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EFFECTS OF WATER QUALITY ON INFILTRATION RATE AND SURFACE PONDING/RUNOFF

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ABSTRACT

Accurate description of infiltration, ponding/runoff is very critical in soil management. A laboratory column studies was designed to investigate the effects of water quality on infiltration rate and time-to-incipient ponding or runoff-generation-time. Clear water, and muddy water comprising sand, silt and clay at different concentrations of 10, 20, 30 and 40 g in 400 cm3 of water were used as the test fluids. Physical and hydraulic properties of the soil columns before and after the infiltration studies were determined. Severe modifications to the soil physical and hydraulic properties were observed following the infiltration experiments. The results of the study on saturated hydraulic conductivity were used to predict the relative time-to-incipient ponding of the various sediment surface seals. Sand suspension at 10 g produced the longest time-to-incipient ponding due to an immense increase in the saturated hydraulic conductivity. Again, unrealistic parameter values signifying that the occurrence of ponding/runoff was observed for some of the test fluids at certain rainfall rates. Overall, clay suspension at all concentrations gave the shortest time to cause surface ponding and/or runoff.

1. INTRODUCTION

An important process in the hydrologic cycle is infiltration, wherein water from precipitation, ice, or irrigation enters the soil through the surface. Water from these sources may also runoff over land and cause erosion, flooding, or flow into streams, lakes, rivers and oceans. Thus, infiltrating water, which constitutes the sole source of water to sustain the growth of vegetation, is filtered by the soil, which removes many contaminants through physical, chemical and biological processes, and replenishes the ground water supply to wells, springs and streams [1, 2].

Due to the sequential periods of rapid wetting followed by drying in agricultural fields during irrigation, soils, in due course, tend to have low aggregate stability [3, 4]. When water is applied to these soils, there is slaking of aggregates and/or dispersion of individual clay particles into suspensions. For example, the impacting force of raindrops results in breakdown and dispersion of soil aggregates, and smaller suspended sediment particles are filtered out at the surface as the water infiltrates and kept in place by the negative water phase pressure below the soil surface [5]. This may cause the soil to collapse and become denser, resulting in surface sealing and hard-setting, which can greatly overshadow other factors affecting infiltration on bare soil surfaces, and consequently, result in surface ponding where the land is relatively flat or runoff, where the land is sloping [6]. The objective of the study, therefore, was to estimate the time-to-ponding/runoff following the infiltration of muddy water with different sediment particles at different concentrations.

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2. MATERIALS AND METHODS

2.1. Description and Collection soil cores

Nta series or Gleyic Arenosol [7] obtained from the Department of Horticulture, KNUST was used for the study. The soils are poorly drained with coarse sand texture. They also have slow internal drainage, slow runoff, rapid permeability and low water holding capacity [8]. Random sampling technique was employed and 20 core samples from 0-20 cm soil depth were collected from each field. Undisturbed soil cores were collected from the field site using a 10 cm diameter PVC sewer pipe cut to a length of 30 cm and bevelled at the outer part of the lower end to provide a cutting edge to facilitate the insertion of the core. Field cores were collected by first digging a circular trench around an intact “pillar” of undisturbed soil which was taller and had a slightly larger diameter than the core sampler. The core sampler was then inserted directly into the pillar of soil by striking a wooden plank positioned across the top of the ring, with a mallet. By this, the edges of the pillar were allowed to fall away from the core as it was inserted. Following complete insertion the core was excavated by hand. When taking the soil core the inner ring created an air filled annulus, hence a sealant was used to ensure good contact between the soil and core and thereby minimised any edge flow down the core. Therefore, the air gaps between the soil and inner surface of the core were filled with melted petroleum jelly (Vaseline was used in this case).

