International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:7, No:8, 2013

Plants Cover Effects on Overland Flow and on Soil Erosion under Simulated Rainfall Intensity

H. Madi, L. Mouzai, and M. Bouhadef

Abstract**—**The purpose of this article is to study the effects of plants cover on overland flow and, therefore, its influences on the amount of eroded and transported soil. In this investigation, all the experiments were conducted in the LEGHYD laboratory using a rainfall simulator and a soil tray. The experiments were conducted using an experimental plot (soil tray) which is 2m long, 0.5m wide and 0.15m deep. The soil used is an agricultural sandy soil (62.08% coarse sand, 19.14% fine sand, 11.57% silt, and 7.21% clay). Plastic rods (4mm in diameter) were used to simulate the plants at different densities: 0 stem/m^2 (bared soil), 126 stems/m², 203 stems/m², 461 stems/m² and 2500 stems/m²). The used rainfall intensity is 73mm/h and the soil tray slope is fixed to 3°. The results have shown that the overland flow velocities decreased with increasing stems density, and the density cover has a great effect on sediment concentration. Darcy–Weisbach and Manning friction coefficients of overland flow increased when the stems density increased. Froude and Reynolds numbers decreased with increasing stems density and, consequently, the flow regime of all treatments was laminar and subcritical. From these findings, we conclude that increasing the plants cover can efficiently reduce soil loss and avoid denuding the roots plants.

Keywords**—**Soil erosion, vegetation, stems density, overland flow.

I. Introduction

WATER erosion is one of the biggest environmental problems; it is defined as three processes, detachment, transport and deposition. Vegetation has been identified for a long time as an effective way to fight against erosion, and widespread as an important measure of soil conservation [10]. A large of field and laboratory studies have demonstrated the effectiveness of various soil surface covers (e.g., crop residues, rock fragments, organic mulches, vegetation, root and stems of vegetation) in reducing runoff and soil loss under different environmental conditions e.g.:, [6], [15], [11], [12]. A vegetation cover (grasses, shrubs …etc.) can be used to restore degraded areas or to protect newly built bare slopes in the long term [2].

Canopy and ground covers developed in these fertility islands are a natural cushion against the impact energy of rainfall. Also, greater levels of organic matter improve the soil physicochemical properties, promoting infiltration and reducing runoff and soil erosion in comparison with the open spaces between them [10], [11].

H. Madi, L. Mouzai, and M. Bouhadef are with the LEGHYD Laboratory, Faculty of Civil Engineering, University of Sciences and Technology Houari Boumediene (USTHB), BP 32, Bab-Ezzouar, Algiers, Algeria (e-mail: elhoo11@yahoo.fr, mouzail@yahoo.fr, mbouhadef@usthb.dz).

Several experiences [8], [12] proved that runoff may be trapped by the stems of plant reducing the amount of eroded and transported soil.

The main objective of this investigation is to study the impact of density plants cover (stems of plants) on surface runoff characteristics and soil erosion.

II. Equipment and Experimental Procedures

A. Experimental Procedures

The rainfall simulator used in the laboratory is an EID 340 ORSTOM type with a spray nozzle fixed on a gantry at a height of about four meters This simulator, has been used by [13]. The procedure used to measure the rainfall intensities was the simple volumetric method.

1. Soil Preparation

The soil materiel used to run the experiments was an agricultural soil and was examined for stones and roots which were removed in order to have a homogenous structure. It is consisted of 62.08% coarse sand, fine sand 19.14%, 11.57% silt, and 7.21% clay. To run an experiment, a layer of examined soil was deposited and spread gently over the surface tray. To obtain a flat plot (Fig. 1), in the purpose to generate a flat sheet of water, a straight piece of hardwood was used to flatten the surface until the top soil is level with the downstream end of the tray. Afterwards, the soil was wetted gently without disturbing the soil structure, with a watering can (fine rain) until saturation; then the rainfall simulator is put on to run the experiment. The slope of the soil tray was fixed on 3°. This slope angle is appropriate to generate an interrill overland flow.

