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On the Fixed Rainfall Intensity: Effects on Overland Flow Resistance, Shear Velocity and on Soil Erosion

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***Abstract*—**Raindrops and overland flow both are erosive parameters but they do not act by the same way. The overland flow alone tends to shear the soil horizontally and concentrates into rills. In the presence of rain, the soil particles are removed from the soil surface in the form of a uniform sheet layer. In addition to this, raindrops falling on the flow roughen the water and soil surface depending on the flow depth, and retard the velocity, therefore influence shear velocity and Manning's factor. To investigate this part, agricultural sandy soil, rainfall simulator and a laboratory soil tray of 0.2x1x3 m were the base of this work. Five overland flow depths of 0; 3.28; 4.28; 5.16; 5.60; 5.80 mm were generated under a rainfall intensity of 217.2 mm/h. Sediment concentration control is based on the proportionality of depth/microtopography. The soil loose is directly related to the presence of rain splash on thin sheet flow. The effect of shear velocity on sediment concentration is limited by the value of 5.28 cm/s. In addition to this, the rain splash reduces the soil roughness by breaking the soil crests. The rainfall intensity is the major factor influencing depth and soil erosion. In the presence of rainfall, the shear velocity of the flow is due to two simultaneous effects. The first, which is horizontal, comes from the flow and the second, vertical, is due to the raindrops.

***Keywords*—**Flow resistance, laboratory experiments, rainfall simulator, sediment concentration, shear velocity, soil erosion.

I. Introduction

SOIL erosion by rainfall includes the detachment and transport of soil particles by rain splash and overland flow. It is a major contention of this work that the interaction between rainfall and shallow overland flow causes more soil loss than either process alone.

The action of raindrop impact on the sheet of flowing water further complicates the overland flow characteristics. It disturbs the hydraulics of overland flow such as depth and velocity and all the parameters related to these two factors. It creates turbulence within the flow layer which greatly increases its transport capacity and results in more rapid erosion.

Soil properties and surface characteristics, such as soil texture and surface roughness (agricultural soil), also have an important role to play in interaction between the overland flow characteristics and soil erosion.

In this paper, we will investigate the effects of fixed rainfall intensity on shear velocity of overland flow, on Manning's factor which represents the roughness of an agricultural sandy soil (32% sand, 40% silt, 28% clay and 1.9% organic carbon) and on soil erosion.

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II. Experimental Equipment and Procedures

The simulator chosen was as used by many authors, only the shape and sizes were modified. Similar devices have been used, for example, in [1], [2]. Artificial rainfall was produced using a commercially available type of nozzle (1/2HH 25 Fulljet). This simulator consisted of a 3.5 meters steel tube rigidly mounted in a rectangular carriage which was longer than the flume soil tray in order to cover the total area of the soil. Two nozzles 1.5 m apart were fitted. The carriage that supported the sprinkler (tube with nozzles) was 3.5 meters above the soil surface and was supported by four bars. These bars were surrounded by a plastic sheet in order to protect the surroundings of the simulator against the excess spray. Water was centrally supplied by a pump to the sprinkler unit from a tank through a gate valve and pressure gage. Using plastic cups, the sprinkler can be calibrated; thus, the intensity of the precipitation was related to the manometer indication.

As regards the rainfall intensity measurements, the rainfall simulator was equipped with valves and a pressure gauge to vary and adjust the rate of water supplied to the nozzles. Considering the size of the tray, a very dense network of rain-gauges (cups having the same orifice area =60.79 cm^2) was placed on the soil tray. The volume of water collected in each gauge is determined using a graduated cylinder. The intensity is determined by the measurement of time, using a stopwatch, and the orifice area. The valve located between the pump outlet and the pressure gauge controls the variation of the rainfall intensity.

The soil tray was constructed with a plywood bed, supported by a steel frame. The whole system was mounted on two steel supports. One side of the support consisted of two drilled legs; these holes allow the slope angle of the tray to be adjusted. The other contained a simple bearing. The tray walls were 20 cm high and made of clear plastic. The width was 1 m and the length was 3 m. A tank at the top end of the soil tray supplied the soil surface with water to generate overland flow. This tank was controlled with a calibrated inlet tap to vary the rate of water delivery. On the other end of the soil tray, a water/sediment mixture collector was fixed.

