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The implications of spatial variability in surface seal hydraulic resistance for infiltration in a mound and depression microtopography

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Abstract

Soil surface crusting has a major impact on water infiltration and erosion in many soils. Considerable progress has been made in describing crusting processes and in modelling the impact of crusting on infiltration. Most studies, however, have neglected the high spatial variability in crust characteristics observed in the field. The objective of this experiment was to determine the influence of runoff depth on infiltration rate in the presence of a surface seal varying in hydraulic characteristics with microtopography. The Blosseville silt loam has a low aggregate stability and forms crusts readily. The Villamblain silty clay loam has a greater aggregate stability due to its greater clay and organic matter contents, and it is more resistant to aggregate breakdown processes under rainfall. Samples of the soils were sieved to retain aggregates less than 2.0 cm and packed in $50 \times 50 \times 15$ cm soil trays. The trays were surrounded by a 10 cm soil border to compensate for splash loss. After molding the surface into a mound and depression microtopography, the samples were subjected to simulated rainfall at an intensity of 22.8 mm h^{-1}. Hourly measurements of surface roughness showed that the original roughness was smoothed out due to the infilling of depressions by sediments detached from the mounds. For the final hour, runon was added to the top of the soil tray to increase the runoff rate and depth. For both soils, infiltration rate increased more than could be attributed to the increased ponding pressure head. The change in infiltration rate was particularly great for Villamblain. The measurements of hydraulic resistance showed that structural crusts had a lower hydraulic resistance than sedimentary crusts. They also

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showed that the crusts formed on Villamblain were of a lower hydraulic resistance than those of Blosseville. It appears that small changes in runoff depth can significantly increase infiltration rate when structural crusts of lower hydraulic resistance are inundated. The effect was less important in Blosseville which formed seals of relatively high hydraulic resistance everywhere. The results provide a suitable explanation for field observations of increasing infiltration rate with either increasing rainfall intensity or runoff rate. The results also have implications for the relationships between surface roughness, surface water storage, and infiltration.

Keywords: Microtopography; Surface crusting; Structural crust; Sedimentary crust; Runoff depth; Infiltration; Spatial variability

1. Introduction

The influence of surface sealing on infiltration rate was perhaps first noted in the literature by Duley (1939), and intense investigation began with the landmark papers of McIntyre (1958a,b). Surface sealing is a physico–chemical process of aggregate breakdown and subsequent compaction and/or deposition under conditions of rapid wetting or raindrop impact (Bresson and Boiffin, 1990; West et al., 1992). Raindrop impact compacts the thin surface layer into a ‘structural crust’ and the deposition of detached particles in micro-depressions forms ‘sedimentary crusts.’ The crust or seal is a layer of low hydraulic conductivity at the soil surface whose presence significantly reduces infiltration.

Some authors (Casenave and Valentin, 1989; Bresson and Boiffin, 1990; Gascuel-Odoux et al., 1991) have observed systematic changes in crust characteristics in the field. Surface storage depressions with an inflow of sediments form thick sedimentary crusts of very low hydraulic conductivity, and crusts thin outwards and upwards from the depression. Gascuel-Odoux et al. (1991) looked at the variation in crust characteristics for row and interrow zones in a silt loam soil under silage maize. Maximum crust thickness was observed in the centre of the interrow with regular thinning towards the interrow boundary. Bulk density was also greater in the interrows than in the rows. The upper layer of row surfaces had meta vughs and channels from faunal activity, and it was assumed that these surfaces did not generate runoff due to their high porosity. Row spacing was 0.8 m apart and elevation differences were in the order of 10 cm, so seals of considerably different hydraulic conductivity were in close proximity, particularly near the row–interrow boundary.

Although sedimentary crusts have been described widely in the literature (Bresson and Boiffin, 1990; West et al., 1992), most experimental studies of surface crusting have used designs that greatly favour the formation of structural crusts: the soil surface in flumes or soil trays is usually smoothed flat and slope angles and runoff rates are great enough to eliminate sediment deposition (Poesen, 1984; Fox et al., 1997a). Only a few of the several studies conducted over the last few decades have attempted to measure or model the implications of horizontal variability in seal characteristics for infiltration. Levy et al. (1988) were among the first to attempt to quantify spatial variability in surface seal characteristics. When an uncrusted soil (74.4% sand, 5.6% silt, 20% clay) was exposed to simulated rainfall with an intensity of 45 mm h^{-1}, the surface developed a plain and mound microtopography. Plains were of significantly greater bulk density than adjoining mounds and the structure of the mounds resembled that of the uncrusted soil material. The diameter of the mounds was in the order of 0.8 to 1.0 cm, and they may have been remnants of more stable aggregates. The apparent hydraulic conductivity of the mounds was about 250% that of the plains. The authors did not attempt to measure the effect of ponding depth or runoff rate on infiltration.