2.2. Laboratory Measurements

The hydrometer method [9] was used in the determination of the particle size distribution. Soil water content was determined on volume basis before and after the laboratory infiltration tests. The gravimetric method [10] was used to establish initial soil water content for the different soil samples. Wet samples were weighed and oven-dried at 105°C for 24 hours, and then weighed again. Gravimetric soil water content was then determined by the following equation:

$$\theta_g = \frac{M_w - M_s}{M_s} \tag{1}$$

Where,
M_w = Mass of wet soil
M_s = Mass of dry soil

To convert to volumetric soil water content, the bulk density of the soil was obtained. The length and diameter of the soil rings were measured and the volume was calculated by:

$$V = \pi r^2 h \tag{2}$$

Bulk density was calculated by:

$$\rho_b = \frac{M_s}{V_t} \tag{3}$$

Total porosity (f) was calculated from bulk density as:

$$f = 1 - \frac{\rho_b}{\rho_s} \tag{4}$$

Where, ρ_s is the particle density (assumed to be 2.65 g/cm^3)

Volumetric water content was then calculated by the equation:

$$\theta_v = \theta_g \times \left(\frac{\rho_b}{\rho_w}\right) \tag{5}$$

Where,
ρ_w = Density of water (assumed to be 1.0 g/cm^3)

The saturated hydraulic conductivity (K_s) measurements were made on the cores in the laboratory using the modified falling head permeameter method similar to that described by Bonsu and Laryea [11]. Saturated hydraulic conductivity was calculated by the standard falling head equation as:

$$K_s = \left(\frac{aL}{At}\right) \ln\left(\frac{h_o}{h_t}\right); \tag{6}$$

Where,
a = Surface area of the cylinder [L^2]
A = Surface area of the soil [L^2]
h_o = Initial hydraulic head [L]
L = Length of the soil column [L]
h_t = Hydraulic head after a given time t [L]

By rewriting equation (6), a regression of $\ln\left(\frac{h_o}{h_t}\right)$ on t with slope $b = K_s\left(\frac{A}{La}\right)$ was obtained. Since $a = A$ in this particular case, K_s was simply calculated as:

$$K_s = bL \tag{7}$$

2.3. Separating soil particles

The different soil particles were obtained by dry sieving through a series of graduated sieves with different mesh sizes. The sample was shaken over nested sieves (in a decreasing order from top to bottom) which were selected to furnish the information required by specification. During sieving, the sample was subjected to a tap mechanism (i.e., both vertical movement or vibratory sieving and horizontal motion or horizontal sieving) for approximately 120 minutes to provide complete separation of the fine (i.e. dispersible) soil particles of the order 0.05 mm for fine sand, 0.02 mm for silt and < 0.002 mm (assumed herein as 0.001 mm) for clay, according to FAO classification.

2.4. Laboratory column infiltration test

The experiment was carried out with a series of ponded infiltration tests with clear and muddy water. The experiments were designed to test predictions by investigating a range of saturated hydraulic conductivities, initial and saturated water contents, sediment concentrations (c) and particle diameters which have not been extensively examined in previous infiltration studies. The infiltrating liquids were made of clear water, and suspensions of different soil particle diameters, viz., fine-sand, clay and silt, at different concentrations. The different c were made by adding clean (distilled) water to, 10 (T1), 20 (T2), 30 (T3) and 40 g (T4) of soil to make a total of 400 cm^3 and dispersed in a mechanical shaker for 60 minutes. Additionally, an infiltration test was conducted with distilled water (T5), which served as a reference for the study. Infiltration rates and cumulative infiltration amounts were determined by one-dimensional absorption into vertical soil columns of loamy sand texture in five replications. The bottom of each column was supported with cotton cloth and was wetted from below to expel any entrapped air. Excess water on top of the soil was siphoned out at zero hydraulic head difference.

