is related to texture in different ways for soils and overburdens. For soils, increasing silt and clay is related to decreasing erodibility, while for overburdens the opposite is true. Interill erodibility on overburdens is also strongly negatively correlated with the proportion of particles >5 mm, reflecting the significant levels of rock present in these media.

Predictive equations

Based on the analysis presented in the previous section, regression procedures were carried out to develop predictive equations for rill and interill erodibility. The aim was to be able to achieve a coefficient of determination ≥0.6, using 3 or less soil properties to predict erodibility coefficients. Media properties with a high inter-correlation with other properties, or a low correlation with erodibility, were identified and removed from further analysis. Texture classes identified in the previous section as having high correlations with erodibility were included in the analysis. Where a satisfactory r^2 value could not be achieved using the above properties, logarithms of the property values were calculated and included in the regression.

The following equations for the prediction of interill and rill erodibility values for use in Eqns 3 and 6 were developed using stepwise multiple regression procedures.

Soils:

$$\text{Interill erodibility } (10^{-6} \times K_i) = 3.72 - 0.8891 * \text{OC} \quad (r^2 = 0.59) \tag{7}$$

$$\text{Rill erodibility } (K_{r3}) = 63.96 + 0.00008797*(\%0.02\text{–}1\text{ mm})^3 - 3.20*\text{pH} - 30.47*\text{BD} \quad (r^2 = 0.71) \tag{8}$$

Overburdens:

$$\text{Interill erodibility } (10^{-6} \times K_i) = -2.8307 + 0.11089*\text{clay} + 4.13*\text{D20} \quad (r^2 = 0.82) \tag{9}$$

$$\text{Rill erodibility } (K_{r3}) = 25.02 - 30.55*\text{D20} - 0.18*\text{ESP} + 4.80*\text{EC} \quad (r^2 = 0.61) \tag{10}$$

OC is organic carbon content as a percentage; (%0.02–1 mm) is % by weight in this particle size class; clay is % by weight <2 μm; BD is bulk density (g/cm^3); ESP is exchangeable sodium percentage; EC is electrical conductivity (dS/m); and D20 is dispersion ratio silt and clay (as a fraction). Soils from Blackwater and Curragh were not included in the soils analysis.

Thus, for the soils, interill erodibility was negatively related to the level of organic carbon, while rill erodibility was positively related to the proportion of particles in the 0.02–1.0 mm range and negatively related to the pH and bulk density. For overburdens, positive relationships with the clay content and the silt and clay dispersion ratio were found for interill erodibility. For rill erodibility, a negative relationship with the silt and clay dispersion ratio and the ESP, and positive relationships with the EC, were found.

Fig. 4 plots the predicted rill and interill erodibility values from Eqns 7–10 against the observed values used to develop the above multiple regression equations. The results indicate that the multiple regression equations developed from this research are

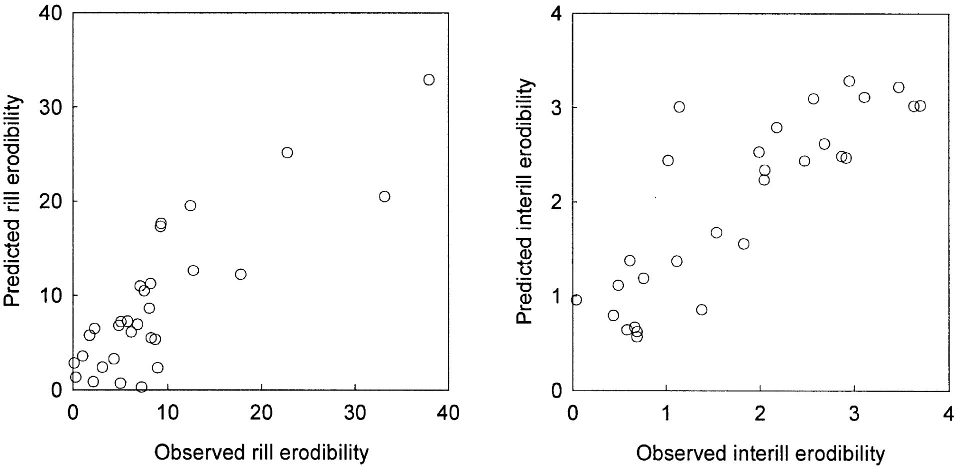

Fig. 4. Observed rill and interill erodibility values plotted against predicted values from Eqns 7–10.

appropriate for the prediction of erodibility for the range of media types investigated in this study.