Infiltration rate has been observed to increase with increasing rainfall intensity and runoff rate (De Ploey et al., 1976). Runoff discharge was increased on a slope and the infiltration rate was observed to increase with increasing discharge until a threshold was reached. Beyond this threshold, discharge rate had no effect on infiltration rate. The reason for the increase was not apparent.

Bristow et al. (1995) used a model to demonstrate that spatial variability in surface seal hydraulic conductivity can significantly affect infiltration rate. In their model, surface seals were allowed to form only in depressions and not on neighbouring mounds; if runoff depth were allowed to increase on the surface to inundate the uncrusted mounds, then infiltration rate increased substantially. The model had not yet been validated with experimental data.

In a soil column ponding experiment (Fox et al., 1998), it was demonstrated that small changes in ponding depth can significantly influence infiltration rate if a surface seal of lower hydraulic resistance is submerged under deeper ponding. In their experiment, crust characteristics were held constant under different ponding treatments. Freebairn et al. (1991), however, observed changes in crust characteristics related to ponding depth, so a dynamic approach may be more realistic. In this study, variability in surface seal characteristics was allowed to evolve under rainfall as a function of the initial microtopography. The objectives of the experiment were 1) to quantify the relationship between seal hydraulic resistance and microtopography, and 2) to identify the influence of runoff depth on infiltration in the context of spatially varying seal hydraulic resistance.

2. Methods

Two soils, a Blosseville silt loam and Villamblain silty clay loam, were collected from the A horizon, air-dried to a gravimetric water content of about 10% and stored in plastic bags in a cold room at 5°C. Characteristics of the soils are reported in Fox et al. (1998). Blosseville has a weak aggregate stability and is susceptible to intense surface sealing. Villamblain is much more stable due to its higher clay and organic matter contents. Results of aggregate stability tests performed for these soils are reported in Le Bissonnais and Bruand (1993) and Le Bissonnais et al. (1995). Samples of the soils were passed through a 2.0 cm sieve and packed in the $50 \times 50 \times 15$ cm soil tray shown in Fig. 1. About 0.5 cm above the base of the soil tray was a perforated board overlain with 2.5 cm of gravel. The soil was added in 3.0 cm layers with slight compaction and smoothing between layers. The thickness of the soil overlaying the gravel was 12.0 cm. Bordering the measuring area was a 10.0 cm wide band of soil to compensate for splash loss from within the tray. Using a 6×6 cm square grid, the surface was molded into 64

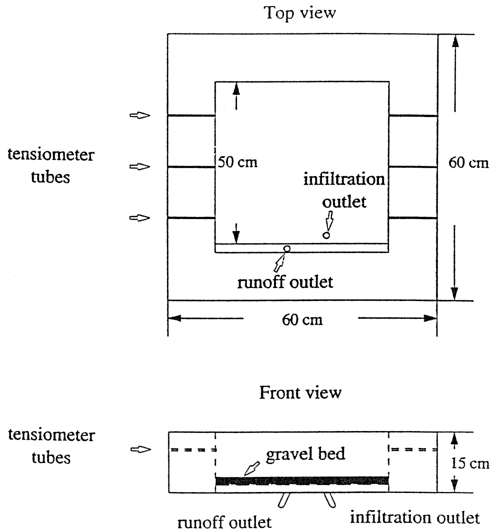


Fig. 1. Experimental soil tray showing surrounding buffer area, tensiometer locations, and infiltration and runoff outlets.

randomly located mounds and depressions (32 of each). Microtopographic variation for a mound or depression was in the order of about 1.5 cm.

