Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981). IAHS Publ. no. 133.

Soil erosion under simulated rainfall in the field and laboratory: variability of erosion under controlled conditions

RORKE B. BRYAN
Department of Geography, Scarborough College, University of Toronto, Canada

ABSTRACT Although rainfall simulation is widely used, little attempt has been made to standardize simulators or test procedures, and comparability of results has suffered. Even where major rainfall parameters are held constant detailed design variations induce significant comparison errors. These are examined with new experimental data. The problems of extrapolation or comparison of results where test procedures vary are examined, and the requirement for standardization is stressed. Even where simulators and test procedures are standardized soil loss results show considerable variation. This is examined in the light of new experimental data which show that rainfall simulation can only be employed as a precise experimental tool if considerable test replication is practised.

Erosion du sol sous des pluies simulées sur le terrain et au laboratoire: variabilité de l'érosion dans des conditions contrôlées

RESUME Quoique les simulateurs de pluie soient largement untilisés, peu de tentatives ont été faites pour standardiser ces simulateurs et les protocoles d'essais, et les possibilités de comparaison en ont souffert. Même lorsque les paramètres principaux de la pluie ont été maintenus constants des différences de détail entre les divers dispositifs entraînent dans les comparaisons des erreurs significatives. Celles ci sont etudiées avec de nouvelles données expérimentales. Les problèmes d'extrapolation ou de comparaison des résultats lorsque les protocoles d'essais varient sont étudiés et on souligne le besoin d'une standardisation. Même lorsque les simulateurs et les protocoles d'essais sont standardisés, les résultats concernant les pertes en sol présentent des variations considérables. Ceci est examiné à la lumière de nouvelles données expérimentales qui montrent que les simulateurs de pluie peuvent être employés comme outil expérimental précis uniquement lorsque un grand nombre de répétitions des essais sont effectuées.

INTRODUCTION

Rainfall simulation is increasingly widely used by hydrologists, geomorphologists and soil conservationists involved in theoretical research and its applications to field problems. It is attractive as it provides some possibility for control of a critical variable, and therefore for isolation of other sources of variation. It also permits precise replication of storm events and sequences which recur in nature only over a prolonged period. Simulation has been used in many projects and a wide variety of simulators have evolved in response to precise research requirements and to local technical, financial or logistic conditions. While this is comprehensible it has seriously limited the scientific use which can be made of data obtained.

ACCURACY OF SIMULATION OF NATURAL RAINFALL CHARACTERISTICS

The fundamental problem is the limited accuracy with which simulators replicate natural rainfall characteristics. This is a primary objective in simulator design, but in no case is perfect replication achieved. Attention has been focussed primarily on certain critical characteristics such as duration, recurrence frequency, intensity, drop size and kinetic energy generated. Duration and recurrence are easily replicated but intensity/drop size/energy relationships present much greater difficulty. Terminal velocity in free fall is achieved for large raindrops only after fall heights of approximately 12 m, and even very high simulators, such as De Ploey's laboratory unit, achieve only about 95% of terminal velocity. Entirely satisfactory simulation of natural intensity/drop size/energy relationships is claimed only for a few elaborate and expensive units such as those of Meyer & McCune (1958) and Morin *et al.* (1967), and in each case this is achieved by replacing continuous with intermittent rainfall. Even in the absence of a surface water film this can produce fluctuating pore-water pressures and unnatural disturbance of soil detachment processes (Sloneker & Moldenhauer, 1974; Sloneker *et al.*, 1974). When surface water is present intermittent rainfall will generate fluctuating hydraulic conditions (Savat, 1977; Yoon & Wenzel, 1971) which can markedly affect detachment threshold conditions.

Apart from the problem of intermittent application, few simulators provide for the random spatial variations of intensity and raindrop impact now known to characterize natural rainfall; on the contrary, most units are designed to provide uniform coverage. Likewise few units provide any possibility for varying intensity or drop size characteristics during a rainstorm; recent observations (Morgan, 1979) indicate that intense convective rainstorms frequently start with very short (up to 5 min) periods of rain at very high rates (up to 250 mm h^{-1}) before more moderate conditions are established.