The used agricultural sandy soil (32% sand, 40% silt, 28% clay and 1.9% organic carbon) was cleaned only of pebbles larger than 20 mm maximum dimension. The tray was filled with soil until the surface was level with the collector rim and flattened to have a homogeneous surface and to obtain a flat sheet of water.

Measurements of flow depth were obtained with a point gauge, mounted on a precision-leveled carriage, which slid on the rails of the tray frame.

The flow discharge of water/sediment mixture was measured volumetrically at the output of the collector, every minute from the commencement of flow, using cylinders of 1000 ml and a stop watch, of 0.01 second precision, to record the time of collection. Samples of these measures (200 ml) were taken and dried in the oven for 24 hours. The soil residue was used to represent the sediment concentration of the runoff.

Before presenting the various results obtained, let us recall the definition of some overland flow factors.

The shear velocity U* is given by:

$$U_* = \sqrt{\frac{\tau}{\rho}} \text{ or } U^* = \sqrt{gRS} \tag{1}$$

where τ is the shear velocity, ρ the density of the water, R the hydraulic radius (generally equals the water depth), S the slope of energy gradient and g is the acceleration due to gravity. The Manning's factor, which is a coefficient of roughness, is defined as:

$$V = \frac{1}{\eta} h^{\frac{2}{3}} S^{\frac{1}{2}} \text{ or } \eta = \frac{h^{\frac{2}{3}} S^{\frac{1}{2}}}{V} \tag{2}$$

where η is Manning's factor, h overland flow depth and V is overland flow velocity.

III. Discussion of the Results

A. Shear velocity, Manning's Factor and Soil Erosion of Overland Flow without Rainfall

1. Sediment Concentration

The sediment concentration, observed in the samples taken during this investigation, illustrates the capacity of overland flow to erode and transport sediments. One important observation is the higher concentration of sediment in the initial runoff and the decrease in concentration during the rest of the run of overland flow. After each run, the remaining soil was re-surfaced with additional soil to obtain a homogeneous soil with the same roughness. So, the surface particles were initially less compacted but, during the run, the compaction increased with time. This compaction could be the result of the penetration of the fine particles into the soil voids or the settlement of the heaviest particles.

The first value of sediment concentration, corresponding to the first depth h=3.28 mm, demonstrated that overland flow can erode and transport in laminar flow regime. Sediment concentration, at low Reynolds number, has shown that it is not necessary for the flow to be turbulent to erode and transport particles.

2. Sediment Concentration and Shear Velocity

Some researchers have concluded experimentally that sediment concentration within overland flow is related to shear velocity. Foster et al. [3] explained this relationship theoretically. After simplification, they found that $D = a_s \tau_e^{\varepsilon}$, where D is the detachment rate by rill erosion, a_s is a factor related to the soil's susceptibility to rilling, τ_e is effective shear stress and ε is an exponent.

$$\tau_e = C_\tau \gamma y S or \quad U^* = (gRS)^{1/2} \tag{3}$$

τ_e is assumed proportional to average overland flow depth and slope steepness.

$$y = (f_c/8gS)^{1/3} q^{2/3} \tag{4}$$

where f_c is the coefficient of friction, g is acceleration due to gravity, q is the flow discharge, and γ is weight density of the runoff.

$$C_\tau = \frac{\tau_e}{\tau_a} \tag{5}$$

τ_a is the average stress given by $\tau_a = \gamma y S$ where y is the flow depth and S is the soil plot slope. The shear velocity $U^* = f(\tau_e)$ is then a function of γ, y, f_c, S and q. So, theoretically, the soil erosion is a function of shear velocity.

The description of the entrainment/erosion process, at the water-soil surface, is a part of understanding the relationship between shear velocity, which represents the flow's capacity to erode the soil, with sediment concentration and rills as the consequences. This description is based on visual observations and is as follows. When overland flow is taking place, the particles with less cohesiveness start to move with the flow. The forces causing this motion are evidently greatest at the bed flow surface [4]. At the beginning of a run, only the surface particles (top layer) are significantly affected by the drag force. Transporting force action depends on how the particles are exposed, and on the particles' concentration in the flow. In addition to this, agricultural soil, used in these experiments, is characterized by a microtopography which causes an increase in overland flow depth and, therefore, in shear velocity. During the run, the flow lines developed between the major crests of the soil surface, and particle transport was concentrated in these lines. The convergence of some of these lines has built narrow channels. These channels converged and built rivulets. These rills formed a network, which developed downstream with time until the incision was deep enough to concentrate and conduct the water/sediment mixture.