The soil trays were wetted from below overnight, set at slope of 5% and allowed to drain freely for one hour before being subjected to simulated rainfall at an intensity of 22.8 mm h^{-1} (std. dev. = 3.1 mm h^{-1}). Rainfall characteristics are given in Le Bissonnais et al. (1995). For each soil type, 5 replicates were included. Each simulation lasted a total of 5 h, divided into two periods of 3 and 2 h, respectively. After the initial 3 h of rainfall, the trays were allowed to drain overnight before commencing the 2 h rainfall simulation. The first simulation (3 h) permitted the establishment of a steady infiltration rate and spatially varied seal, whose characteristics were closely related to microtopography. The remainder of this publication deals almost uniquely with the 2 h rainfall simulation, and references to the ‘first’ and ‘second’ hour refer to this final two hour period.

During the rainfall simulation, water flux through the base of the tray and runoff were collected continuously during 5 min intervals. Subseal pressure head was measured every 12 min at a depth of 3.5 cm using 4 to 6 microtensiometers per soil tray. Tensiometer cups were located at about 15 cm from the inner tray wall. In order to increase the runoff depth during the second hour, an additional 100 mm h^{-1} of runon was added to the surface at the top of the tray. The runon was added uniformly across the tray and a highly permeable cloth protected the seal from disruption where the runon first touched the surface. The second hour therefore had a combination of both rainfall and runon.

To monitor changes in microtopography, a rod and ruler system (Hudson, 1996) was used to measure surface roughness at 2.0 cm intervals at 2 cross-sections within the tray every hour. Rainfall was stopped and the surface was allowed to drain freely for these measurements. Accuracy is estimated at ± 0.5 mm. Ponding depth was measured in 8 to 10 depressions chosen randomly every 20 min during the experiment using a ruler. Accuracy of this measurement is estimated at ± 1 mm. Despite the relatively large error of measurement for ponding depth, the difference in depth for the two periods (rain, rain + runon) was sufficiently great to be statistically significant in an analysis of variance test ($\alpha = 0.01$, $r^2 = 0.47$). However, the explained variance is only 0.47, and a greater number of measurements (15 to 20 per tray) would probably have increased it substantially.

After the simulation, samples of the structural and sedimentary seals were taken for measurement of hydraulic resistance. These were taken using 5 cm long cylinders with an inner diameter of 4.6 cm. The procedure for measuring hydraulic conductivity was similar to the one used by McIntyre (1958a). A total of 6 replicates per soil and crust type was collected for these measurements.

3. Results

3.1. Microtopography

The surface roughness decreased with time as depressions filled with sediments and micro-aggregates detached from the mounds. The progressive flattening of the surface with cumulative rainfall is consistent with the observations of others (Courault et al.,

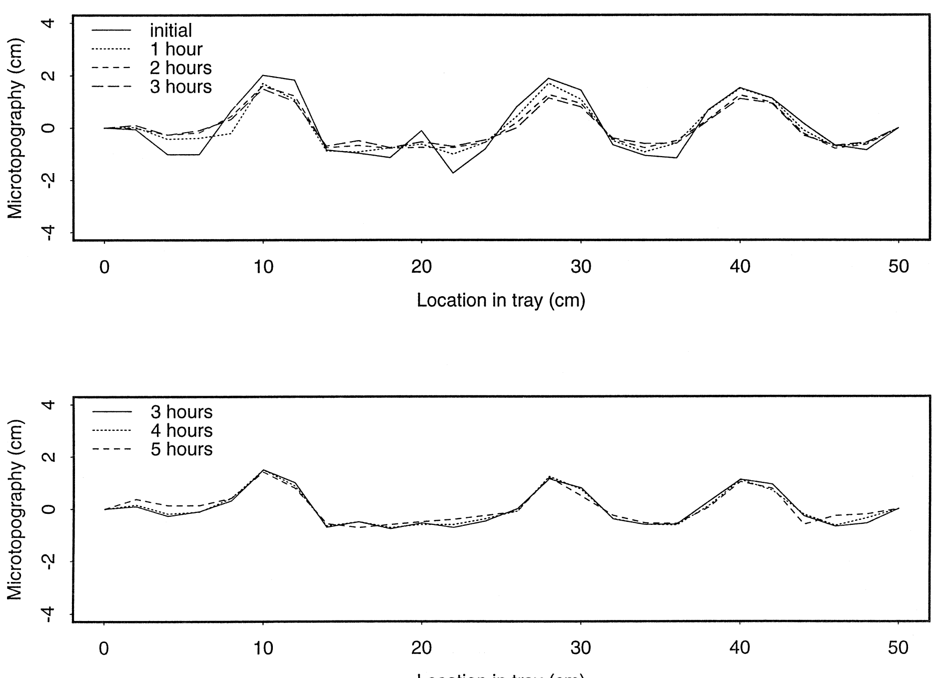
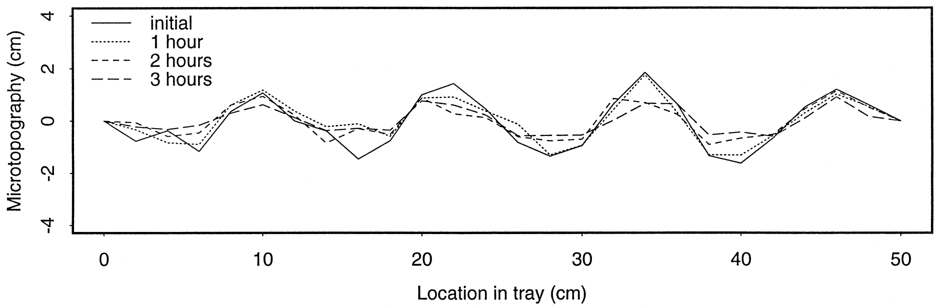