COMPARABILITY OF RESULTS OBTAINED WITH DIFFERENT SIMULATORS

Influence of simulator design

The brief comments above and an abundance of development work on different simulators suggest that the problem of perfect rainfall simulation is intractable; although it may be solved by prolonged effort, any resulting unit is liable to be too complex, cumbersome or expensive for widespread adoption. This does not negate the value of "imperfect" units in specific research projects, but focusses attention on the comparability of results. If simulation is perfect and test procedures similar, results are automatically comparable; otherwise they will be immediately comparable only between units which are "imperfect" in precisely the same details.

The interactions of rainfall and soil characteristics which control infiltration and flow initiation and which, together with hydraulic variables, determine soil detachment, are extremely complex. Any small variation in a contributory factor can disturb relationships and significantly alter results. Sloneker *et al.* (1974), for example, found that an increase in the "off-time" in intermittent sprinkling from 50 to 40 s changed median pore pressure in sand from -7.3 to -15.3 mbar, which can change sand detachment rate by up to 50% (Sloneker *et al.*, 1976). Likewise very minor variations in median drop size can markedly affect kinetic energy reproduction, with repercussions on detachment processes and rates. These, like the effects of intermittent periodicity variations, will certainly be affected in nature and magnitude by variations in soil properties. The net result is that even where major rainfall parameters are held constant, variations in minor properties can alter results sufficiently to invalidate comparisons. Although the effects of some minor factors are known qualitatively far too few data are available to permit confident extrapolation of results.

It is surprising that few experiments have been carried out to test the significance of the effects of simulator design on soil detachment. Such an experiment is currently in progress in Leuven and Toronto, using two compact laboratory simulators. The Leuven unit applies rainfall continuously from a drip-screen with a fall height of 7.2 m, while the Toronto unit provides intermittent application from spray arcs with a fall height of 2.2 m. Both units have been described in detail elsewhere (Bryan, 1974a; De Ploey *et al.*, 1976). The greater fall height of the Leuven unit provides higher kinetic energy replication, and the continuity of rainfall is also significant. Otherwise rainfall properties are very similar, and all major rainfall parameters have been held constant. Identical samples from a variety of Belgian and Canadian soils are used with both units, testing being carried out on a uniform 10° slope with standardized procedures.

The initial results (Table 1) suggest that although the erodibility ranking is very similar, actual soil loss rates differ markedly, with the Leuven unit giving consistently higher rates. The data include an adjustment for size difference between the Leuven plot (20 x 100 cm) and the Toronto plot (30.5 x 30.5 cm). This assumes that the complete plot area contributes flow and sediment; in fact, Morgan's (1979) observations suggest that virtually all soil detached even on the Toronto plot comes from within 15 cm of the collection trough, in a microscale

Table 1 Soil loss from Belgian and Canadian samples in different rainfall simulators but constant test procedures

Soil type	Soil loss ($g\ mm^{-1}$)	
	Leuven simulator	Toronto simulator
Hart House	0.03	0.03
Lockport	0.46	0.28
Everberg 7	1.25	0.41
Stabroek	1.45	0.35
Pontypool	1.80	0.28
Lier	2.07	0.27
Everberg 5	4.40	0.59

operation of partial area contributions. If this is correct for other plot sizes, then an adjustment factor is not necessary and the spread in erosion rates would be lower than suggested.

The results in Table 1 are tentative and the study is currently being extended to a wider range of soils. Nevertheless they demonstrate that significant discrepancies can arise even when simulators have very similar characteristics and all major rainfall parameters are held constant. Where such similarity is not present, discrepancies must be very much larger. In practice very few simulation experiments are designed to provide a basis for accurate comparison with other studies. Major rainfall parameters such as duration and intensity are usually allowed to vary widely, being determined either by local climatic conditions or, more frequently, by the technical capacity of equipment or the water supply available. This greatly accentuates the problem of result comparison.

