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Determining the susceptibility of soils materials to erosion by rain-impacted flows

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Abstract

Conceptually, rain has a capacity to cause erosion (rainfall erosivity) and soils have a susceptibility to erosion by rainfall (soil erodibility) but no absolute measure of rainfall erosivity exists. Consequently, soil erodibility is nothing more than an empirical coefficient in the relationship between an index of rainfall erosivity and soil loss. Erosion by rain-impacted flow is influenced by the size, velocity and impact frequency of the raindrops but also flow depth and velocity. Experiments with artificial rainfall falling on sloping surfaces in the field usually do not enable flow depth and velocity to be well measured or controlled. Also, sprays produce artificial rainfall where the spatial uniformity in rainfall intensity, drop size and frequency is often less than desirable. Artificial rainfall produced by pendant drop formers can produce rainfall that has better spatial uniformity. Equipment for controlling flow depth and velocity over eroding surfaces has been developed and used to calibrate the effect of flow depth on the discharge of sediment by rain-impacted flow using artificial rainfall having a uniform drop-size distribution under laboratory conditions. Once calibrated, laboratory experiments can be conducted to rank soils according to their susceptibility to erosion under the flows impacted by the artificial rainfall under conditions where the erosive stress applied to the eroding surface is well controlled.

Key Words: Rainfall erosion; soil erodibility; laboratory experiments; rainfall uniformity.

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
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Published: 1 February 2016

28 # 1 Introduction

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30 Conceptually, rain has a capacity to cause erosion (rainfall erosivity) and soils have a
31 susceptibility to erosion by rainfall (soil erodibility). Rainfall erosion is a complex process and, in
32 reality, no absolute measure of rainfall erosivity exists. Various parameters (eg. rainfall kinetic energy)
33 and combinations of parameters (eg. product of storm rainfall energy and the maximum 30-minute
34 intensity) are used as indices of rainfall erosivity and, as a consequence, soil erodibility is nothing more
35 than an empirical coefficient in the relationship between an index of rainfall erosivity and soil loss. Also
36 the ranking of soils according to their erodibility values can vary depending on how those erodibilities
37 are determined experimentally and the model being used. For example, Kinnell and Risse (1998)
38 presented soil erodibility values in SI units obtained using runoff and soil loss plot data at a number of
39 locations in the USA for the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1965, 1978),
40 which uses the EI_{30} as the event erosivity index, and the USLE-M which uses the product of the runoff
41 ratio (Q_R) and EI_{30}. Table 1 shows the ranking obtained using the soil erodibilities for the USLE (K)
42 published by Risse et al (1993) and the erodibilities observed Kinnell and Risse for the USLE and the
43 USLE-M (K_{UM}) for the bare fallow plots at 14 locations. All three rankings are different. In addition
44 field experiments designed to determine K factor values using artificial rainfall in the USA measure soil
45 loss under different moisture states (dry, wet, very wet) and weight the result so as to provide an
46 estimate of K for central USA (Romkens, 1985). Consequently, K factor values determined using the
47 soil erodibility nomograph (Wischmeier et al, 1971) need to be adjusted for the difference in climate
48 when applied outside that geographic area (USDA, 2008).

49

50 Modern understanding of rainfall erosion recognizes that rainfall erosion is caused by the
51 expenditure of the kinetic energies of raindrops and surface water flows acting either singly or together.
52 Detachment of soil material from the soil surface is essential before the transport of soil material away
53 from the site of detachment leads to soil erosion. Detachment in sheet and interrill erosion which erode
54 the most chemically active layer of the soil, the soil surface, is dominated by the expenditure of the

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

kinetic energy of the impacting raindrops. Raindrop impact is also involved in transporting soil particles in rain-impacted flows. The WEPP model ((Flanagan and Nearing, 1995) was developed to predict soil loss by modelling flow driven erosion in rills and raindrop driven erosion in interrill areas as separate processes. In the WEPP interrill erosion model, the event erosivity index is the product of the runoff rate (q_w) and rainfall intensity (I) so that D_s (mass/area/time), the rate sediment is discharged from the interrill area, is given by

$$D_s = k_i\, q_w\, I\, S_f \qquad (1)$$

where, k_i is the interrill erodibility and S_f is a function of slope gradient. However, the ranking of the soils in the field experiments of Elliot (1989) depends on whether the plots had inclined surfaces similar to those used in ridge tillage agricultural systems or were relatively flat (Table 2). The correlation between the interrill erodibilities on the flat and ridged plots was also poor (Figure 1). One reason for this is that sediment discharge rate ($q_{s,}$, mass/width/time) generated by raindrop-induced saltation that often controls erosion on sheet and interrill areas is influenced by a water depth (h), drop size and flow velocity (u),

$$q_s(h,d) = k_{sd}\, u\, I_d\, f[h,d] \qquad (2)$$

where k_{sd} is a coefficient that depends the characteristics of material being eroded, u is flow velocity, I_d is the intensity of the rain made up of drops of size d, and f[h,d] is a function accounting for the effect on sediment discharge of the interaction between flow depth (h) and drop size (Kinnell, 1993b), but the effects of u, I_d, h and d are not taken into account in Eq. (1). Many subsequent experiments have been performed in many parts of the world, in some cases, the surfaces have been inclined at angles commonly observed in ridge tillage systems used in agriculture, but in many cases, relatively flat surfaces have been used. Consequently, given the results presented in Table 2, misleading modelled results may have been produced using interrill erodibilities from many experiments because of the lack of adequate control of the factors that influence soil loss generated by rain-impacted flows in those experiments.

Rain-impacted flows dominate erosion in sheet and interrill erosion areas. As noted above, these areas are important given that erosion removes soil from the soil surface and usually, the soil

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
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surface is the most chemically rich and active part of the soil. Consequently, it is important to determine the susceptibility of soil surfaces to erosion by rain-impacted flows when the factors that influence soil loss generated by rain-impacted flows are known and well controlled. As demonstrated here, this is possible under laboratory conditions.