Fig. 2. Changes in microtopography for Blosseville showing the progressive flattening of the surface with time (a) during first 3 h rainfall simulation, (b) during final 2 h rainfall simulation.



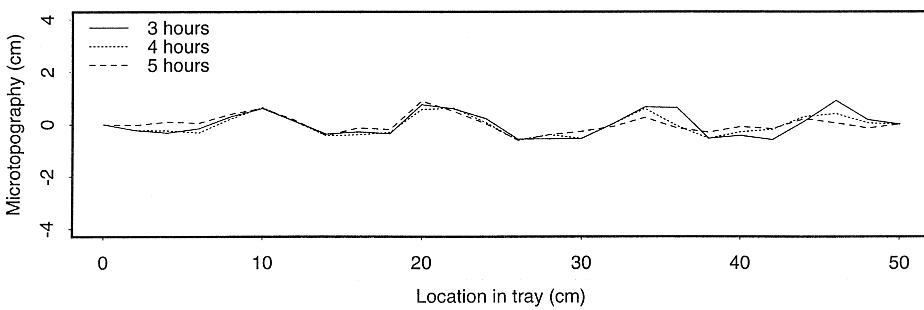


Fig. 3. Change in microtopography for Villamblain showing the progressive flattening of the surface with time (a) during first 3 h rainfall simulation, (b) during final 2 h rainfall simulation.

1993; Onstad et al., 1984; Govers and Poesen, 1985), and the process is facilitated by the protection from raindrop impact of depression surfaces (but not of mounds) by puddling (Lafforgue, 1978). The evolution is shown in Figs. 2 and 3 for selected samples of each soil type. The major changes in microtopography appear to have occurred in the initial 3 h rainfall simulation (initial 3 h) with lesser changes in the final 2 h (3–5 h).

Zobeck and Onstad (1987) reviewed several indices of random roughness, and the standard deviation of the microtopographic cross-sections was used as an index of surface roughness here (Onstad et al., 1984; Courault et al., 1993). Rougher surfaces had higher standard deviations, and as the surface flattened, the standard deviation decreased. Mean standard deviations for all replicates are shown in Fig. 4. For both soils, the infilling of depressions and erosion of mounds decreased the surface roughness during the entire simulation. The rate of change decreased with time. For Blosseville, the surface evolution was quasi-stable after about 4 h of rain. The Villamblain soil was less susceptible to rainfall detachment, so the surface evolution was slower and the infilling of depressions continued throughout the simulation.

3.2. Ponding depth

The remainder of the discussion will be restricted to the final 2 h rainfall simulation period. During the first hour, rainfall alone was applied to the surface. During the second