Influence of test parameters and procedures

Rainfall intensity and duration Erosional study frequently requires comparison of natural storms of widely varying intensity and duration. The kinetic energy generated is frequently used as a basis for comparison. Various procedures can be used, the most common probably being Wischmeier's EI_{30} factor, incorporated in the universal soil loss equation. Where, as Wischmeier (1977) states, soil erosion and kinetic energy are directly related, this is a valid basis for comparison. This is not always the case as both rainfall intensity and duration can affect soil detachment without direct involvement of kinetic energy (although it is, of course, correlated with both intensity and duration). The very few observations available for very high intensity rainfall (Hudson, 1971) suggest that kinetic energy does not increase significantly as intensity rises above 125 $mm\ h^{-1}$, yet experimental data from Morgan (1979) for 14 soils (Table 2) show, with three exceptions, substantial increase in soil loss as intensity rises from 100 to 200 $mm\ h^{-1}$.

In Africa, Hudson (1971) found that the EI_{30} factor did not predict soil loss as effectively as a measure (the KE>1 factor)

Table 2 Variation in soil loss with rainfall intensity (after Morgan, 1979)

Soil	Soil loss ($g\ m^{-2}\ m^{-1}$)		
	50 mm h^{-1}	100 mm h^{-1}	200 mm h^{-1}
1	0.50	0.29	1.73
2	0.70	14.33	17.70
3	0.82	1.57	7.40
4	0.48	0.68	5.15
5	4.70	12.92	20.58
6	0.32	6.71	12.35
7	1.86	15.18	16.30
8	1.08	1.93	13.60
9	0.28	1.07	1.23
10	0.70	2.61	8.63
11	0.76	1.89	0.76
12	0.86	3.00	2.68
13	1.44	5.58	6.09
14	0.68	5.86	3.48

which eliminated low intensity rains below 25.4 mm h^{-1}, which were found to be essentially non-erosive. Essentially this recognizes that total kinetic energy alone is not always a good basis for comparison. Although the KE>1 factor was found to be effective in Zimbabwe it is not certain that it can be applied uniformly throughout the tropics. In Tanzania, for example, hyetographs for Arusha between 1972 and 1980 show only 19 rainstorms above Hudson's threshold, with a total duration of only 14 h. The highest intensity recorded was 76.0 mm h^{-1}, but in a storm of only 15 min duration. Despite the low frequency of "erosive" rain, soil erosion has been highly active in the area throughout the period, as shown by the gully in Fig. 1, incised between 1974 and 1980.

It is less easy to separate the effect of rainfall duration from that of accumulated kinetic energy. On some soils, the rate of water intake of individual soil particles, as well as the complete soil body, is a critical control on soil entrainment resistance. Montmorillonitic soils frequently have an extremely high water-holding capacity, but this is reached very slowly. In laboratory conditions, sodium-saturated montmorillonite can continue to absorb water for up to 3 weeks. In simulation experiments on montmorillonitic shales in western Canada, Hodges & Bryan (1981) found that rain at 29 mm h^{-1} intensity invariably produced runoff well before the saturation capacity was reached and, with one exception, below the liquid limit. More prolonged rainfall at lower intensities would unquestionably allow this limit to be reached. Runoff starting below saturation is usually attributed to aggregate disintegration and surface sealing or crusting caused by raindrop impact (and therefore related directly to kinetic energy). On many soils this is an important factor, but on the montmorillonitic shales tested field observations showed that raindrop impact was totally ineffective in aggregate disintegration, probably due to high shear strength developed at low moisture contents (Table 3). Runoff invariably started before moisture content increase and shear strength decline reached the point at which aggregates become vulnerable to raindrop impact, and invariably before desiccation cracks sealed (Fig. 2). If rainfall is sufficiently prolonged,