2 Equipment

The objective of the equipment described here is to produce the situation where an erodible surface is eroded by rain-impacted flow where flow depth and velocity are controlled in order to control the erosive stress applied by the impacting raindrops to the eroding surface. The apparatus shown in Figure 2 is a modification of the one originally developed by Moss and Green (1983). Basically, the erodible material is contained in a box within a flume with an adjustable weir to facilitate the control of flow depth and velocity. A ripple guard is placed at the downstream end to prevent ripples produced by drop impacts affecting the capacity of the weir to control flow depth and velocity. Inflows are controlled so that, together with adjustments to the height of the weir, flow depths and velocities can be set. A rain bleed is used to bleed water from the flume when rainfall is applied in order to maintain the outflow at the inflow rate. This bleed is of major importance in obtaining flow depth and velocity control when flows are very shallow. In experiments using sand by Moss and Green (1983) and Kinnell (1988, 1993b), the eroding area was 500 mm by 500 mm. In the experiments by Kinnell, flow depth prior to rain was measured by having a removable horizontal bridge above the bed and measuring the distance from the top of the bridge to the eroding surface when there was no flow, and the distance to the water surface when the was flow using a vernier depth gauge with a sharp pointed end. Contact with the water and erodible surfaces was detected electrically. A pressure port located at the bottom end of the sand box enabled the flow depth to be monitored during rain when eroding sand (Kinnell, 1988).

Often, laboratory experiments on rainfall erosion involve packing loose soil material into boxes and exposing them to rain. Loose soil can packed into the box as an alternative to sand in order to erode

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

soil under controlled flow conditions. However, a version of the apparatus has also been developed that enables experiments to be undertaken using intact soil monoliths having a surface area 250 mm wide by 500 mm long (Kinnell and McLachlan, 1989). Experiments have been performed on surface soils from Ginninderra near Canberra, Australia and near Coolabah in New South Wales using this apparatus. Metal sampling frames as depicted in Figure 3 were used to collect blocks of soil 500 mm long, 250 mm wide and 100 mm deep. The area to be taken was dug around to produce a block of soil a little bigger than 500 mm by 250 mm by 100 mm deep. The frame was bevelled on the bottom edged to aid cutting the soil as it was pushed down over the block. Once in place, 125 mm by 5.6 mm nails were then hammered through the sides to provide a support structure. The bottom of the block was then cut to free the monolith and the frame tipped gently on its side. The bottom of the monolith was then trimmed square with the base and the monolith tipped back onto a supporting base of marine ply having an area a little larger than 500 mm by 250 mm. A similar piece of wood was placed on the top of the frame and straps used to make a package for transport. Prior to the experiments with rain-impacted flow, the top piece of wood was removed and the frame containing the soil supported by the marine ply base placed in the flume. The monolith was then saturated by wetting from the bottom. Each monolith was subjected to 10 minute of rainfall with d = 2.7 mm produced 11.2 m above the surface and a rainfall intensity of 64 mm/h with flow depth at the maximum and u = 20 mm/s as a pre-treatment. Then 10 mins of rain was applied at each of 4 flow depths with I_d = 64 mm/h and u = 20 mm/s with flow depths decreasing over the range 7.5 mm to 3.2 mm.

Some soil particles detached by raindrops impacted flows travel in the flow in suspension while others saltate or roll along the surface. Saltation and rolling can occur in unimpacted flows only if they have flow velocities that exceed certain critical values. Below these critical flow velocities, soil particles may be induced saltate or roll only in association with the impact of individual raindrop impacts. Flow velocities below those causing flow driven saltation and rolling are common in many sheet and interrill erosion areas and consequently, the experiments were undertaken at flow velocities set about 20 mm/s so that only raindrop driven saltation and rolling could occur for particles not travelling in complete suspension.

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

Modules producing pendant raindrops from hypodermic needles 11.2 m above the eroding surface produced the artificial rainfall applied in the experiments reported by Moss and Green (1983) and Kinnell (1988, 1993b). The modules produced drops over an area 1 m by 1 m. The needles were spaced 25 mm apart. Rainfall intensity was controlled using a metering pump because previous work established that using hydrostatic pressure as a mechanism to control rainfall intensity did not provide good temporal control of rainfall intensity. The modules were moved back and forth 250 mm along the line of flow at 4.2 mm/s. Spatial variations in rainfall intensity do occur in rain produced from hypodermic needles due to variations in the drop production rate between nearby needles and variations in the trajectory of drop fall. Moving the modules back and forth helps produce high levels of spatial uniformity in rainfall intensity which are important in facilitating the movement of particles travelling by raindrop induced saltation and rolling (Kinnell, 1991). In raindrop induced saltation and rolling particles move a limited distance from the point of drop impact and remain sitting on top of the soil matrix until disturbed again by a subsequent drop impact. Consequently, any positive or negative variation from the mean in respect to drop size, drop velocity and drop impact frequency at the downstream end of an eroding surface will result in sediment discharges that differ from those where these factors are completely uniform spatially.

3 Calibration

In order to determine soil erodibilities using the apparatus described above, equations that describe the flow depth – drop size function in Eq. (1) specifically for the experimental conditions are needed particularly when, as is often the case in many laboratory situations, drops are travelling at considerably less than terminal velocity. The procedure for setting flow depth involves setting a height for the weir and running a set of inflow rates and measuring the flow depths associated with them. Given data on flow depth and inflow rate, flow velocity is then calculated and the inflow rate meeting the desired flow criteria selected for the erosion experiments.

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

Prior to undertaking the experiments to calibrate flow depth and velocity, the erodible surface should have been prepared and put in place. Experiments for determining f[h,d] for drops travelling at or near terminal velocity by Kinnell (1991, 1993b) were undertaken using beds of 0.2 mm sand, leveled and smoothed prior to flow conditions being set. 0.2 mm sand was also used for the experiments at subterminal velocity (Kinnell, 2005a). Beds of uniform sized sand are best to use since all particles have the same potential rate of travel. The duration of exposure to rain was arbitrarily set at 10 minutes and gave measureable quantities of eroded material without a loss of material sufficient to change the height of the surface appreciably from the original height over the bottom half of the eroding surface. Although 0.2 mm was used here in the calibration exercise, Eq. 2 has been shown to apply to the erosion of beds of sand containing particles ranging in size between 0.1 mm and 0.9 mm (Kinnell 1991, 1993b).