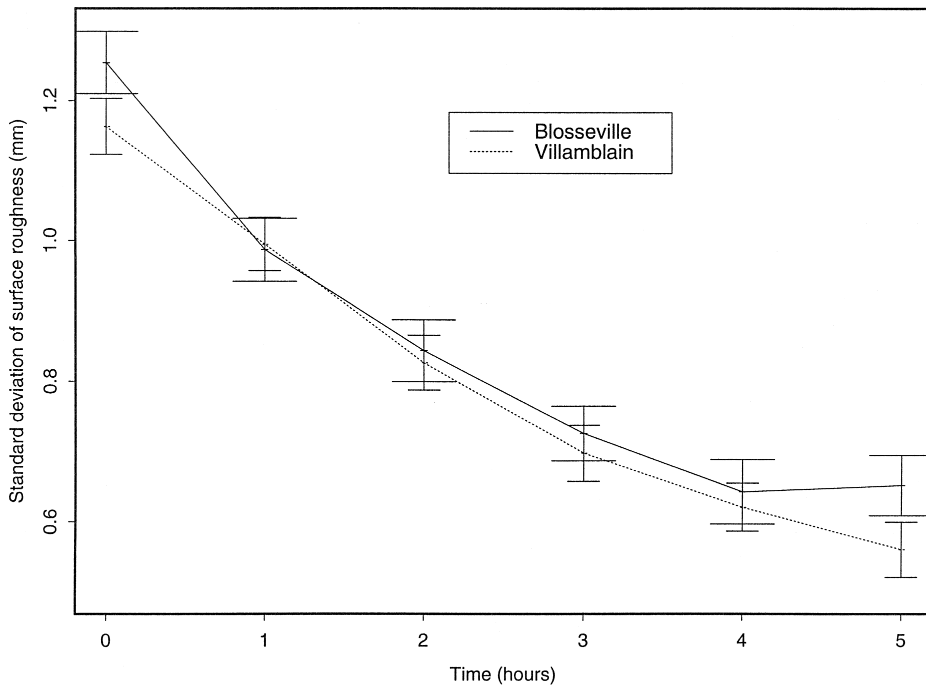


Fig. 4. Changes in standard deviation of surface roughness during 5 h of rainfall simulation (error bars are ± 1 standard error).

hour, runon at the top of the tray was applied in addition to the rainfall. These periods corresponded to 'shallow' and 'deep' runoff treatments. Changes in ponding depth are shown in Fig. 5 and summarised in Table 1. The increases were roughly the same for the two soils, and the change in runoff depth was in the order of about 1.3 mm. An analysis

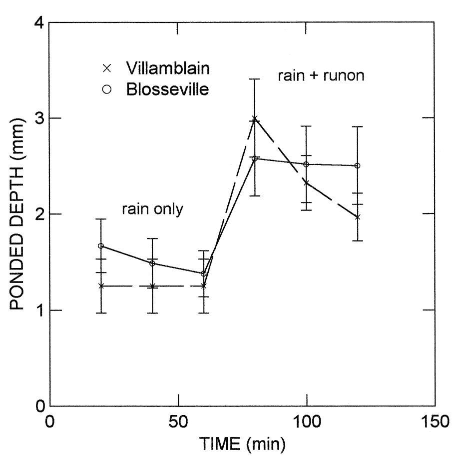


Fig. 5. Change in ponded depth with the addition of runon (error bars are ± 1 standard error).

Table 1
Changes in ponded depth, pressure head, and infiltration rate with added runon and predicted infiltration rates from Eqs. (4) and (5) (values in parenthesis are standard errors)

Soil	Ponding treatment	Ponded depth (mm)	Pressure head (cm)	Infiltration rate (mm h^{-1})	Predicted infiltration rate (mm h^{-1})
Blosseville	Shallow	1.21 (0.34)	−6.80 (0.47)	4.36 (0.18)	8.8
	Deep	2.38 (0.46)	−6.24 (0.38)	5.66 (0.35)	7.5
Villamblain	Shallow	1.02 (0.22)	−9.96 (0.55)	6.60 (1.36)	25.2
	Deep	2.32 (0.21)	−8.36 (0.53)	25.4 (4.71)	43.3

of variance test ($r^2 = 0.47$) confirmed that the runoff depths were not significantly different for the two soils, but they were different for the two runoff treatments ($\alpha = 0.01$). In the presence of a subseal pressure head of from −6 to −10 cm, an increase in ponding pressure head at the surface of 1–2 mm can be considered negligible with respect to its direct influence on infiltration.

3.3. Pressure head

Mean subseal pressure heads for all replicates are shown in Fig. 6 and summarised in Table 1. For Blosseville, there was a small increase in mean pressure head (about 0.5 cm) with the increase in runoff rate. The increase was greater for Villamblain (about 1.5 cm), indicating there was substantially more water infiltrating through the seal with the additional runon than under rainfall alone. In an analysis of variance test ($r^2 = 0.79$), both soil type ($\alpha = 0.001$) and runoff rate ($\alpha = 0.01$) had a significant influence on pressure head.