The initiation of rills is determined from a threshold shear velocity between 3 cm/s and 3.5 cm/s [5]. Raws and Govers [6] stressed this value and found a sharp increase in sediment concentration once the shear velocity exceeded 3.0 cm/s.

The results issued from our experiments have shown that the shear velocity varied between 3.74 cm/s and 4.99 cm/s, with corresponding overland flow depths of 3.28 mm and 5.80 mm. The plotting of sediment concentration versus shear velocity, Fig. 1, shows that the sediment concentration increases slowly from the first point (3.74 cm/s) to the second point (4.89 cm/s) and increases more rapidly to the fifth point (4.99 cm/s). In general, we can divide this curve in three parts and relate the variation of the curvature to the flow depth/microtopography proportionality. In the lower part of the curve, the depth is equal to/or slightly greater than the scale of the microtopography (less than the major crest).

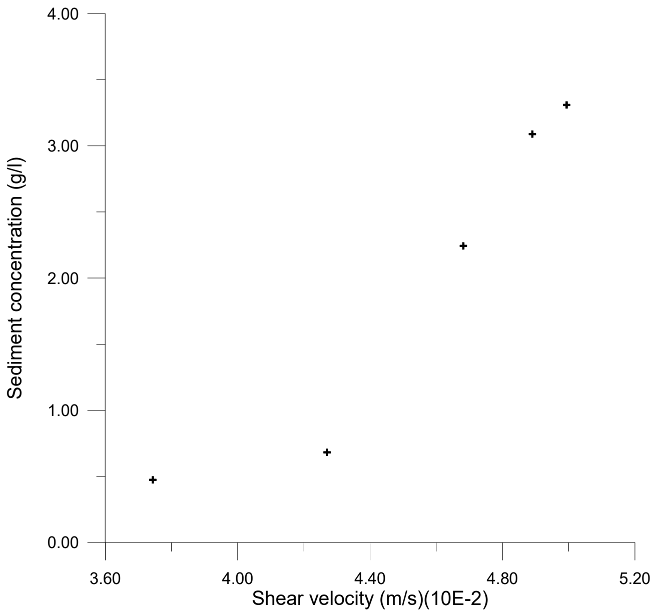

Fig. 1 Evolution of the sediment concentration with shear velocity

In the middle of the curve, the overland flow depth just covered the soil rugosity. In the upper part, the flow depth is greater than the scale of the roughness, and the particles detached by the greater depth of water are fewer than in the middle of the curve.

Govers [5] prefers to present the function Sc=f(U*) as two straight lines (see Fig. 2). The first one is characterized by a very low slope which extends to the threshold shear velocity of 3.2 cm/s. The second line is characterized by a very steep slope for which the coefficient of correlation equals 0.97 [5].

The contrast between the results from the graphs is clear. In our graph, the sharp increase in sediment concentration started from point two, which corresponds to 4.26 cm/s. This value is bigger than the threshold of shear velocity found between 3.0-3.5 cm/s proposed by Govers [5] and supported by Raws and Govers [6]. Also, the rill initiation started with shear velocity less than 4.26 cm/s. In contrast to our results and Govers' results, Moss et al. [7] found a sharp increase in sediment concentration from ≅ 2.5 cm/s. This difference could be based on the experimental conditions (soil, flume sizes, slope angles …). However, it is important to note that sediment concentration relation to shear velocity is of the same form.

Savat [8] concluded that any increase in the viscosity of the water, as may result from a heavy suspended sediment load, increases the thickness of the water film and diminishes its mean velocity, its Froude number and, therefore, the net drag exerted on the bottom grains. Rill formation will thus be retarded. Our results generally support this view, notably in the second part of the graph, between point two and point four, but the retardation of rill formation is in contrast with these results. In the interval from point two to point four, the sediment concentration increased sharply, which means increased viscosity [9] and rill formation developed only gradually.