The experiments undertaken by Kinnell (1991, 1993b) showed that the rate sand was discharged varied linearly with rainfall intensity and flow velocity as indicated in Eq.(2). Sediment discharge (q_s, mass/width/time) is given by the product of water discharge (q_w, volume/width/time) and sediment concentration (c_s), the mass of material discharged with the flow per unit volume of water;

$$q_s = q_w c_s \quad (3)$$

so that

$$c_s = q_s / q_w \quad (4)$$

and, from Eq. (1),

$$c_{sd} = k_{sd} I_d f[h,d]/h \quad (5).$$

where c_{sd} is the sediment concentration produced by the impact of drops of size d and k_{sd} is a coefficient related to the susceptibility of the eroding material to erosion. Dividing both sides of Eq. (5) by I_d gives

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

194

195 $$c_{sd}/I_d = k_{sd}\, f[h,d]/h \qquad (6),$$

196

197 Consequently, for an eroding surface of uniform sized sand, using sediment concentration per unit
198 rainfall intensity as the dependent variable provides an equation where the effect of the drop size - flow
199 depth interaction can be evaluated even when rainfall intensity and flow velocity vary. Figure 4 shows
200 the relationship between sediment concentration per unit rainfall intensity and flow depth obtained for
201 2.7 mm drop impacting flows at close to terminal velocity over beds of 0.2 mm sand in experiments
202 reported by Kinnell (1991, 1993b). As illustrated by Figure 5, the relationship between sediment
203 concentration per unit rainfall intensity and flow depth determined for 0.2 mm sand provides a
204 mathematical expression that is linearly related to sediment concentration per unit rainfall intensity for
205 sediment discharged from other sand surfaces and this leads to the equation

206

207 $$c_{sd}/I_d = k_s\,(0.0015\,h^2 - 0.0291\,h + 0.1443) \quad , d=2.7, h<9 \text{ mm} \qquad (7)$$

208

209 where k_s varies with the particle size. In addition, Kinnell and McLachlan (1989) showed that the form
210 of the relationship between sediment concentration and flow depth when rain-impacted flows erode
211 cohesive soil surfaces was the same as that for sand. However, as indicated by Figure 6, a different
212 calibration equation is required when drop size and velocity conditions vary from those used in the
213 experiments that produced Eq. (7).

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SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

4 Ranking surface susceptibility to erosion by rain-impacted flow.

In Eq. (7), k_s for 0.2 mm sand is, in theory, equal to 1.0 so that the k_s values for other sized sands are scaled relative to the susceptibility of 0.2 mm sand to erosion by flows impacted by 2.7 mm drops travelling at near terminal velocity. A more general equation for the effect of drop size and eroding material on the ratio of c_{sd} to I_d is given by

$$c_{sd}/I_d = k_{sd} (a_d h^2 - b_d h + 1.0) \quad (8)$$

where k_{sd} acts as an index of the susceptibility of the eroding surface to erosion by drops of size d, and a_d and b_d are coefficients that vary with d. For 2.7 mm drops travelling at near terminal velocity and h< 9mm, $a_d = 0.0104$ and $b_d = 2.017$. Figure 7 shows the application of Eq. (8) when surfaces of soil monoliths were exposed flows impacted by 2.7 mm raindrops travelling at near terminal velocity in the modified version of the apparatus shown in Figure 1. As noted above, the Ginninderra soil monolith came from bare fallow runoff and soil loss plots near Canberra, Australian Capital Territory (Kinnell, 1983) while the Oakvale monoliths came from a location near Coolabah, New South Wales, Australia and had differing levels of cryptogamic crust cover. k_{sd} in Eq. (8) is an index of the susceptibility of the soil to erosion only in a qualitative sense.

In the experiments preformed with sand, new surfaces were prepared for each rainfall event. In the experiments with soil monoliths, each monolith was eroded by 4 rainfall events starting with 2 rainfall events at the maximum flow depth used. The first event was a pre-treatment but in reality, each rainfall event that precedes another is a pre-treatment to subsequent events. Starting the sequence from the shallowest flow produces a different result (Kinnell et al., 1996).

Over a limited range of flow depths, a linear relationship also exists with the inverse of flow depth minus 0.1 when the 2.7 mm drops fall from 11.2 m (Figure 8);

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

$$c_{sd}/I_d = k_{1sd} / (1/h - 0.1) \quad , d=2.7,\ 3d < h > 4mm \qquad (9)$$

where k_{1sd} is a coefficient that is related to the susceptibility of the soil to erosion by rain impacted flow. The upper depth limit is, in the case of drops travelling at close the terminal velocity, equal to 3d because the cavity carved in the water by the impacting drop had a maximum depth equal to 3d (Engel, 1966). For flow depths less than about 4 mm (1/h = 0.25), the depth of flow imposes an appreciably constraint on particle travel distance so that sediment concentrations divided by 1/h – 0.1 are less than predicted using the relationship for deeper flows .

Figure 9 shows the relationships between the sediment concentrations per unit rainfall intensity for the soil monoliths and 1/h – 0.1. The relative rankings for the susceptibility of the surfaces to erosion using 1/h – 0.1 and $0.0104\ h^2 - 0.2017\ h + 1.0$ are similar (Table 3). Equation 9 was also used to determine the erodibility of microphyte-dominated calcareous soils in woodland near Wentworth, New South Wales, Australia (Eldridge and Kinnell, 1997).

5 Discussion

The method described above is unique to the extent that no other method reported in the literature provides as high a degree of control on the factors known to influence the erosive stress applied to the soil surface when raindrops impact shallow surface water flows. In using the method, the ranking of soils in respect to their susceptibility to erosion is obtained through an empirical factor that results from experiments when flow depth is varied in a manner that controls the erosive stress applied to the soil surface that is not achieved by laboratory and field experiments where natural or artificial rain is applied to inclined surfaces. It can be argued that flow depth is, for a given rainfall, a soil specific property (determined by infiltration, crust formation etc.), so that controlling runoff depth is not

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

required to estimate an erodibility coefficient commonly used in erosion models. However, as illustrated by the erodibility data for WEPP shown in Table 2, that argument is hardly compelling.