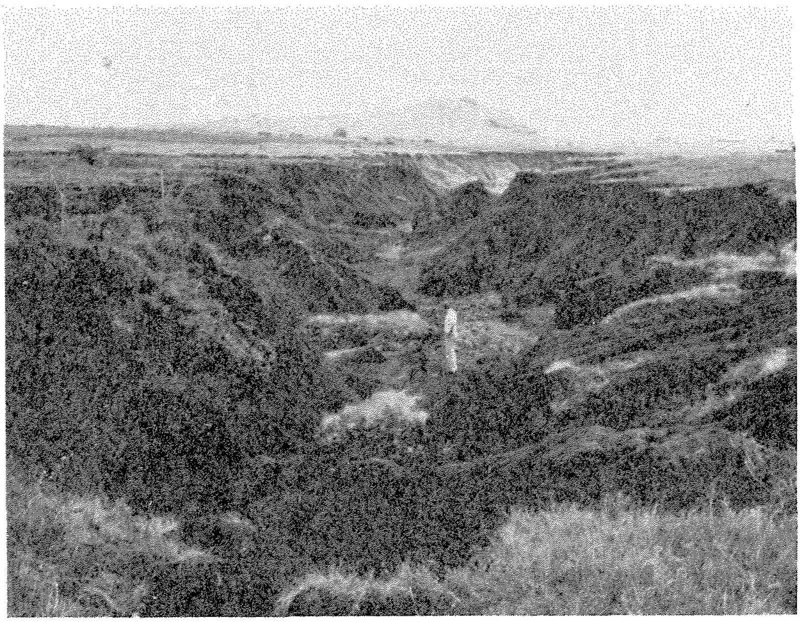

Fig. 1 Gully in Karatu-Oldeani area of Tanzania formed between 1974 and 1980.

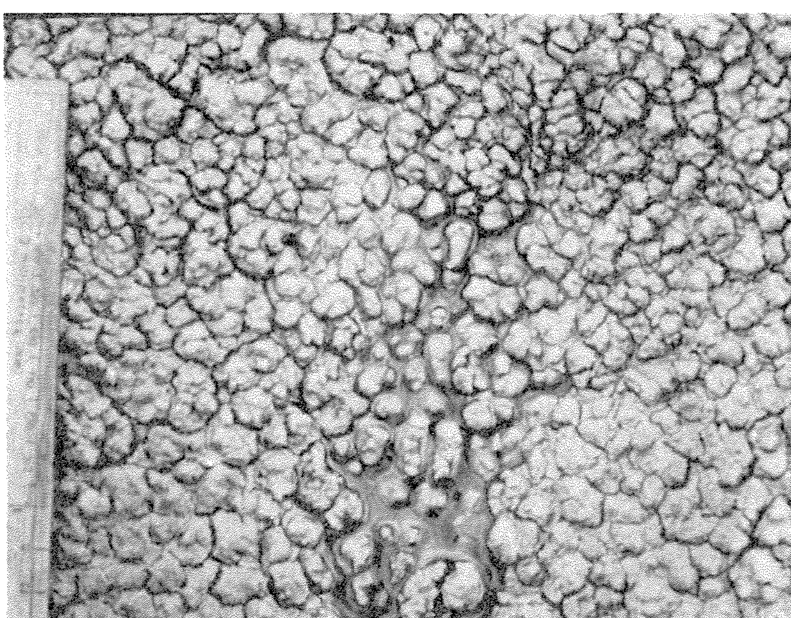

Fig. 2 Initiation of runoff on montmorillonitic shales prior to closing of desiccation cracks.

Table 3 Relationship between moisture content at runoff, saturation water-holding capacity, liquid limit and shear strength for montmorillonitic shales from the Alberta badlands, Canada

Unit	Moisture content at runoff (%)		Saturation water capacity (%)	Liquid limit (%)	Shear strength (kN m^{-2}) for moisture content		
	*D	W			15%	30%	75%
6	86.5	56.6	213	89.5	2.15	14.0	8.0
7	59.2	49.0	172	78.0		75.0	3.0
6-11 (debris)		70.7	146	69.0	240.0	115.0	3.8
10		48.2	137	63.0		90.0	4.0
11		49.7	214	107.0		150.0	9.5
12		85.9	234	93.5	36.0	25.5	16.5
13	69.1	74.8	194	89.5	600.0	55.0	2.5
15	24.7		119	54.5	405.0	35.0	1.3
16	41.0		163	63.0	10.5	6.8	3.7
17	28.8		115	45.5	46.0	15.0	3.4
18	40.1		183	92.5	25.0	16.0	9.2
19	48.9		114	50.5	410.0	26.0	0.8
20	41.9		77	36.5	54.0	15.0	2.8
21	41.6		116	53.0	170.0	23.0	1.7
22	46.6	55.0	130	35.0	225.0	45.0	5.5
24	38.1	41.6	244	28.2	330.0	30.0	1.2
26		31.0	234	62.0	86.0	31.0	8.0
27		19.9	215	81.5	110.0	30.0	6.0
29		50.5	225	110.5	400.0	76.0	8.6
30		48.5	248	57.0	100.0	50.0	21.0