3.4. Infiltration rate

Percolation through the base of the soil tray was measured directly as described above. It was noted that changes in percolation rate with the onset of rainfall or the

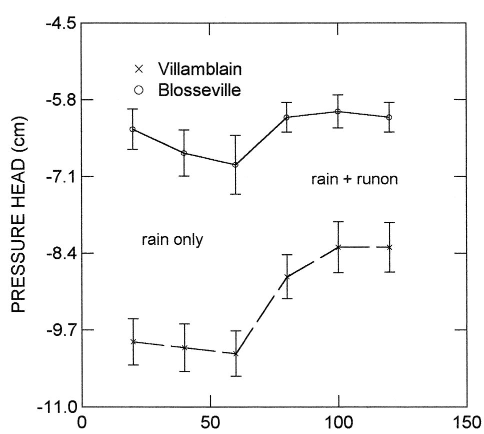


Fig. 6. Increase in pressure head with the addition of runon (error bars are ±1 standard error).

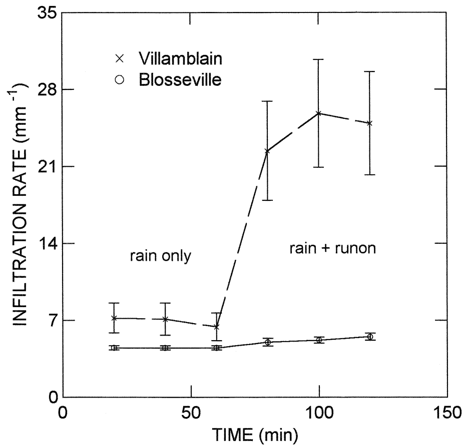


Fig. 7. Increase in infiltration rate with the addition of runon (error bars are ± 1 standard error).

addition of runon occurred within a period of less than 10 min, so the steady-state percolation flux (cm^3 h^{-1}) was considered equal to the infiltration flux. This flux was converted to infiltration rate (mm h^{-1}) by converting units and dividing by the surface area.

The changes in infiltration rate shown in Fig. 7 and summarised in Table 1 were consistent with the pressure head trends discussed above. With the addition of runon, infiltration rate for both soils increased more than would be expected for an increase in ponding pressure head of less than 2 mm. The increase was particularly great for Villamblain whose infiltration rate increased from about 6.6 mm h^{-1} to 25.4 mm h^{-1}. An analysis of variance test ($r^2 = 0.76$) showed that both soil type ($\alpha = 0.01$) and runoff treatment ($\alpha = 0.01$) had a significant impact on infiltration rate. The effect was significantly greater for Villamblain than for Blosseville ($\alpha = 0.01$).

3.5. Hydraulic resistance

Flow through a surface seal can be described using the Darcy equation (Eq. (1)) (Hillel and Gardner, 1969). The thickness of the sedimentary seal was in the range of about 0.7 to 1.0 cm depending on the depression. This range was estimated from the microtopographic cross-sections. The thickness of the structural seal could not be measured easily with any certainty since Mualem et al. (1990) argue that changes in porosity that cannot be observed visually can significantly affect infiltration. The thickness of the seal will therefore not be taken directly into consideration, and the hydraulic resistance (ratio of seal thickness to seal hydraulic conductivity) of the surface layer under shallow and deep ponding will be presented instead of estimated hydraulic conductivity.

The mean hydraulic resistance for a random selection of 6 replicates per soil and crust type are shown in Table 2. Two trends are apparent. Firstly, hydraulic resistance of Villamblain was lower than of Blosseville. This is in good agreement with the greater

Table 2
Hydraulic resistance values for both seal and soil types (values in brackets are standard errors)

Soil	Seal type	Hydraulic resistance (h)
Villamblain	Structural	0.53 (0.05)
	Depositional	3.40 (0.71)
Blosseville	Structural	5.90 (0.23)
	Depositional	33.2 (5.50)

infiltration rates observed for Villamblain under both ponding treatments. Secondly, hydraulic resistance of structural seals was lower than of sedimentary seals. This is particularly true for Villamblain. This second trend is consistent with the much greater increase in infiltration rate with added runon observed for Villamblain than for Blosseville. These trends were confirmed by an analysis of variance test ($r^2 = 0.47$) which showed that both soil type ($\alpha = 0.01$) and crust type ($\alpha = 0.05$) had a significant effect on hydraulic resistance. The low r^2 value results from the high variability in crust resistance and difficulty in obtaining accurate estimates from a limited number of samples.