The apparatus shown in Figure 2 can be used under artificial rainfall produced by sprays provided that the depth effect is determined for that rainfall producing system. Spray rainfall simulators are widely used because that have a wide drop size distribution that may be similar to those found in rainfall but many different types of nozzle have been used without good knowledge of the variation of the intensity and kinetic energy of the rain within the target area. As demonstrated by Iserloh et al (2013) and Lassuet al (2014), the drop size, drop velocity and drop impact frequency characteristics of rain produced by many rainfall simulators using nozzles are far from spatially uniform. Also, spatial variations in rainfall characteristics can vary with the pressure of the water supplied to the nozzle and, in many cases, the control of that pressure in not well maintained. As noted earlier, spatial variations in rainfall characteristics particularly in the zone near the bottom end of the eroding surface can have an appreciable influence of sediment discharge under rain-impacted flows. The spatial uniformity of the rainfall characteristics, and control of raindrop size and energy, is better maintained in systems the produce rain from drop formers such as described above.

Although the method is based on the model described by Eq. 2, the results from the experiments reported above have been used in a qualitative assessment of the susceptibility of the eroding surfaces rather than as quantitative values of erodibility that can be applied to predicting sheet and interrill erosion even though equations that model the effect of flow depth on f[h,d] over the range of drop sizes commonly observed in natural rainfall exists (Kinnell, 1993b). For a surface of uniform sized sand, the particle size distribution of the eroding surface remains constant with time so that k_{sd} remains constant with time. However, as noted above, some soil particles detached by raindrops impacted flows travel in the flow in suspension while others saltate or roll along the surface and as a consequence, particles of different size travel at different rates from the point where there were initially mobilized. This, in effect, results in fast moving particles being winnowed from the eroding surface so that the particle size composition of the particles sitting on the surface changes with time. Also, loose particles sitting on the

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

surface provide a degree of protection against detachment of soil particles from cohesive soil surfaces (Kinnell 2005b, 2006) with the result that k_{sd} varies with time. As noted above, for each soil surface, 10 mins of rain was applied to at each of 4 flow depths with I_d = 64 mm/h and u = 20 mm/s with flow depths decreasing over the range 7.5 mm to 3.2 mm. Using the reverse sequence with flow depth increasing over the range 3.2 to 7.5 mm resulted in a different value of c_{sd}/I_d being obtained being produced for a given flow depth (Kinnell et al, 1996) as a result of the temporal changes that occur on the eroding soil surface. Varying the time of exposure to rain and the length of the eroding surface may also result in different values of c_{sd}/I_d being produced for a given flow. Erosion by rain-impacted flows involves complex interactions between raindrops, flowing water and the soil surface so that the susceptibility of the soil surface to erosion by rain-impacted flow varies in time and space even when rain and flow characteristics do not.

Although the method described above can be used to provide a qualitative rather than quantitative assessment of the susceptibility of the eroding surfaces to erosion by rain- impacted flows, the high degree of control of the factors that affect the erosive stress provides an environment with a potential to be used in the study of how factors like cohesion affect soil erodibility. It also has the potential to be used in studies on how surfaces eroding by rain-impacted flows mobilize carbon and chemical pollutants to flows that transport them across the landscape.

6 Concluding remarks

Given flow depth, flow velocity, raindrop size, raindrop velocity and raindrop impact frequency influence the erosive nature of rain-impacted flows, it is necessary to control and measure these factors when determining the susceptibility of soil to erosion by rain-impacted flow. The apparatus shown in Figure 2 is designed to produce controlled and measurable flow conditions over the eroding surface. Such conditions are not achievable when applying artificial rainfall on field plots. While sprays from nozzles may produce drop-size distributions comparable to those that occur in natural rainfall, uniform

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

spatial distributions of rainfall intensity, drop sizes and velocities are seldom achieved. Producing drops from pendent drop formers can produce rainfall that is more spatially uniform provided care is taken to ensure that spatial variations produced by the fact that adjacent droppers do not necessarily produce drops at the same rate are dealt with appropriately.

In most practical situations, drops produced from pendant drop formers do not achieve terminal velocity before impacting flows over erodible surfaces. Consequently, a calibration equation for the effect of flow depth needs to be obtained that differs from that shown in Figure 4 in many practical cases. Once that calibration equation has been developed, it can, as illustrated in Figure 7 and Table 3, be used obtain qualitative values of the susceptibility of the soil surfaces to erosion by rain-impacted flow.

In the experiments with soil monoliths reported above, the event duration was arbitrarily set at 10 minutes and using a different event duration may produce different results given that exposure to erosion by rain-impacted flow may cause appreciable changes to occur in the soil surface, particularly if the surface has been recently disturbed. In addition to the development of surface crusts which can cause changes in erodibility to occur during a rainfall event, particles travelling by raindrop-induced saltation and rolling may provide a degree of protection against detachment by raindrop impact (Kinnell 2005b, 2006) and influence how the particle size characteristics of sediment discharged by rain-impacted flow varies over time (Kinnell, 2009). These factors need to be considered when interpreting results for experiments involving rain-impacted flows. Also, monitoring both sediment discharge and composition may facilitate studies on the effects of factors such as soil chemistry and aggregate stability on erosion by rain-impacted flows.

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

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Manuscript under review for journal SOIL
Published: 1 February 2016

Table 1. Soil erodibilities in SI units associated with the USLE published by Risse et al (1993) and the values observed by Kinnell and Risse (1998) for the USLE and USLE-M models