The ponded infiltration experiments were conducted with a surface ponded thickness of 5 cm. A plastic sheet was used to cover the surface of the soil as the suspension was being added, in order to prevent disturbance of the surface. The plastic sheet was removed and a flexible tubing, which had already been filled with water, was used to connect the surface of the suspension to a constant head device to indicate the cumulative volume of infiltration. There was a slight mixing of the water and the suspension at the initial stage but, after a while, as the suspension flowed into the column, there was a clear separation between the water above and the suspension below. All the clamps were removed and the cumulative outflow of water from the bottom of the matrix was measured with a weighing balance. Measurements were made for a range of values of c, each on a new soil column. The vertical infiltration was measured in the soil column for 60 minutes. The initial infiltration was measured at 30 seconds interval for the first five minutes after which the interval was increased to 60, 180 and 300 seconds, respectively, as the process slowed down towards the steady state. The cumulative infiltration amount (I) was plotted as a function of time for each run on a linear scale with GraphPad Prism 6.0. The slopes of the cumulative infiltration amounts taken at different time scales represented the infiltration rates (i), which were plotted against time and the steady state infiltrability (K_o) was obtained at the point where the infiltration rate curve became almost parallel to the time axis [11, 12].

2.5. Estimation of time-to-incipient ponding (t_p)

Analysis of Time-to-incipient ponding (t_p) or runoff initiation was conducted based on an expression modified from Mein and Larson [13]:

$$t_p = \frac{K_x(D) h_f \Delta\theta}{R_r[R_r - K_x(D)]} \tag{8}$$

Where,

R_r = Rainfall rate [L/T]

Hypothetical R_r values ranging from 5 mm/h (0.0014 mm/s) to 30 mm/h (0.0083 mm/s) were employed in estimation of t_p. The other parameters are as already defined.

3. RESULTS AND DISCUSSIONS

The measurement data obtained from the experiment are presented in the following Tables 1 and 2 below. The results revealed both significant and insignificant differences among treatment combinations for the various soil properties investigated. The results of initial analysis of soil physical and hydraulic properties of the study area are presented in Table 1. The results showed that the texture of the field surface (0 - 20 cm) was predominantly loamy sand, with sand, silt and clay fractions of 84%, 4.30% and 11.70%, respectively. The average bulk density was 1.34 g/cm^3 with total porosity of 49.43% .The average antecedent and saturated moisture contents were 23.58% and 47.70%, respectively. Average saturated hydraulic conductivity was 0.0025 mm/s.

Table 1 Summary of initial soil physical and hydraulic properties

Soil property	**Value**
Saturated hydraulic conductivity (mm/s)	2.50E-03
Bulk density (g/cm^3)	1.34
Total porosity (%)	49.43
Volumetric moisture content (%)	23.58
Saturated moisture content (%)	47.70
Moisture deficit (%)	24.12
Sand (%)	84.00
Silt (%)	4.30
Clay (%)	11.70
Texture	Loamy sand

Table 2 presents the summary of the results of the measured physical and hydraulic properties after the infiltration experiment. Comparison of Tables 1 and 2 indicated substantial changes in the soil properties after the infiltration experiment. Repeated measures one-way ANOVA and Tukey's multiple comparisons test also showed significant differences among the means of the measured parameters under the different treatments. Therefore, the observed changes could not have arisen by chance.

Table 2 Summary of soil physical and hydraulic properties after infiltration

Soil property	**Fluid**												
	Clear water	**Clay suspension†**				**Silt suspension†**				**Fine sand suspension†**			
		10	**20**	**30**	**40**	**10**	**20**	**30**	**40**	**10**	**20**	**30**	**40**
K_s **(mm/s)**	2.5E-3	1.0E-4	5.0E-5	3.3E-5	2.5E-5	2.0E-3	1.0E-3	6.7E-4	5.0E-4	5.0E-3	2.5E-3	1.7E-3	1.3E-3
ρ_b **(g/cm^3)**	1.34	1.37	1.45	1.53	1.55	1.37	1.43	1.48	1.52	1.36	1.41	1.45	1.47
f **(%)**	49.43	48.30	45.28	42.26	41.51	48.30	46.04	44.15	42.64	48.67	46.79	45.28	44.53
θ_v **(%)**	23.58	21.01	19.28	17.28	16.65	21.74	20.44	19.21	18.04	22.53	21.38	19.61	18.97
θ_s **(%)**	47.70	43.50	42.60	40.90	40.10	45.00	44.40	43.50	42.30	46.30	45.70	43.30	42.60