To simulate the natural plants, a number of artificial stems by unit of surface (stem/m²) have been used. The distance between the stems must be respected to have a uniform plants cover. The effects of roots on infiltration, soil strength, and the hydrological effects caused by plant (e.g.: interception, stem flow, leaf drainage, evaporation, etc.) are ignored. The plants cover density is related to the space between stems. The lines space of 2cm · 5cm, 7cm and 10cm were used in addition to bare soil plot (see Table I).

TABLE I
SPACING BETWEEN STEMS AND THEIR DENSITIES

spacing between the stems (cm)	2	5	7	10	bare soil
Stems density (stem/m²)	2500	461	203	126	0

2. Discharge and Sediments Concentration

The simulated rainfall intensity of 73mm h^{-1} has been run for 30min. The discharge was measured volumetrically. Samples were taken at the output of the tube collector every 3 minutes from the commencement of flow using cylinders of 1000ml and a stop watch of 0.01 second precision to record the time of collection.

For each run, overland flow initiating time was recorded; all discharges and sediment samples were collected in a pail; and flow velocity was measured every 3 minutes intervals during the experiment. Sediments were separated from the water/sediments mixture by putting the bechers in the oven for 24 hours at 105C°, and the differences between the weights represent the sediment concentration. Sediment concentration was determined as the ratio of dry sediment mass to overland flow volume.

3. Surface Velocity Measurements

Surface flow velocities (Vs) were measured using $KMnO_4$ dye tracer. Time tracer traveling across a marked distance (50 cm) is determined according to the color-front propagation using a stop-match. The measured values of Vs are used to estimate profile mean velocities (V) by the relationship V = kVs, where, k is a coefficient. Assuming that the vertical velocity distribution in laminar flow, depth follows a quadratic equation, then, the theoretical value k is 0.67 [7], [15], [9].

Fig. 1 Soil tray

III. Overland Flow Characteristics

Flow depth is an important factor of surface flow, but it is difficult to measure, because of erosion process on agricultural plot surface. Assuming that, slope flow is uniform, then, mean flow depth can be calculated from:

$$h = \frac{Q}{v\,B} = \frac{q}{v} \tag{1}$$

h is the flow depth (cm), q is the unit discharge ($cm^2\ s^{-1}$), Q is the runoff volume during t time (ml), v is the mean flow velocity (cm/s) and B is the width of water-crossing section (cm).

Vegetation stems change the hydraulic radius by breaking up the flow into individual flow paths between the stems. Each flow path is considered as a rectangular channel on the soil surface. The stems lines form the channel sides. A revised hydraulic radius (Rs) can be then calculated, based on the spacing (SS) and flow depth (h) and defined as:

$$R_s = \frac{SS.k}{2k + SS} \tag{2}$$

This formula is reported by [3] and [9].

SS is the distance (space) between the stems and **k is the stem height** [16].

Flow Reynolds number (Re) and Froude number (Fr) were calculated from (3) and (4) respectively:

$$Re = \frac{4R_S V}{\nu} \tag{3}$$

$$Fr = \frac{V}{\sqrt{gh}} \tag{4}$$

ν is the kinematical viscosity ($cm^2\ s^{-1}$) and g the acceleration due to gravity ($cm\ s^{-2}$).

Darcy–Weisbach (*f*) and Mannings friction coefficients (*n*) were used to characterize flow retardation and could be estimated by (5) and (6) respectively:

$$f = \frac{8ghS}{V^2} \tag{5}$$

$$n = \frac{h^{2/3} S^{1/2}}{V_m} \tag{6}$$

S is the surface slope ($m.m^{-1}$)

Reference [5] expresses the coefficient of Darcy-Weisbach, for a vegetated soil, by (7):

$$f = \frac{8gR_S S}{V^2} \tag{7}$$

IV. Results and Discussion

A. Impact of Stems Plants on Overland Flow Hydraulics

The results found have shown that the mean flow velocity deceased with increasing stems density (Fig. 2) and the stems decreased overland flow velocity to about 27.45% in comparison to the bared soil.