Erodibility (t hr MJ^{-1} mm^{-1})								erodibility relative to that at Arnot		
Rank	location	pub K	location	obs K	Location	K_{UM}	location	pub k	obs K	K_{UM}
1	Arnot	0.0026	Arnot	0.0031	Arnot	0.0088	Arnot	1.0	1.0	1.0
2	Tifton	0.0066	Tifton	0.0067	Tifton	0.0185	Tifton	2.5	2.2	2.1
3	Watkinsville	0.0237	Guthrie	0.0119	Guthrie	0.0256	Watkinsville	9.0	8.5	6.2
4	Madison	0.0290	Presque Isle	0.0162	Statesville	0.0504	Madison	11.0	17.9	11.8
5	Guthrie	0.0290	Castana	0.0262	Presque Isle	0.0536	Guthrie	11.0	3.8	2.9
6	Presque Isle	0.0303	Watkinsville	0.0264	Watkinsville	0.0547	Presque Isle	11.5	5.2	6.1
7	Marcellus	0.0369	Statesville	0.0270	McCredie	0.0728	Marcellus	14.0	12.6	9.5
8	Morris	0.0369	McCredie	0.0327	Castana	0.0737	Morris	14.0	11.1	15.2
9	Castana	0.0435	Morris	0.0345	Marcellus	0.0836	Castana	16.5	8.5	8.4
10	Statesville	0.0474	Marcellus	0.0390	Holly Springs	0.0933	Statesville	18.0	8.7	5.7
11	La Crosse	0.0500	La Crosse	0.0521	La Crosse	0.0996	La Crosse	19.0	16.8	11.3
12	Holly Springs	0.0672	Madison	0.0554	Madison	0.1037	Holly Springs	25.5	21.5	10.6
13	McCredie	0.0817	Bathnay	0.0619	Bathnay	0.1228	McCredie	31.0	11.1	8.3
14	Bathnay	0.1027	Holly Springs	0.0667	Morris	0.1337	Bathnay	39.0	20.0	14.0

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

Table 2 WEPP Interrill erodibilities for flat and ridged plots determined by Kinnell (1993b) from the data presented by Elliot et al (1989).

Interrill erodibility (10^{-6} kg s m^{-4})					K_i relative to Heiden	
rank	Location	Ki.ridge	Location	Ki.flat	Ki.ridge	Ki.flat
1	Heiden	1.62	Portneuf	1.79	1.00	0.53
2	Portneuf	2.31	Sverdrup	2.00	1.43	0.59
3	Sharpsberg	2.51	Barnes-ND	2.02	1.55	0.60
4	Barnes-MN	2.58	Pierre	2.72	1.59	0.81
5	Pierre	2.72	Barnes-MN	2.84	1.68	0.84
6	Barnes-ND	3.06	Woodward	3.04	1.89	0.90
7	Los Banos	3.27	Whitney	3.10	2.02	0.92
8	Williams	3.55	Academy	3.32	2.19	0.99
9	Zahl	3.84	Heiden	3.37	2.37	1.00
10	Academy	3.97	Keith	3.82	2.45	1.13
11	Sverdrup	3.97	Hersh	3.89	2.45	1.15
12	Keith	4.26	Los Banos	4.13	2.63	1.23
13	Whitney	4.38	Zahl	4.19	2.70	1.24
14	Nansene	4.93	Sharpsberg	4.53	3.04	1.34
15	Palouse	5.20	Nansene	4.64	3.21	1.38
16	Amarillo	6.19	Williams	5.10	3.82	1.51
17	Hersh	6.80	Amarillo	5.51	4.20	1.64
18	Woodward	7.56	Palouse	6.41	4.67	1.90

Table 3. Relative susceptibility to erosion by 2.7 mm raindrops travelling at near terminal velocity impacting flows over soil monoliths in the apparatus shown in Figure 1

	relative susceptability	
Soil	Eq. (10)	Eq.(11)
Ginninderra	1.000	1.000
Oakvale D	0.719	0.700
Oakvale IC	0.345	0.351
Oakvale OC	0.077	0.081

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

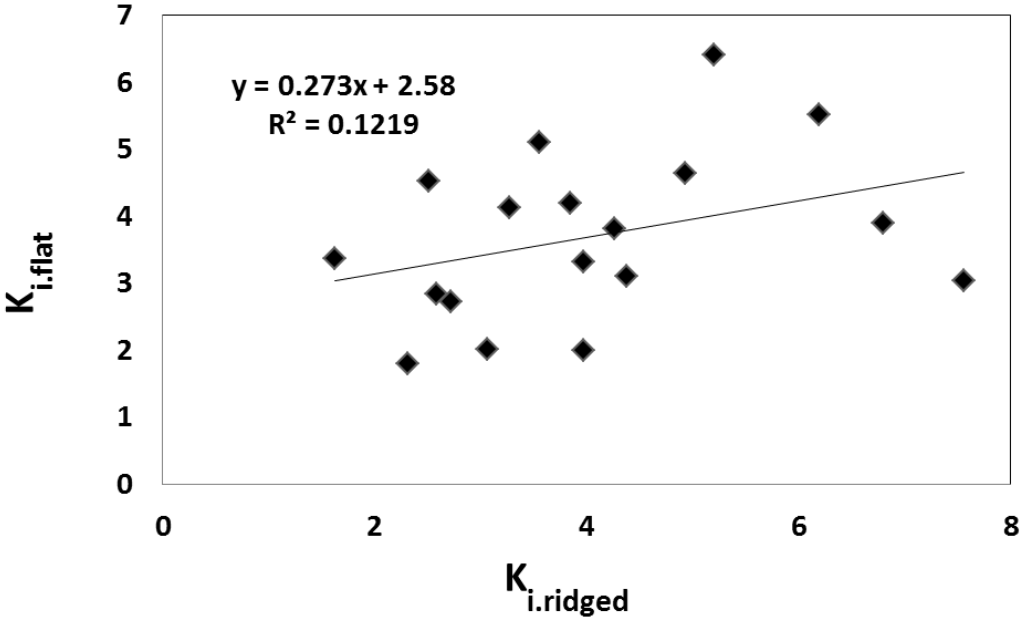

Figure 1. Relationship between flat and ridged erodibilities obtained by Kinnell (1993a) from the experiments of Elliot et al (1989).