†Mass of sediment particles in suspension; θ_v (%) = Volumetric water content at field capacity; ρ_b (g/cm^3) = Bulk density; f (%) = Total porosity; θ_s (%) = Saturated water content; K_s (mm/s) = Saturated hydraulic conductivity

3.1. Infiltration rate

The infiltration characteristics were determined in terms of the infiltration rate, which is a measure of the speed at which soil is able to absorb water (from rainfall or irrigation). A summary of the measured infiltration parameters for the different sediment suspensions and their respective concentrations is presented in Table 3. The experimental data for cumulative infiltration (I) with time (t) for clear water and the different sediment suspensions, and their concentrations are presented in Figures 1 – 4. In all the tests, lower infiltration rates were measured for the sediment suspensions after 60 minutes (Table 3). The results clearly showed that infiltration was highly dependent on the characteristics of soil and fluid. Somewhat, the saturated conditions (high soil water contents) created in this study inhibited the higher infiltrabilities that are commonly experienced in unsaturated soils [14]. This resulted in the lower and more equal infiltration rates for and within each sediment suspension. The trends of the infiltration rate curves (Figures 1 – 4) also suggest that the process could best be described by a quasi-steady state regime, wherein, infiltration decreased slowly with time. However, field observations of infiltration into natural soils reported by Tuffour et al. [11, 12] and Khalid et al. [15] exhibited dissimilar patterns, where, infiltration rates were described by two distinct regimes: a transient regime and a quasi-steady state regime; infiltration rates decreased rapidly with time in the transient regime and slowly in the quasi-steady state regime.

Table 3 Effects of different soil particles at different concentrations on infiltration rate

Fluid	‡Sediment concentration (g)	Infiltration rate (mm/s)
Clear water **Clay suspension**	0	0.114
	10	0.112
	20	0.051
	30	0.021
	40	0.020
Silt suspension	10	0.118
	20	0.062
	30	0.039
	40	0.036
Sand suspension	10	0.121
	20	0.100
	30	0.051
	40	0.048

‡ = Mass of soil sediment

Critical observations of the infiltration rate curves (Figs. 1 – 4) showed that the presence of soil sediment in the infiltrating water had a considerable impact on the infiltration rates. The main features of the soil particle that influenced infiltration were the size, the concentration, and the settling velocity of the soil particles, which greatly influenced the viscosity of the moving water. Thus, the presence of soil sediments resulted in reduced conductivity and infiltration of water through the soil. This observation, thus, supports earlier reports that the presence of soil sediments in ponded and flowing water can drastically reduce infiltration [14, 16, and 17].

The reduction in infiltration rates could be attributed to the creation of a layer from the capture of sediments within the pore spaces and at the soil surface (surface seal formation), partly due to direct interception, and size exclusion [14]. In addition, it was clearly observed that, in all the soil columns, the sediment concentration in water decreased with time in the course of the infiltration test. This was a clear indication that the suspended sediment continued to deposit at the column perimeter. The differences in particle sizes of sediments in the depositional layers resulted in differences in the hydraulic properties (i.e. saturated hydraulic conductivity) across the seal-soil layer interface. Substantial reductions in hydraulic conductivity were observed due to the deposition of sediment transported by water through the soil.

In view of this, it was clear that the deposition and accumulation of suspended sediments, especially clay and silt, eventually, resulted in the blocking of pores. However, the seal layer resulting from the deposition of sand particles recorded very high K_s at low concentrations (10 – 20 g) and lower K_s than that of the original soil surface at higher concentrations (30 – 40 g).