Our results are similar to those reported by [15] on vegetated slope land for lower slopes. Their results have shown that flow velocity deceased with increasing cover. In addition to this, the grass cover has more important effect on lower slope velocity than upper slope one.

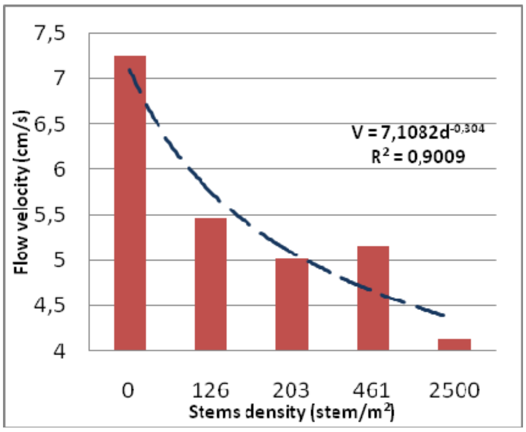

Fig. 2 Relationship between mean flow velocity and stems density

The relationship between the mean flow velocity (V) and the stems density (d) has been analyzed statistically and was found to be best presented by a power function.

$$V = 7.11\ d^{-0,304}\quad R^2 = 0.90 \tag{8}$$

The mean flow velocities through the stems plants were between 14.11% and 27.45% lower than on the bared soil. The flow velocity determines the rate at which water flow transports sediment [14].

The effect of the cover density on mean flow velocity is supported by the findings of other studies [9], [12].

The results illustrated on Table IV show overland flow characteristics for each density of stems. Froude number decreased with increasing stems density. The stems reduced it by 20% to38% compared to bared soil plot (Fr = 0.999, Table V). However, there was a clear difference in Reynolds number with the density covers, ranging from 76.43 to 156. We note a reduction in Reynolds number from 8.76% to 34.2%. The results of Table IV also show that, all the values of the Froude number (Fr) were less than 1 and all the values of the Reynolds numbers (Re) were less than 500, so the overland flow of the present study was always tranquil and laminar according to the criteria for open-channel flows. Except for a bare soil, where, overland flow appeared to be critical, because the Froude number equals 1 (Fr = 0.999).

Our results differ from the findings reported by [9] in which the values of the Reynolds number Re were much greater than those of this study. The difference may be explained by the concentrated runoff with greater velocity and flow depth.

The results plotted on Fig. 3 have shown that an increase in density cover increases significantly Darcy–Weisbach (*f*) and Mannings (*n*) friction coefficients. Their values evolve from 0.243 to 1.959 and from 1.47 x10^{-2} to 4.74 x10^{-2} times those of the bared soil respectively.

Similarly, [1] found that the cover is mainly attributed to surface roughness. The magnitudes of the friction factors *(f)* and *(n)* directly reflect the resistance to overland flow. A consequence of greater resistance to overland flow, indicated by higher values of *f* and *n*, leads to a larger proportion of the potential energy of the water and overcome land surface resistance, and consequently reducing the flow velocity.

TABLE II
EVOLUTION OF THE FLOW DISCHARGE, FLOW VELOCITY, FLOW DEPTH AND SEDIMENT CONCENTRATION WITH THE STEM DENSITY

I=73 mm/h				
Stem density (Stem/m²)	Discharge 10^{-4} cm²/s	Flow velocity (cm/s)	Flow depth (mm)	Sediment concentration (kg/m3)
Bare soil	3.9	7.26	0.537	5.274
126	3.7	5.46	0.680	3.709
203	3.69	5.01	0.722	3.260
461	3.72	5.16	0.721	2.889
2500	3.6	4.13	0.860	3.027

TABLE III
EVOLUTION OF THE FLOW DISCHARGE, FLOW VELOCITY, SEDIMENT CONCENTRATION AND FLOW DEPTH IN COMPARISON WITH THE BARE SOIL

I=73 mm/h		**Decrease** (%)		**Increase (%)**
Stem density (Stem/m²)	Discharge	Flow velocity	Sediment concentration	Flow Depth
Baresoil	--	--	--	--
126	2.42	14.11	17.43	11.74
203	2.69	18.32	23.60	14.65
461	2.40	16.91	29.22	14.57
2500	4.64	27.45	27.07	23.10

Thus, the presence of grass increases the resistance to overland flow and hence reduces its velocity; the greater the grass cover, the greater the reduction in velocity. Our results are similar to those reported by [1] who found that the degree of coverage influenced surface roughness.