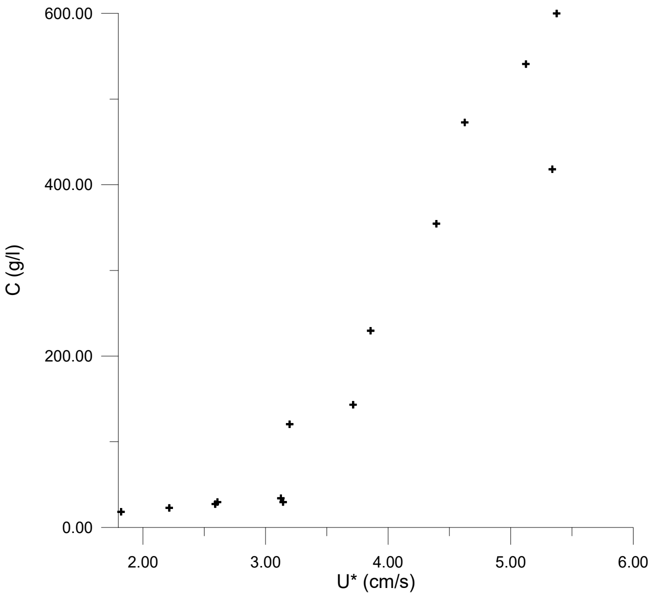

Fig. 2 Sediment concentration as a function of a shear velocity [5]

Some authors classify the rill initiation by the rill sizes. For Torri et al. [10], at least one rill of 5 cm long, 0.5 cm deep and 1 or 2 cm wide, must be incised into the soil. Others used the volumetric evolution of the rill pattern to measure the quantity of erosion in the field [11]. Nearing et al. [12] concluded that the best overall predictor for unit sediment load from the experiments was stream power. Other variables, including shear stress, shear modified by hydraulic friction, unit stream power, and effective stream power, did not produce as high a level of statistical fit to the sediment load data as did stream power.

3. Roughness Coefficient-Depth and Sediment Concentration

The resistance factors to the flow are presented by Manning's factor (coefficient of roughness). An agricultural soil surface is classified as a rough surface according to its high rugosity. Emmett [13] found, in the laboratory, that the effect of roughness is to retard the flow and increase the depth. The sand grain surface roughness increased depths up to 30% over those on a smooth surface. Savat [14] stressed the importance of soil roughness when he investigated the resistance to flow in a rippled supercritical sheet flow. The waves are not remodeled during their migration and a considerable slowdown and acceleration of the flow causes significant energy loses. He calculated the head loss ΔS due to retardation from the Euler-Rateau equation:

$$\Delta S = \frac{(V_1 - V_2)^2}{2g} \qquad (6)$$

where V_2 is the mean velocity under the crest of the viscous wave, and V_1 is the mean flow velocity. The scatter of Savat's data showed the significant effect of small depth changes in the computation of the friction factor (Manning's factor). The same remark was made by Emmett [13] in calculating resistance terms. This observation is explained by taking an example from the results found in the present study.

The experimental data show the difference between depth one and depth two as 1 mm, but the difference in time corresponding to these depths is evaluated to $t \approx 10.2$ seconds (this time t is the time to collect the same volume (1 litre) of water/sediment mixture at the output of the collector). This large difference in time indicates a large difference in flow velocity. Flow velocity of depth two is more than twice that of depth one. This effect could be explained by the fact that most of the flow runs between the big crests of the soil (agricultural soil), for the small depths; only a very thin layer flows over the roughness height. The flow flattens the surface and decreases the rugosity very slowly, which resists the flow velocity. The greater depths sufficiently cover the total rugosity, and have enough capacity to transport and demolish the crests. Also, during transport, particles are deposited to increase the surface smoothness while the rest are transported to the output and measured as sediment concentration.

As regards the Manning's factor effect on sediment concentration, this relationship is plotted in Fig. 3. The curve shows a sharp decrease followed by a very slow decrease in sediment concentration with increasing Manning's factor. This fact is always related to the microtopography/flow depth proportionality. When the depth increases, the flow resistance is reduced. Indeed, only the bottom layer of the flow is affected by the roughness and sediment concentration is increased.