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

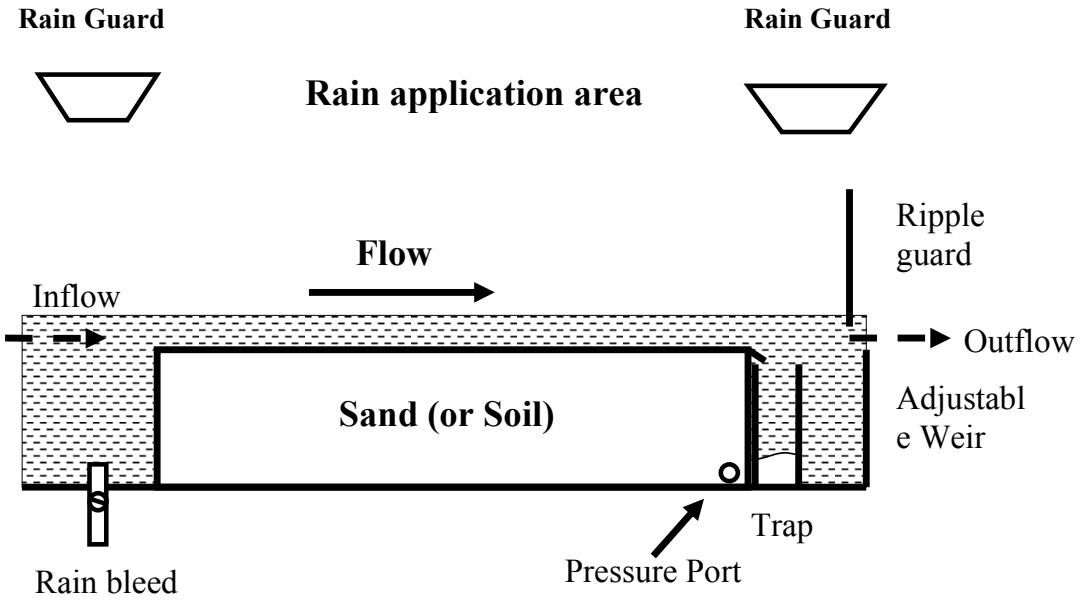

Figure 2. Apparatus used to determine the flow depth function for flows impacted by drops travelling at or near terminal velocity by Kinnell (1993b).

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

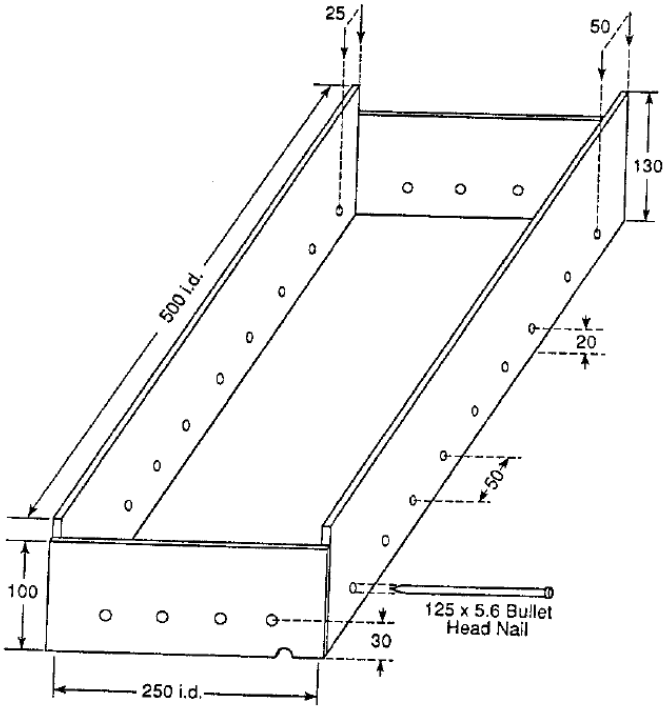

Figure 3. Sampling frame for collecting soil monoliths

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

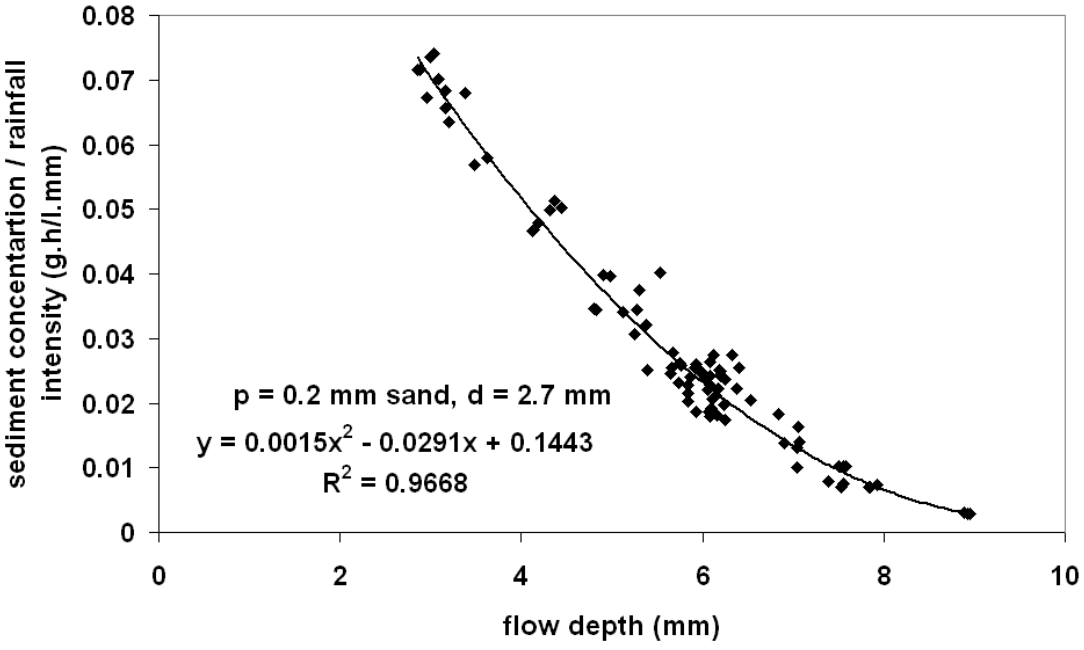

Figure 4. Relationship between sediment concentration per unit rainfall intensity and flow depth for 0.2 mm sand under flows impacted by 2.7 mm drops travelling at close to terminal velocity in experiments reported by Kinnell (1991, 1993b). (From Kinnell, 2009). Note the equation is not valid when h>9 mm.