*D, W = Dry, Wet antecedent moisture conditions.

aggregates will eventually reach the liquid limit and shear strength will decline sufficiently to make raindrop impact an effective force. By this stage, however, much of the surface will be partially protected by a surface water film. In any case very few natural storms are sufficiently prolonged for this level to be approached, and so in this environment it is the amount of water supplied rather than the kinetic energy which is the critical rainfall factor.

Slope parameters Many attempts have been made to quantify the general, though indirect, relationship between soil loss and slope parameters (e.g. Neal, 1937; Zingg, 1940; Young & Mutchler, 1969). Most attention has focussed on slope angle both because of the difficulty of replicating long slopes in the laboratory, or finding extensive homogeneous conditions in the field. Most studies have related soil loss and slope angle by power or logarithmic functions though Smith & Wischmeier (1957) and Bryan (1979) found polynomial functions more appropriate on steep slopes. The largest body of data on the influence of slope parameters comes from the erosion plots of the US Soil Conservation Service and are incorporated in the universal soil loss equation as a combined topographic factor. These data are all derived from plots 22.34 m long at inclinations of 5°. Although nomograph extrapolations to slopes of 31° and 615.38 m are provided (Wischmeier, 1977), the reliability of such extrapolation is questionable. In any case, as Bryan (1979) has shown, it is difficult to justify the use of any single mathematical function as the relationship varies, not only between soils, but for each soil with different antecedent moisture conditions. The data in Fig. 3 encourage no confidence in extrapolation to different slope conditions on the basis of generalized functions.

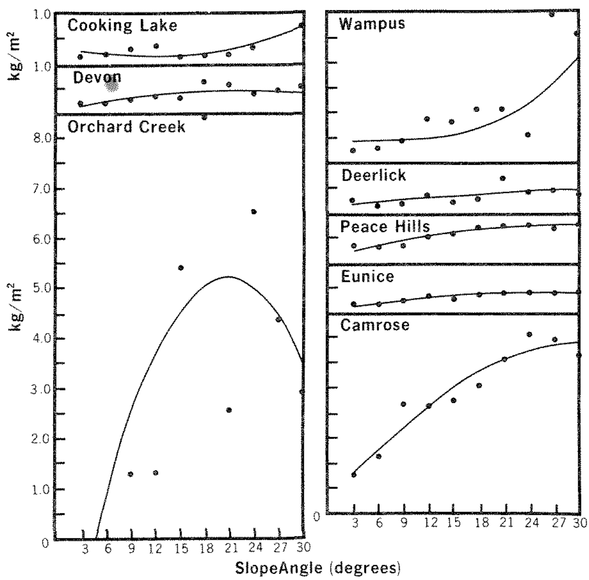

Fig. 3 Variations in relationship between slope angle and soil loss for eight Alberta soils.

Sample and site preparation Attempts are rarely made to replicate precise preparation conditions yet small variations can affect soil loss greatly. Three factors are particularly important: vegetation cover, antecedent moisture and physical soil disturbance. Many simulation tests are carried out on bare plots which improves comparability though the actual impact of "clearing" on soil loss will vary greatly with the vegetation character.

Antecedent moisture content affects runoff incidence and timing and, through shear strength and slaking, entrainment resistance. Although generally recognized, the full implications of this influence are not often considered and few attempts are made to replicate conditions precisely. In some shales, for example, a moisture content variation of 5% can change shear strength, and resistance by 400% (Table 3). In such circumstances simple classification into "wet" and "dry" antecedent conditions is not a sufficiently precise basis for comparison.