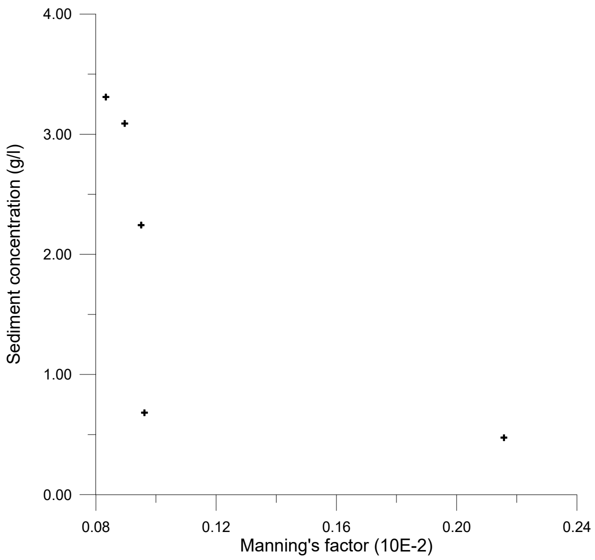

Fig. 3 Sediment concentration versus Manning's factor

Deposition can modify bed roughness and slope [3]. The depth of the flow and the cohesiveness of the particles, which is a part of flow resistance, can control soil erosion in terms of concentration/depth proportionality. Ramser [15] discussed the relationships between velocities, channel cross-sections, and frictional resistance to flow, as they may be controlled to reduce erosion and silting. There is a critical velocity at which no silting or erosion will occur if the water is already fully charged with silt.

4. Statistical Analysis of the Relationship between Sediment Concentration and Shear Velocity

The purpose of this statistical analysis is to represent the shape of the relationship between sediment concentration and shear velocity by a corresponding mathematical function.

According to the form of the curve shown in Fig. 1, corresponding to $Sc=f(U_*)$, the logistical function has been chosen to investigate the sediment concentration as a dependent variable in regression models with the independent variable U_*.

The logistical function applied on our experimental data is defined in the general form as:

$$Y = \frac{b}{1 + c.\exp^{-ax}} + d \tag{7}$$

where Y represents sediment concentration Sc_1, x represents the hydraulic parameter U_* and a, b, c and d are constants to be determined statistically.

In the logistical function, (b+d) and d represent the upper and lower asymptotes of the curve respectively. In our case, the lower asymptote is the x axis, so d=0 and the model is simplified to:

$$Y = \frac{b}{1 + c.\exp^{-ax}} \tag{8}$$

To find the function parameters a, b, and c, non-linear regression procedures, CNLR and NLR SPSS-X were used.

As regards the relationships between sediment concentration and shear velocity, some workers preferred to apply polynomial and linear models to statistically analyze this relationship.

Govers [5] conducted his experiments to evaluate the transport capacity of thin flows using a very well sorted Tongrian sand. Runs were carried out with four unit discharges and for three different slopes. Each run was repeated five times. Sediment transport capacity was then taken as the mean of the five measurements. He plotted sediment concentration as function of U_* (loamy material), where U_* is shear velocity. The regression model obtained was:

$$C=0.90U_*^{4.00} R^2=0.95 \text{ (D50 = 105 – 121 μm)}. \tag{9}$$

The data of Kramer and Meyer [16] gave:

$$C=0.90U_*^{4.72} \qquad R^2=0.97 \tag{10}$$

From these models, it may be remarked that only the polynomial equations have been tested and no attempt was made to use a logistical model, even though Fig. 2 has a similar shape to the logistical function.

This logistical function has been tested on the relationship between sediment concentration and shear velocity; the following model has been obtained:

$$Sc = \frac{4.90}{1 + 4673370.7 \exp^{-323.49U_*}} \quad (11)$$

with a coefficient of determination of 98.13%. From the coefficient of determination, we can conclude that the sediment concentration is significantly non-linearly related to shear velocity and the experimental data fitted very well to the logistical model.

B. Shear Velocity, Manning's Factor and Soil Erosion in the Presence of Fixed Rainfall Intensity

1. Sediment Concentration

The sediment concentrations measured in this investigation have shown that the effect of rainfall on sheet flow is dominant. This factor varied from 10.3 g/l to 6.3 g/l, whereas, in the absence of rainfall, it varied from 0.4735 g/l to 3.3100 g/l. from these values we remark that the soil is eroded more in the presence of rainsplash than by overland flow alone. In comparison to the effect of water drops in the presence of a stagnant depth, in this case the only effect of the depth is to weaken the bindings between the particles, whereas in the flowing water, most of the detached particles are transported or displaced from the original position. These two findings lead to the conclusion that moving water in the presence of rainsplash is more effective or more erosive than still water with water drop impact. From this conclusion, the physical reduction of the flow energy could reduce soil erosion significantly.