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

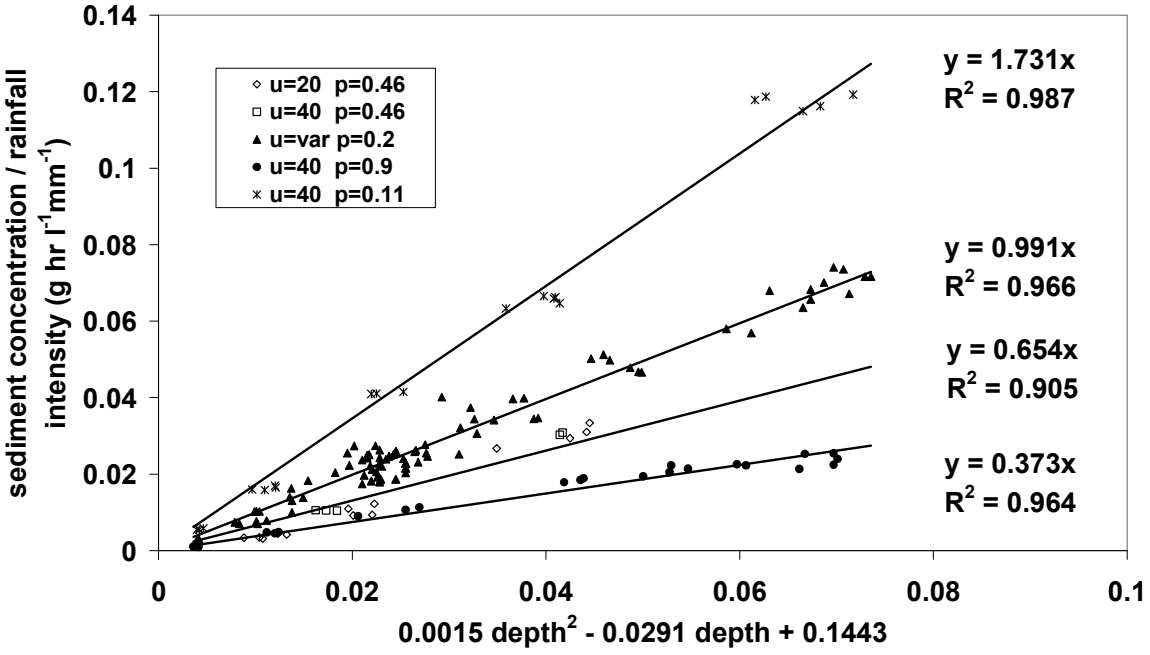

Figure 5. Relationships produced by Eq. (7) for beds of sand of various sizes eroding under flows impacted by 2.7 mm drops travelling at close to terminal velocity (from Kinnell, 2009).

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

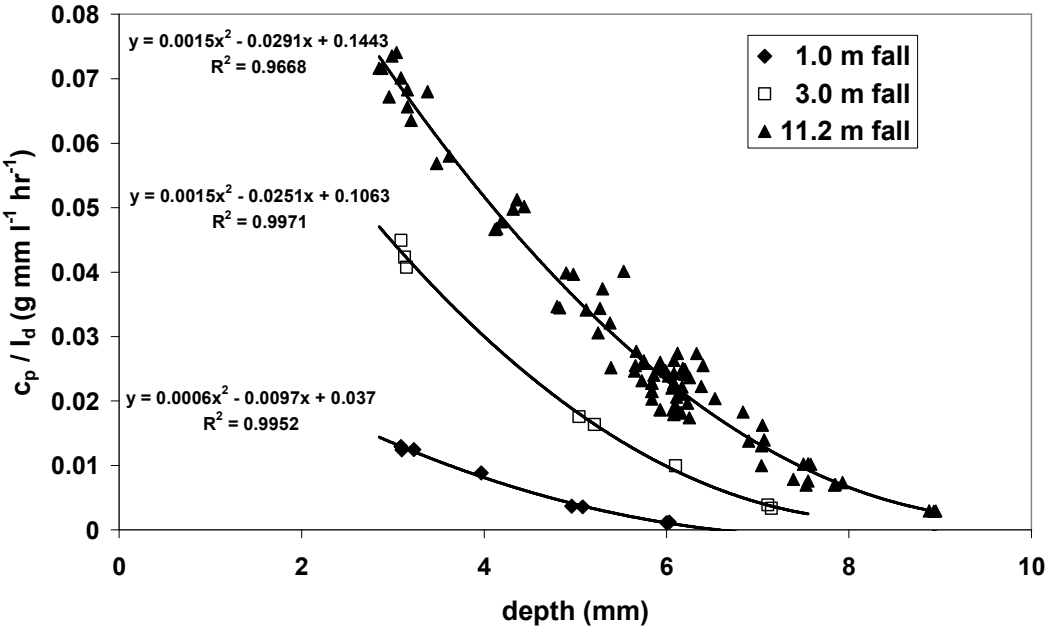

Figure 6. The effect of flow depth on sediment concentration per unit rainfall intensity for 0.2 mm sand under flows impacted by 2.7 mm drops falling from 1, 3 and 11.2 m (Kinnell, 2005a)