This was mainly because deposition of the sand particles created preferential flow paths through fingering and large connected void spaces in the depositional layer [14]. On the other hand, the finer sediments (especially clay) moved into the large pores, attached to other soil particles, filled pore spaces, and thus, reduced porosity and K_s. This low conductivity of the surface seal limited the downward movement of water (i.e. infiltration) and held the infiltrating water in the finer pores by capillary forces [14]. These findings are in consonance with earlier reports by Green et al. [18] who revealed that the formation of a surface seal caused by the physical breakdown of aggregates and clay dispersion resulted in a decreased infiltration rate. Similarly, Lado and Ben-Hur [19] reported that due to seal and/or crust formation, the resultant infiltration rate will tend to decrease to a minimum value irrespective of the initial soil moisture content.

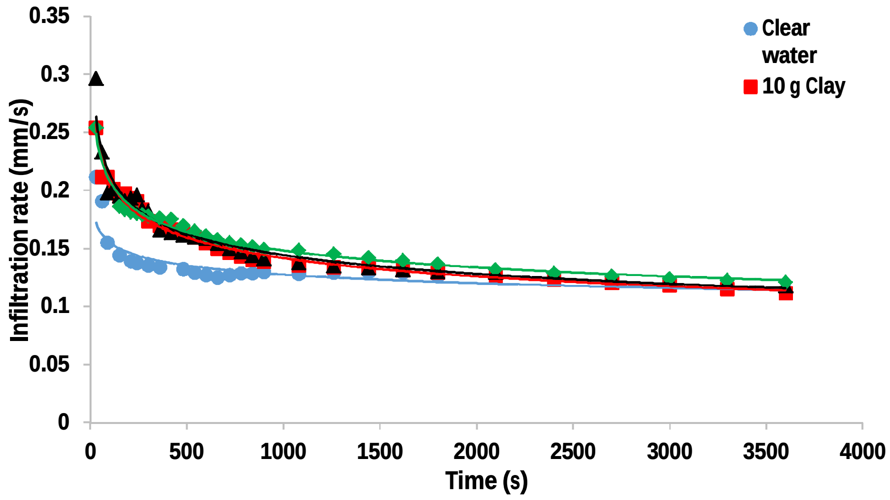

Figure 1 Plots of Infiltration rate with time for clear water and 10 g soil particles in suspension

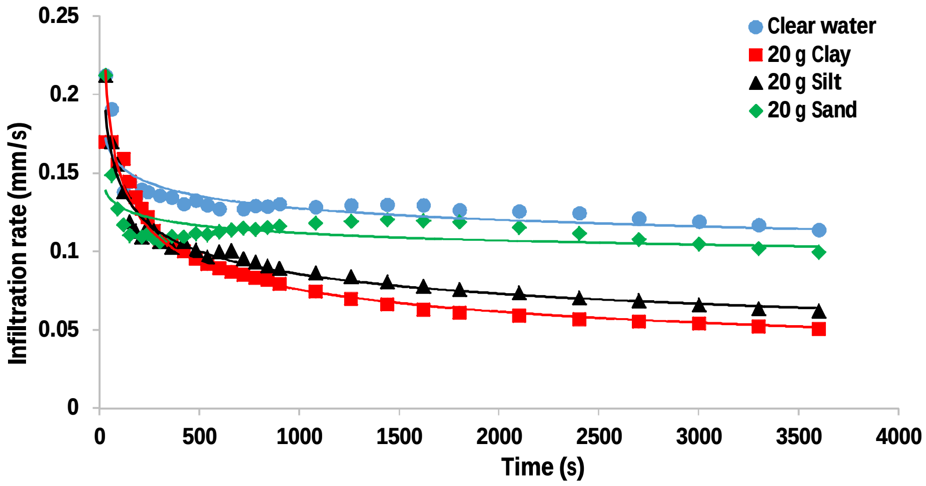

Figure 2 Plots of Infiltration rate with time for clear water and 20 g soil particles in suspension