2. The Relationship between Sediment Concentration and Shear Velocity

Experimental data for soil erosion, computed under measured hydraulic parameters, have shown that when rainfall was absent, a sharp increase in sediment concentration was found once the shear velocity exceeded 4.26 cm/s (Fig. 4). However, when rainfall was present, sediment concentration was significantly higher at the lowest value of shear velocity and decreased sharply once this hydraulic parameters reached the value of U_*=5.280 cm/s (Fig. 4). The erosive capacity of the flow U_* increased in the presence of rainfall, whereas the sediment concentration decreased. Once the value of the shear velocity of 5.28 cm/s is exceeded, the influence of this parameter on sediment movement is very limited. In this case, the sediment concentration is then no longer affected by the hydraulic flow capacity U_*, but mostly it is limited to the amount of sediment detached by rainfall drops and the flow turbulence produced by the rain and transported by the flow to the collector.

The particles of agricultural soil in the flow were found in two states; single particles or small aggregates of particles (sets). The motion of these in the flow, in the presence of rainsplash, is entirely different from their motion in the flow alone. The main trajectory of the soil particles is translation accompanied by rotation. The translation motion is in all directions, but mostly in a downstream direction depending on the original position of the particle when the drop impact took place. When the particle was on the downstream side of the splash, the particle is accelerated by the pressure given to the flow by the drop, but retarded when it was on the upstream side. The rotational motion, which was quite clear from observation (after three minutes into the run, when the water clearance was taking place) of the particle masses, is created by the splash impact and the contact with the bed crests when the particle is accelerated by the flow. Walker et al. [17] reported that grains of 0.25 mm to 4 mm fractions were observed to move by rolling when they were momentarily undisturbed by raindrop impact. On slopes of 0.5%, the net downslope movement of sand grains was relatively slow, consisting of apparently random movements in response to raindrop impacts.

The high shearing rate of the particles or masses consistently occurred at the beginning of the run because the soil used was always ploughed and mixed to obtain a new 'natural' soil surface condition.

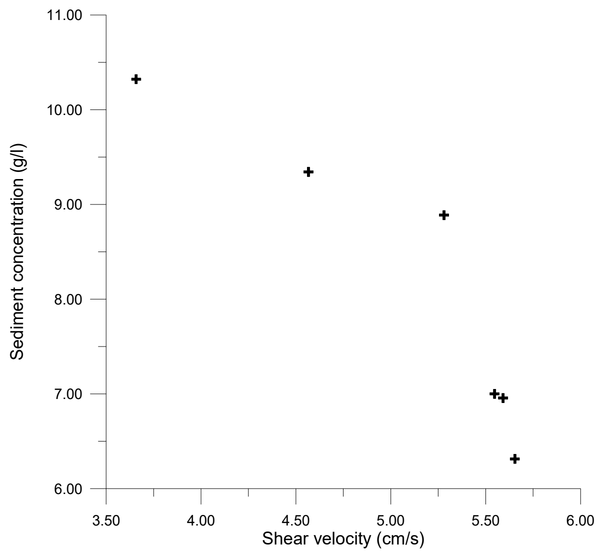

Fig. 4 Sediment concentration versus shear velocity

Between the period of two and three minutes from the run, the clearance of a turbid appearance began and increased slowly with time. The water clearance could be the consequence of the soil compaction. This compaction might have two origins. It might be from the drop impact, from the soil preparation or from both of them (the soil compaction increases with soil depth). The rate of shearing decreased slowly with time on the basis of this compaction.

The shear velocity of the flow, in the presence of rainfall, is the product of two effects; the first one was produced horizontally by the flow and the second one was produced vertically by the impact of the drops (U_h + U_v). The rate of these shear velocities depends on flow depth h. When the flow depth increases, the vertical shear velocity decreases and only the horizontal shear velocity erodes the soil surface with a small effect from the drop impact.

3. The Augmentation of Shear Velocity Caused by Splash

The presence of rainfall increases the detachment capacity of the flow, and the effect of rainfall decreases with increasing flow depth and shear velocity. The data, from Table I, have shown a decrease in the augmentation of shear velocity and sediment concentration caused by rainsplash with increasing depth of overland flow alone. This concentration augmentation is highly significant, especially for the first and second values of 8.87 g/l and 8.20 g/l, which correspond to the lowest overland flow depths. They are approximately twice the sediment concentration with overland flow alone. This indicates that there is a great effect of rainfall on the shallow depth of overland flow. In addition to this, the bed slope angle of 2.5° is not negligible but increases the splash detachment more downslope than upslope. The vertical shear velocity is increased until the water-film becomes so thick that drop impacts no longer reach the bed.