Physical disturbance of the soil surface prior to testing can significantly alter soil loss patterns. As all simulation tests are ultimately designed to solve field problems, where possible they should be carried out in the field with soil *in situ*. Even then subtle differences in pre-test treatment, such as the period of exposure without vegetation, may make comparison tenuous. When samples are moved to a laboratory, disturbance becomes greater and less predictable. It is impossible to maintain all sample characteristics intact as the slightest vibration or torsion can change pore fabric and distort hydrological response.

It is impossible to ensure constant disturbance, even with similar soils and procedures, and comparability is inevitably dubious. For this reason Bryan (1968, 1974b) adopted air-drying and sieving, a procedure retained for the comparative tests in Table 1. Although this presents difficulty in extrapolating results to the field it does provide a sounder basis for comparison.

Morgan (1979) compared several preparation procedures in the field and laboratory using different soils and moisture conditions. In the field undisturbed and "tilled" (with a trowel) plots were treated, while in the laboratory "block", "tilled" and sieved samples were compared. In each case both rainwash and splash were measured. The results showed very complex variations in soil loss between treatment procedures, and none of the laboratory results were correlated with all field soil loss measurements. "Block" samples were significantly correlated only with rainwash on undisturbed soils under class B (Horton, 1933) storms. Rainwash on "tilled" soils was significantly correlated only with sieved samples in the laboratory and only for class A storms. Field splash on both "tilled" and undisturbed soils was significantly correlated with "tilled" samples in all storm conditions, and selectively with sieved samples, but not with "block" samples. Although these results are tentative, being based only on 14 soils, they emphasize the difficulty of comparing results based on different physical treatments of the soil.

The preceding examples and discussion clearly show that although simulation tests have provided considerable local information on geomorphic, hydrologic and pedologic processes, they do not yet provide a sound basis for generalization. While the reasons underlying the diversity of units and procedures are understood, it does appear that much of the potential value of the technique is missed because standardized units and procedures are not adopted. One set of procedures will not be suitable for all applications but it should be possible to establish a limited set of recommendations for certain types of study. With regard to simulator units, the search for perfect simulation has overshadowed the benefits of standardization. Provided a reasonable standard of simulation is achieved, with well-defined divergence from natural conditions, it does not matter much which unit is chosen. To ensure use in a wide range of field circumstances it should be cheap, simple and portable. If it can also be used in the laboratory its utility will be greatly increased.

VARIABILITY OF SOIL LOSS IN STANDARDIZED CONDITIONS

Although simulation offers good possibilities for experimental replication few attempts have been made to determine soil loss variability when major contributory factors are held constant. Luk (1975) carried out nine test replicates on a Rocky Mt soil on a 30° slope under 102 mm h^{-1} rainfall and found that soil loss ranged from 1.1 to 1.9 g m^{-2} min^{-1} with a variation coefficient ((standard deviation/mean) x 100) of 18.4%. Bryan (1979) completed eight replicates on a chernozem and nine on a calcareous loess with similar rainfall on a 15° slope and found soil loss to range from 3.3 to 15.7 g m^{-2} min^{-1} (CV 16.6%) and from 18.3 to 47.3 g m^{-2} min^{-1} (CV 39.1%) respectively. In California, Singer *et al.* (1977) tested six bare and six vegetated replicates of an Auburn soil on a 4° slope, finding soil loss of 9.7 to 15.7 g m^{-2} min^{-1} (CV 14.9%) and 6.5 to 12.8 g m^{-2} min^{-1} (CV 26.9%) respectively. While these data are very limited, collectively they indicate that even where control of test procedures is very close, substantial unexplained variations remain.

An experiment to establish the magnitude and sources of soil loss variability was initiated in Toronto using the simulator used in the tests previously described. Three soils, the Lockport, Milliken and Pontypool, were selected to provide a range of textural and aggregation characteristics. Large, homogenized samples were prepared and 20 test replicates of each were carried out on a 12.5° slope under 63.5 mm h^{-1} rainfall. Extreme care was taken to ensure precise replication of all test procedures, but nevertheless substantial variation in soil loss was recorded (Table 4).