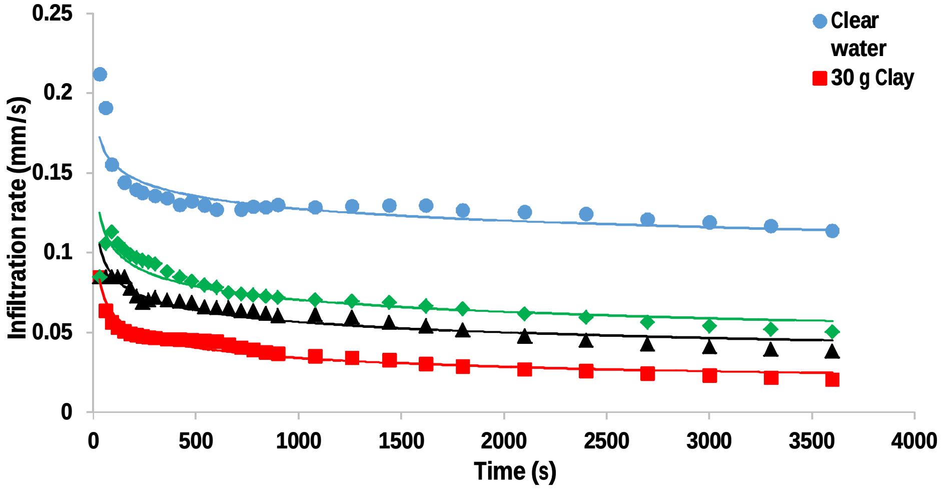

Figure 3 Plots of Infiltration rate with time for clear water and 30 g soil particles in suspension

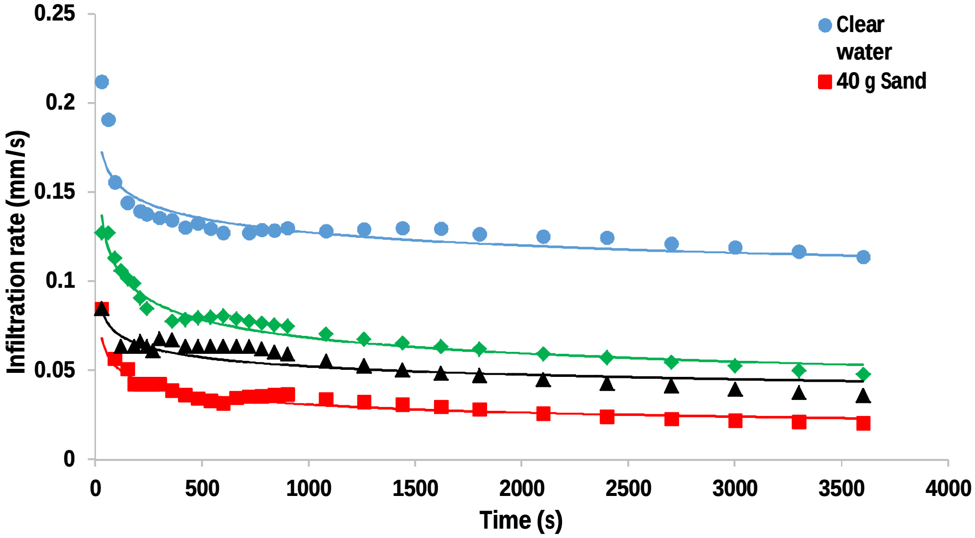

Figure 4 Plots of Infiltration rate with time for clear water and 40 g soil particles in suspension

With increasing time, the differences in infiltration rates among the various fluids changed appreciably. Thus, the differences in infiltration rates were significantly distinguishable following the significant changes in the initial physical and hydraulic conditions of the soil columns. Moreover, steady state infiltrability decreased with increasing sediment concentration. This indicated that the average soil water suctions at the wetting front decreased with increasing sediment concentration in the infiltrating water. The measured infiltration rates can be used to explain the formation of a definable surface layer with a significantly lower permeability (surface seal). It is thus, evident from the results that the smaller the sediment diameter, the lower the infiltration.