TABLE I
INCREMENTS OF DEPTH, SHEAR VELOCITY, MANNING'S FACTOR AND SEDIMENT CONCENTRATION BY RAINSPLASH ON OVERLAND FLOW ALONE

ΔSc (mm)	ΔSc (g/l)	ΔU^* (cm/s)	$\Delta\eta$ (10^{-2})
1.60	8.8702	0.8226	-0.1145
2.24	8.2047	1.0102	0.0356
2.04	4.7552	0.8656	0.0183
1.72	3.8664	0.7018	0.0233
1.64	3.0060	0.6600	0.0131

Δ represents the difference between the factors of overland flow in the presence of intensity and the factors of overland flow alone.

The fixed rainfall depth (or the depth generated by the fixed rainfall intensity) is included in the computed flow depths.

The first flow depth is generated only by the fixed rainfall intensity (overland flow alone depth h=0).

Raws and Govers [6] found that the extra sediment eroded is not only directly detached by raindrop impact, but also by fast flowing water that is transferred to the bed by the drop impacts.

4. Roughness Coefficient-Depth and Sediment Concentration Relationship

The Manning's friction factor has been widely adapted to describe the resistance to flow in the presence of rainfall and is computed from 2.

The data calculated have shown an increasing friction factor with an increasing Reynolds number until the fourth point, where a decrease appeared from $\eta = 0.113\times10^{-2}$ to 0.096×10^{-2} which corresponds to Reynolds numbers of 1976.6 to 2470.05. This decrease might be explained numerically according to (2): the slight increase of velocity, from point four to point six, is more significant than the increasing depth to power ratio of 2/3 ($D^{2/3}$) for a constant slope. This phenomenon could be explained physically. In these experiments within the run the natural roughness, (agricultural soil) in the presence of the thin sheet of flow and rainfall impact, is eliminated and replaced by the roughness created by the rainfall impacts. When the flow is deep, the effect of rainfall impact is absorbed by the flow depth. At this stage, the natural roughness presented by the agricultural soil is broken down by the flow. The heaviest particles are then deposited before reaching the collector. These two subprocesses smoothed the soil surface and decreased the surface roughness or the friction factor.

The increase or variation in friction factor produced by the effect of fixed rainfall intensity on overland flow is random and does not depend on any hydraulic parameters (Table I).

The first $\Delta\eta$ is quite exceptional, with a negative value, which means that the rainfall decreases the friction in this particular case. The explanation of this phenomenon is that, at low depth, the roughness of agricultural soil increases the depth and retards the flow velocity for a given fixed depth in the supply tank. This implies a high friction factor according to (2). In the presence of rainfall, the raindrops break the soil crests and the flow is retarded in comparison to the fluctuations of the water surface.

IV. CONCLUSION

This study reached the following conclusions:

- The agricultural soil used was characterized by a high roughness and was an uncompacted soil, which characteristics increase the flow resistance and, therefore, the flow depth.
- Sediment concentration increased with water depth.
- The sharp increase in sediment concentration started from the shear velocity of 4.26 cm/s. This value is bigger than the threshold proposed by Govers [5]: 3 cm/s - 3.5 cm/s. Also, rill initiation started with shear velocity less than 4.26 cm/s.
- Sediment concentration control is always proportionality related to the microtopography/flow depth.
- The increase in sediment concentration, due to the presence of rainsplash, was highly significant, especially for shallow depths of flow. In addition to this, the rainsplash is the major factor influencing depth and soil erosion.
- Once the value of the shear velocity of 5.28 cm/s was exceeded, the influence of this parameter on sediment concentration was very limited. The shear velocity of the flow in the presence of rainfall is the product of two effects: the first one was produced horizontally by the flow and the second was produced vertically by the impact of the drops.
- At low depth, the roughness of agricultural soil increased the depth and retarded the flow velocity for given fixed depth in the supply tank. This implies a high friction factor, whereas in the presence of rainfall the falling raindrops broke the soil crests which retarded the flow velocity.

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