4. Discussion

Infiltration and surface storage on a non-planar soil surface were examined by Lafforgue (1978). He reasoned that infiltration varies with microtopography since the latter affects the proportion of the surface inundated. At the cessation of rainfall, the area submerged under surface storage decreases significantly, effectively reducing the infiltrating area. His observations are consistent with the results presented here, but he did not consider the influence of varying hydraulic conductivity with microtopography.

The results presented above show a coherent picture of the influence of spatial variability in crust characteristics on infiltration. Infiltration rates through the structural seals were greater than through the sedimentary seals for both soils, so infiltration rate increased as zones of lower hydraulic resistance were submerged under the greater runoff depth. In this process, the determining influence was the difference in hydraulic resistance between the two seal types, and this difference was linked to the aggregate stability characteristics and breakdown dynamics of the two soils as described in Le Bissonnais and Bruand (1993) and Le Bissonnais et al. (1995). Due to the low aggregate stability of Blosseville, aggregate breakdown was more intense in this soil, so there was a higher proportion of elementary particles and fine micro-aggregates in the breakdown products as can be deduced from previous experiments (Le Bissonnais and Bruand, 1993; Fox et al., 1998). This lead to sedimentary seals of lower porosity and higher hydraulic resistance. The relatively low aggregate stability of Blosseville also made it susceptible to compaction under raindrop impact, so structural crusts on the mounds were of relatively high hydraulic resistance. Villamblain, on the other hand, has a much greater aggregate stability, so aggregate breakdown and compaction on the mounds were less intense, and these zones appeared to have developed structural seals of relatively low hydraulic resistance.

The high hydraulic resistance overall for Blosseville and the relatively small difference in hydraulic resistance between the sedimentary and structural seals made it less sensitive to changes in runoff rate than Villamblain. Although the increase in infiltration rate for Blosseville was greater than would be expected from an increase in ponded pressure head of less than 2 mm over no more than 50% of the surface (ie. increase of less than 2% of total pressure head), it can still be considered negligible for practical purposes, being in the order of about 2 mm h^{-1}. This is not the case for Villamblain which had a large difference in hydraulic resistance between the two seal types, and an extremely low hydraulic resistance for the structural seal on the mounds. Therefore, even small changes in the runoff depth caused greater infiltration in the structural crust zones, and the global infiltration rate increased substantially (by about 19 mm h^{-1}). This increase was accompanied by significant changes in pressure head in the subseal zone.

The situation described in this experiment may be analogous to that of Dunne et al. (1991) for vegetated mounds. In their study, hydraulic conductivity varied systematically with microtopography due to the presence of clumps of vegetation on mounds. These mounds were zones of preferential infiltration, so infiltration increased with runoff depth as larger portions of the mounds were submerged. Their experimental study built upon earlier work by Hawkins (1982) who concluded that infiltration rate increased with increasing rainfall intensity. As rainfall intensity increased, a greater portion of the surface was infiltrating at the saturated hydraulic conductivity rate.

The originality of Dunne et al. (1991) work was to associate the variability in hydraulic conductivity deterministically with microtopography, producing a binary distribution of hydraulic conductivity as a function of the mound and intermound zones. The crusting experiment carried out here suggests that this binary distribution can be applied to crusting soils, and the mathematical model described by Dunne et al. (1991) may also be applicable. Based upon their model, the following three conditions can occur.

(1) Ponding over the sedimentary crust only:

$$f = k_{\mathrm{dep}}(1 - C) + IC \tag{1}$$

(2) Ponding over the sedimentary crust and partial ponding over the structural crust:

$$f = k_{\mathrm{dep}}(1 - C) + A_{\mathrm{p}} k_{\mathrm{struc}} + IC(1 - A_{\mathrm{p}}) \tag{2}$$

(3) Both sedimentary and structural crusts are submerged:

$$f = k_{\mathrm{dep}}(1 - C) + k_{\mathrm{struc}} C \tag{3}$$

f = infiltration rate (cm h^{-1}); k_{dep} = hydraulic conductivity of sedimentary crust (cm h^{-1}); C = fraction of surface covered by structural crust (assumed constant); I = rainfall intensity (cm h^{-1}); A_{p} = fraction of surface of structural crust under ponding or runoff; k_{struc} = hydraulic conductivity of structural crust (cm h^{-1})