Overall, the saturated hydraulic conductivity and infiltration rate decreased with increasing sediment concentration, in the order: clay, silt and sand, respectively. As shown in Table 3, final infiltration rate was highest with clear water (0.114 mm/s) and lowest for clay suspension with 40 g clay particles (0.020 mm/s) after 60 minutes. At lower concentration (i.e. 10 g), it appeared that texture had no significant effect on infiltration (Fig. 1). From the experimental results, it was evident that the effect of increasing sediment concentration on infiltration rate differed for the different sediment particles.

Infiltration rate of clear water was significantly greater ($p < 0.05$) than those of the muddy water (sand, silt and clay suspensions). The presence of dispersed soil particles may have caused the sealing of the soil pores, which led to the lowered infiltration of muddy water [14].

It was also evident that the differences among the infiltration rates of the different sediment suspensions and clear water were large except for suspensions of 10 g sediment particles (Figs. 1 – 4). Again, insignificant differences were observed among the infiltration rates of fluids at low concentrations (i.e. 10 g), even though seal conductivities showed high variations with respect to sediment particle diameter (Tables 1 and 2).

3.2. Time-to-incipient ponding

Infiltration under rainfall and/or irrigation is a two-phase process. In the course of the first phase, the potential infiltration rate is greater than the rainfall rate. The actual infiltration rate is equal to the rainfall rate because the water can only enter the soil at the application rate. At a certain time, referred to as the time-to-ponding, the potential infiltration rate equals the rainfall rate and water begins to pond on the soil surface. Green and Ampt [20] defined time-to-incipient ponding (t_p) as the time elapsed between the beginning of rainfall/irrigation and when water begins to pond on the soil surface.

Given a constant rainfall flux, incipient ponding can be defined as the state in which the rainfall rate is equal to the infiltration rate and free water begins to form at the soil surface when the land is horizontal and relatively flat. In this study, the definition of incipient ponding was expanded to include the beginning of runoff on sloping land. The effect of sediment diameter and its concentration on time-to-incipient ponding was estimated from equation (8) for a range of hypothetically selected rainfall rates as shown in Table 4. The condition varied from clear water to muddy water, taking into account the particle diameter and concentration of the sediment particle.

Table 4 Critical time-to-incipient ponding resulting from the interactions among different sediments and their concentrations

R_r (mm/h)	**t_p (s)**												
	Clear water	**Clay suspension†**				**Silt suspension†**				**Sand suspension†**			
		10	**20**	**30**	**40**	**10**	**20**	**30**	**40**	**10**	**20**	**30**	**40**
5	N*	4.36	2.18	1.44	1.074	N*	150.95	56.18	33.96	N*	N*	N*	496.23
10	1005.60	4.20	2.14	1.42	1.065	293.076	67.088	38.51	26.58	N*	1021.44	175.58	96.045
15	266.053	4.15	2.12	1.41	1.062	159.86	56.61	34.85	24.78	N*	270.38	117.83	75.70
20	194.53	4.12	2.12	1.41	1.060	130.26	52.50	33.27	23.97	1996.68	197.70	101.18	68.45
25	168.87	4.11	2.11	1.41	1.060	117.91	50.44	32.44	23.54	776.90	171.62	93.70	64.93
30	154.10	4.10	2.11	1.41	1.058	110.32	49.036	31.87	23.23	538.066	156.61	88.93	62.59

N* = Negative t_p (i.e., no surface ponding within the interval); †Mass of soil sediments