Discussion

Bryan *et al.* (1989) state that the concept of soil erodibility has evolved as a vague, empirical summation of the erosional response of soils, and is based around 3 implicit assumptions:

(*1*) a soil erodibility can be defined which is valid for all erosional processes;
(*2*) soil erodibility can be uniquely defined by measurement of a few, usually physical, soil properties; and
(*3*) relative erodibility ranking is not affected by short-term changes, particularly in soil moisture status.

Bryan *et al.* (1989) concluded that all 3 of these assumptions are more or less incorrect, and the results from this study support that view. In relation to point (*1*), the results in Table 3 illustrate that a medium (e.g. Saraji overburden) can be highly susceptible to interill erosion and yet display a relatively low susceptibility to rill erosion. The opposite can also be true (e.g. Blackwater overburden). Clearly, a medium's susceptibility to erosion is specific to particular forms of erosive stress.

The falsity of point (*2*) is displayed by Table 4. Erodibility cannot be uniquely defined for all media types by measurement of a few simple media properties. A property which is positively correlated with erodibility for one group of media (e.g. overburdens) may be negatively correlated for another group (e.g. soils).

The effect of short-term changes on erodibility (point *3*) due to moisture content and bulk density were shown by a soil from Curragh mine, where erosion rates varied by a factor of 3 depending on the initial condition of the soil (Fig. 3). Erodibility is clearly affected by soil properties that vary temporally both in the short and long term.

This research has gone some way to addressing the above listed limitations to the erodibility concept. Firstly, erosion models have been used where processes have been separated to some extent. Hydrologic processes are separated from erosion processes, and within the erosion component, rill and interill processes are considered separately. The splitting of the dataset into subgroups of soils-only and overburdens-only recognises that there is no one unique set of physical properties that can be used to predict erodibility under all conditions. This approach has enabled the development of Eqns 7–10 for the prediction of erodibility values for soils and overburdens from Queensland open-cut mines. Like all the other multiple regression equations for erodibility prediction that have been developed before (Wischmeier and Mannering 1969; Elliot *et al.* 1989*b*), these equations should only be used within the range of conditions from which they were developed.

Some authors (Loch *et al.* 1998) argue that the soil properties which *directly* effect erosion rates, principally sediment detachment and transport, are most likely to be universal indicators of erodibility. Loch *et al*. (1988) considered the size and wet-density of the sediment on the soil surface under rainfall to be a key indicator of erodibility. Analysis of this type was found to be difficult in this study, as many of the overburdens formed strong surface seals under rainfall and the surface size distribution could not be easily determined. However, those observations indicate that there may be benefits from including the cohesiveness of the surface layer in the range of properties considered when investigating erodibility—especially for unstable materials such as the sodic spoils. Despite difficulties with the method of sampling the soil surface, the strongly aggregated clay soils did appear to produce very low density aggregates and were amongst the most erodible of all the media, consistent with the approach discussed by Loch *et al*. (1998).

Summary

A study was undertaken to enable the prediction of the erodibility of open-cut coal mine soils and overburdens from the easily measured physical and chemical characteristics of the media. It was found that erodibility was not linked to media properties in a unique way, but rather that different properties were best for predicting erodibility under different conditions. Four equations were developed to enable the prediction of rill and interill erodibility values for soils and overburdens from Queensland open-cut coal mines.

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