Table 4 Variability of soil loss and selected variables for three Ontario soils

Variable	Soil		
	Lockport	Pontypool	Milliken
Wash loss (g m^{-2} mm^{-1})	7.0	19.4	2.3
δ	1.7	2.3	0.6
CV	24.3	11.9	26.1
Splash loss (g m^{-2} mm^{-1})	0.6	0.9	0.5
δ	0.2	0.2	0.1
CV	33.3	22.2	20.0
Total loss (g m^{-2} mm^{-1})	7.5	20.3	2.8
δ	1.8	2.3	0.6
CV	24.0	11.3	21.43
Bulk density (g cm^{-3})	1.3	1.3	1.6
δ	0.02	0.03	0.04
CV	1.8	2.3	2.6
Water stable aggregates >0.5 mm (%)	13.9	1.5	3.6
δ	2.8	0.3	0.9
CV	20.1	19.6	24.5
aggregates 5.66–6.73 mm (no. of drops to break)	206.5	15.8	50.5
δ	166.1	7.9	53.9
CV	80.4	50.2	106.9
aggregates 1–2.2 mm (no. of drops to break)	103.5	4.3	8.0
δ	67.9	2.5	4.8
CV	65.8	52.2	60.4

Parallel tests of a number of variables were carried out including bulk density, water-stable aggregation by wet-sieving and drop-testing and detailed analysis of surface micro-relief. These have been described in detail elsewhere (Bryan & Luk, 1981). Variation comparable to that of soil loss was shown only by drop-test aggregate stability and surface roughness. Initial data suggest that variability reflects primarily the superimposition of the effects of two critical variables, raindrops and aggregates, both with wide size spectra. Aggregate size, ranging from 0.002 to 8 mm diameter, strongly influences entrainment resistance and surface roughness, and therefore surface water layer depth. The interaction of varying raindrop sizes on a surface water layer of varying depth, with aggregates of differing size and stability appears more than adequate to explain the variability observed. The interaction changes as the test proceeds, due to increasing runoff, sporadic surface sealing, and selective removal and disintegration of aggregates.

The interacting factors described constitute a source of variability which cannot easily be controlled even in laboratory experiments, and which is liable to show even greater magnitude in the field. It can be accounted for successfully only by replicating tests until a satisfactory average is reached. Test results were analysed to determine the accuracy (i.e. proximity to the average) of soil loss predictions based on different numbers of test replicates (Fig. 4). The curves show that the

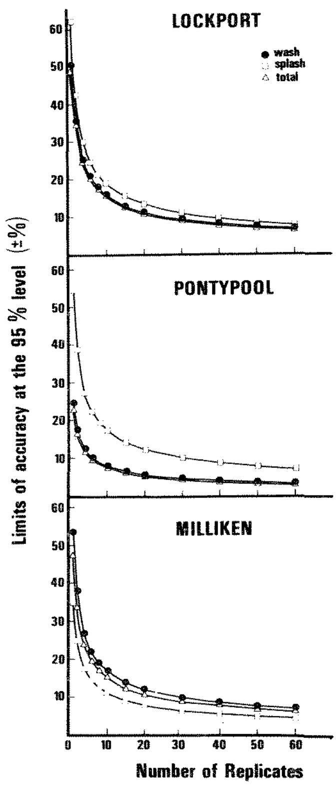

Fig. 4 Curves showing increase in soil loss prediction accuracy with increasing test replication.

accuracy of predictions from a single test ranges from ±25 to ±50%. Virtually all simulation studies apart from the three listed above, base conclusions on the results of a single test.

The acceptability of results with an accuracy of ±25% or more depends on the objectives of the study. Where simulation is being used for rapid reconnaissance of field problems, particularly in developing countries, it may be justifiable. On the slopes of Mt Meru in Tanzania, the author estimated annual soil loss at 706 t ha^{-1} using standard Wischmeier procedures. Clearly in such circumstances even a prediction of ±50% accuracy can be useful. Any more precise scientific use of rainfall simulation unquestionably requires a significant number of test replicates if spurious results are to be avoided.

ACKNOWLEDGEMENTS This paper relies heavily on joint studies with a number of colleagues. My thanks are due to Jan De Ploey, Shiu Luk, Chris Morgan and Bill Hodges. Experimental work was funded by grants from the Natural Sciences and Engineering Research Council, Canada.

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