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

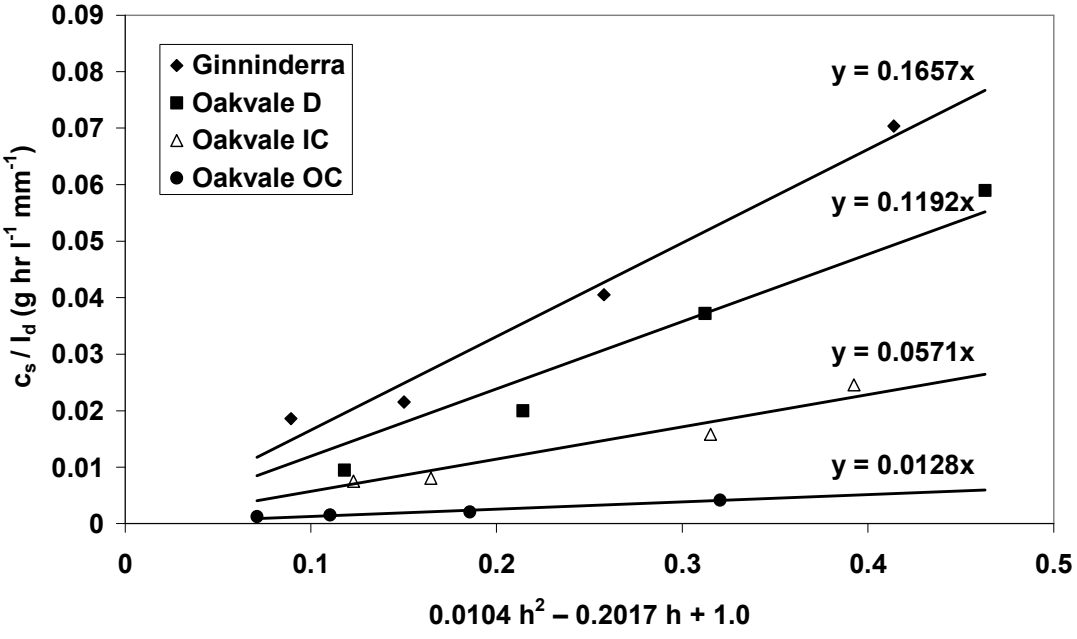

Figure 7. Relationships between 0.0104 h2 – 0.2017 h + 1.0 and sediment concentration per unit rainfall intensity for flows impacted by 2.7 mm drops travelling at near terminal velocity over soil monoliths (Kinnell, 2005b).

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
Published: 1 February 2016

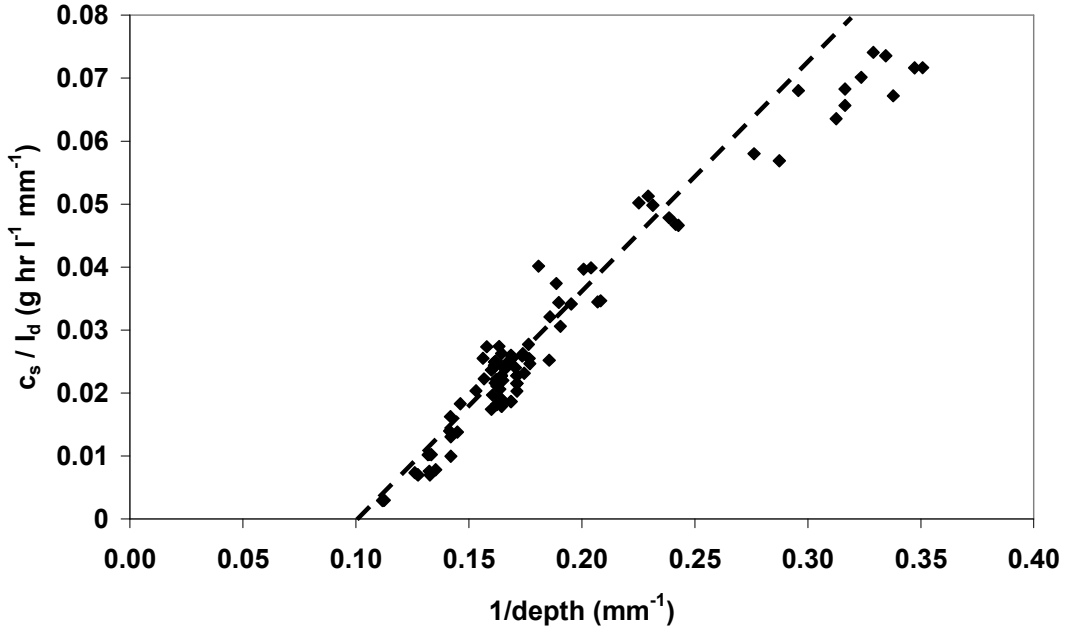

Figure 8. The relationship between sediment concentration per unit rainfall intensity and the inverse of flow depth for 2.7 mm drops travelling at close to terminal velocity impacting flows over 0.2 mm sand. The data are from the same experiments as used for Figure 4.

SOIL Discuss., doi:10.5194/soil-2016-5, 2016
Manuscript under review for journal SOIL
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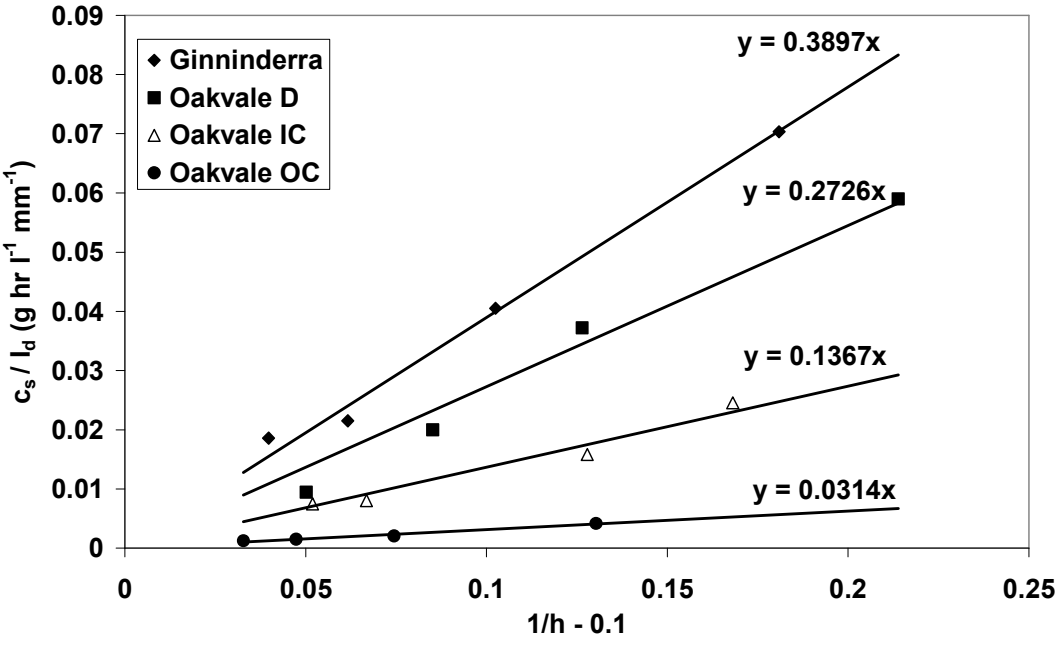

Figure 9. The relationship between sediment concentration per unit rainfall intensity and the inverse of flow depth minus 0.1 for 2.7 mm drops travelling at close to terminal velocity impacting flows over soil surfaces in the apparatus shown in Figure 1. The data are for the same experiments as used in Figure 7.