The performance of equation 8 for the event of clear water infiltration and the case of muddy water infiltration showed that not all situations would cause surface ponding at the different rainfall intensities. For instance, unrealistic and invalid (i.e. negative) parameter values were obtained for 10 g sand suspension at R_r ranging from 5 mm/h to 15 mm/h. Similar results were observed for suspensions with 10 g silt, and 20 and 30 g sand for R_r of 5 mm/h. This occurred as a result of the larger hydraulic conductivity values in relation to rainfall rates for the surface layers (i.e. sediment depositional layers, herein, referred to as surface seals), especially sand. Compared to the clear water, clay suspensions gave the shortest t_p followed by silt and sand, respectively. Since the rainfall rates (5, 10, 15, 20, 25 and 30 mm/hr) were higher than the base K_s of the clay seal, the occurrence of surface ponding was highly expected. It can therefore, be inferred from the data (Table 4) that clear water would take a longer time to pond than muddy water. The t_p of clear water was similar to that observed for the sand suspensions since the sand particles improved the conductivity at the surface upon deposition. This implies that, among other things, the higher the K_s, the less the likelihood of ponding and runoff problems on the land. Thus, the suspensions with clay sediments would probably have the most severe problem of surface ponding and runoff.

The results also indicated that increases in t_p would result in decreases in both runoff and sediment load during erosion. Thus, as t_p increases, water intake would increase with a consequent decrease in runoff and erosion. As soil water content increases through increase in water intake, slaking would be minimized or the forces of aggregate destabilization would decrease. However, as slaking of soil aggregates and dispersion of clay increase, surface seal formation and pore clogging will increase, thereby reducing water intake and t_p, and increasing runoff and sediment load under field conditions. As a result, Oster et al. [21] proposed that irrigation should be stopped when ponding or runoff begins, so as to reduce the damaging effects of low infiltration rate. This is aimed to prevent erosion and deep pools that will take longer to evaporate. Ben-Hur et al. [22], also reported that if the final i increases, the erodibility factors decrease exponentially due to less runoff. In this context, Oster et al. [21] reported that, as 'a rule of thumb', all water should infiltrate within 24 to 48 hours, since longer periods of ponding increase the potential for poor aeration and disease prevalence. However, for the fact that infiltration varies from place to place within a field, it is recommended that more water be applied than is needed by the crop to ensure adequate irrigation. Application of about 20% more water than is needed by the crop compensates for infiltration variability. Conversely, this increase may cause ponding in areas where i is lowest, constraining and making irrigation expensive [23]. This is usually the case when i is slower than sprinkler or drip emitter application rates, resulting in water ponding and reduced application uniformity. Further, ponded water can increase evaporation losses, weed growth, change in weed species mix, and delay access to the field [23, 24].

4. CONCLUSIONS

Measurements showed that infiltration was highly dependent on the characteristics of soil and fluid. The type of sediment in the suspension strongly affected the development of surface seals and infiltration. Again, water-entry suction was affected by the granulometric texture of the sediment. Sediment concentration also greatly affected infiltration. From the data, it was clear that the higher the sediment concentration, the lower the infiltration rate. These observations were attributed to the increase in sediment deposition at the soil surface, with a concomitant increase its thickness. In addition, it was observed that increasing sediment concentration in water resulted in increased viscosity of the suspension, which was clearly noticeable from the infiltration measurements. However, the final infiltration rates for sediment concentration of 30 g was almost the same as those of 40 g. This shows that there is an upper limit for the effects of the sediment concentration on infiltration rate of muddy water.

With exception of 10 and 20 g sand suspension, and 10 g and 30 g silt and sand suspensions, respectively at rainfall rate of 5 mm/h, the t_p for the muddy water (sediment suspensions) were significantly less than those for the clear water for all rainfall rates. Additionally, negative parameter values for t_p were observed for some suspensions at low concentrations. This showed that surface ponding and/or runoff would not occur during the infiltration of these fluids. Time-to-ponding, however, is not a routine measurement unless rainfall simulation studies are being conducted. Conversely, the ability to estimate accurately when surface ponding occurs and how much runoff is produced is important in civil and agricultural engineering, and is essential for the proper design of irrigation systems, rain harvesting reservoirs, and hydraulic structures at the level of the watershed.

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