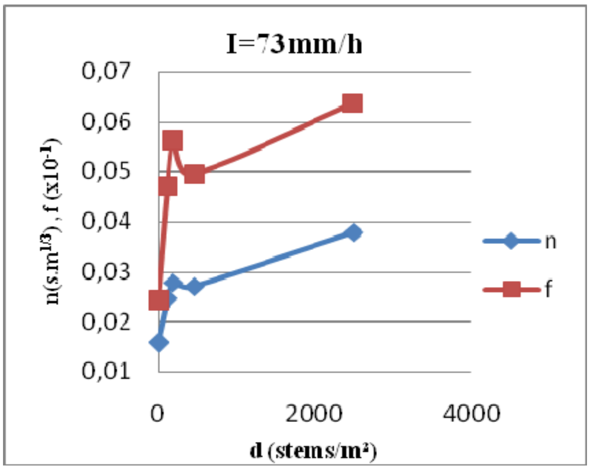

Fig. 3 Effect of stems density on (*n*) and (*f*) friction factors

B. Impact of Stems Plants on Overland Flow Hydraulics

Sediments concentration in overland flow was significantly reduced by increasing stems density (Table II). When compared with the bare plots, sediments concentration was reduced by 17.43% on the vegetated plots. In spite of the higher bulk density of our soil, the results of this study are similar to the results obtained by [8] who observed reductions for the lower slopes. This reduction may be mainly due to the increase in hydraulic roughness due to stems that being able to reduce flow velocity, or may be due to the increase in the interception of raindrops that reduce raindrops energy approaching to soil surface, prevent soil crusting and reduce runoff.

Regression analysis indicated that the sediment concentration (SC) was significantly correlated with the density of stems cover (d), giving the following correlation equation:

$$SC = 5.181 d^{-0.079} \qquad R^2 = 0.91 \qquad (9)$$

C. Relationship between Velocity and Sediments

The results illustrated in Fig. 4 show that the sediments concentration increases with mean flow velocity.

The velocity determines the rate of detached sediments by runoff [4], [13]. Important plant covers reduce the flow velocity and, consequently, reduce the detachment capacity of overland flow. By reducing the flow velocity, grasses enhance deposition of sediments carried in the runoff [11].

Regression analysis indicated that the sediment concentration (SC) was significantly correlated with the mean flow velocity (V), giving the following correlation equation:

$$SC = 0{,}22V^2 - 1{,}82V + 6.67 \qquad R^2 = 0.94 \qquad (10)$$

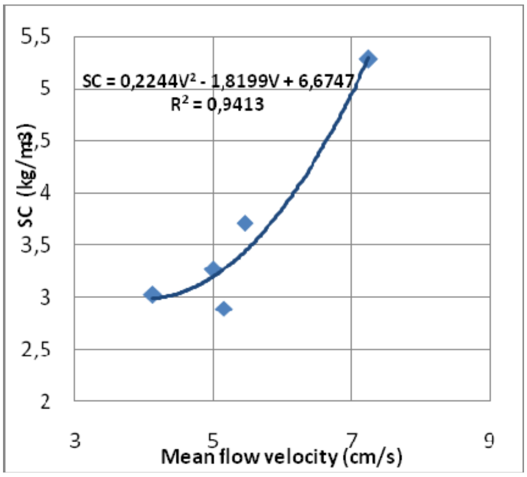

Fig. 4 Relationship between sediment concentration and mean flow velocity

TABLE IV
EVOLUTION OF THE HYDRAULIC RADIUS, MANNING'S COEFFICIENT, DARCY-WEISBACH COEFFICIENT, REYNOLDS NUMBER AND FROUDE NUMBER WITH THE STEM DENSITY