Because of the difficulties involved in measuring seal hydraulic conductivity and thickness (Mualem et al., 1990) and due to the presence of an important subseal pressure head, it may be more appropriate to rewrite Eqs. (1)–(3) in the form of Eqs. (4)–(6), where R is the hydraulic resistance (ratio of seal thickness to seal hydraulic conductivity).

$$f=\frac{-h_i(1-C)}{R_{\mathrm{dep}}}+IC \tag{4}$$

$$f=\frac{-h_i(1-C)}{R_{\mathrm{dep}}}-\frac{h_{\mathrm{i}}(A_{\mathrm{p}})}{R_{\mathrm{struc}}}+IC(1-A_{\mathrm{p}}) \tag{5}$$

$$f=\frac{-h_{\mathrm{i}}(1-C)}{R_{\mathrm{dep}}}-\frac{h_{\mathrm{i}}(A_{\mathrm{p}})}{R_{\mathrm{struc}}} \tag{6}$$

R_{dep} = hydraulic resistance of sedimentary crust (h); R_{struc} = hydraulic resistance of structural crust (h); h_{i} = subseal pressure head (cm)

In this experiment, Eq. (4) applies to the period of rainfall alone and Eq. (5) applies to the period with the additional runon. Total ponding was not considered here. It is probable that the IC term in Eqs. (4) and (5) is an overestimation of actual infiltration through the structural crust since some of the incoming rainfall will be splashed directly into the depressions upon contact with the surface. Mean infiltration rates for the two soils and runoff depths were estimated using Eqs. (4) and (5), and the values are shown in Table 1. For both soils, infiltration rate was overestimated. Although the overestimation for Villamblain was particularly great, the difference in infiltration rate between the two runoff depths agreed well with the actual increase. For Blosseville, infiltration rate was predicted to decrease with increased runoff depth; this was probably due to the lower hydraulic gradient which was not sufficiently compensated for by the different crust hydraulic resistances. Errors are involved in estimating crust surfaces, ponded area, and particularly in obtaining representative hydraulic resistance values, and the example shows the difficulties in obtaining accurate hydraulic parameters even under highly controlled conditions.

The proposal that Dunne et al. (1991) findings can be extended to crusting soils is supported by Valentin's (Valentin, 1991) observations in Niger. Surface crusts were formed on field plots under simulated rainfall. Laminated sedimentary crusts formed under overland flow had lower infiltration rates and more restricted porosity than partially degraded clods. Infiltration was therefore greater in plots with remaining surface roughness compared to plots which had levelled off completely.

From the behaviour of these two soils, it is apparent that the degree of variability in crust properties is soil sensitive. The dominant factors influencing this variability can probably be reduced to the following.

(1) Aggregate stability and the soil water content at the onset of rainfall (ie. at the initiation of breakdown processes): this groups together the various physico–chemical properties of the soil which influence its response to breakdown forces.

(2) Initial surface roughness: this influences the thickness and spatial distribution of the sedimentary crusts and may influence the rates of mound erosion and of infilling of depressions.

(3) Rainfall characteristics: rainfall intensity and duration will affect the intensity of aggregate breakdown and rate of surface levelling.

The results obtained in the experiment can account for increases in infiltration rate with rainfall intensity or runoff discharge observed in the field (De Ploey et al., 1976). They also have important implications for understanding the relationship between surface roughness, depression storage, and infiltration.

5. Conclusions

Due to the large natural variability in aggregate stability found in the field, it is probable that even very small changes in runoff depth can significantly increase the infiltration rate. Infiltration rate can therefore be expected to increase with runoff rate for the same slope, and the increase would be sensitive to the difference in hydraulic resistance associated with microtopography. Increases in infiltration with rainfall intensity may be due to small changes in surface ponding depth or to increases in infiltration rate in zones infiltrating at rates less than the saturated hydraulic conductivity. This suggests that the changes in pressure head observed under greater rainfall intensities may not necessarily signify seal disruption (Römkens et al., 1990). One of the major challenges remaining in crust infiltration modelling is to find simple methods to obtain accurate estimates of seal hydraulic resistance.

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