I=73 mm/h					
Stem density (Stem/m²)	*Rs* (mm)	*n* x10^{-2} (s.m$^{1/3}$)	*f*	*Re*	*Fr*
bare soil	--	1.58	0.2401	156	0.999
126	0.599	2.45	0.4723	130.86	0.668
203	0.598	2.78	0.5611	119.93	0.595
461	0.559	2.70	0.4949	115.41	0.613
2500	0.462	3.79	0.6377	76.43	0.449

TABLE V
EVOLUTION OF MANNING'S COEFFICIENT, DARCY-WEISBACH COEFFICIENT, REYNOLDS NUMBER AND FROUDE NUMBER IN COMPARISON WITH A BARE SOIL

I=73 mm/h	Increase (%)		Decrease (%)	
Stem density (Stem/m²)	*n* (%)	*f* (%)	*Re* (%)	*Fr* (%)
bare soil	--	--	--	--
126	21.713	32.59	8.76	19.83
203	27.630	40.06	13.1	31.98
461	26.230	34.66	15	23.94
2500	41.247	45.29	34.2	37.94

IV. CONCLUSION

In this work, we studied the effects of stems plants on the hydraulics of overland flow generated by rainfall. The stems density were 126 stems/m², 203 stems/m², 461 stems/m² and 2500 stems/m² under simulated rainfall intensity of 73 mm h^{-1} for about 30min, and a bare soil plot (control) at a slope of 3°. The results have shown that the stems of plant could effectively control erosion on a sandy loam soil.

The relationships between flow velocity, sediments concentration and stems density are best described by a negative power functions. Flow regimes of all treatments were laminar and subcritical ($Re < 500$ and $Fr < 1$). Also, the stems density influenced surface roughness.

Finally, this study indicates that, when planted, the soil should improve water and soil conservation, although the reduction in runoff was notably lower than that of eroded sediments.

ACKNOWLEDGMENT

The authors would like to thank the LEGHYD laboratory (DGRSDT, Algeria) for its financial support.

REFERENCES

[1] Abrahams, A.D., Parsons, A.J., Wainwright, J., (1994). Resistance to overland flow on semiarid grassland and shrub land hillslopes, Walnut Gulch, southern Arizona. Journal of Hydrology 156, pages: 431–446.
[2] Adekalu, K. O., I. A. Olorunfemi, and J. A. Osunbitan. (2007). Grass mulching effect on infiltration, surface runoff, and soil loss of three agricultural soils in Nigeria. Bioresource Tech. 98(4): 912-917.
[3] Gilley, J.E., Kottwite, E.R., Simanton, J.R., (1990). Hydraulic characteristics of Rills. Transactions of the ASAE 33 (6), 1900–1906.
[4] Govers, G., (1992). Evaluation of transport capacity formulae for overland flow. In: Parsons,Abrahams. A.J., A.D. (Eds.), Overland flow: Hydraulics and Erosion Mechanics. UCL Press, London, UK. 243–273.

[5] Govers Gerard, Rafael Giménez ,Kristof Van Oost (2007). Rill erosion: Exploring the relationship between experiments, modelling and field observations. Earth-Science Reviews 84 87–102
[6] Gyssels G, Poesen J, Bochet E et al. (2005) Impact of plant roots on the resistance of soils to erosion by water: a review. Prog Phys Geogr 29:189–217
[7] Li, G., A. D. Abrahams, and J. F. Atkinson. 1996. Correction factors in the determination of mean velocity of overland flow. Earth Surf. Proc. Land. 21(6): 509-515.
[8] Ligdi. Etafa Emama, R.P.C. Morgan, (1995) Contour grass strips: a laboratory simulation of their role in soil erosion control. Soil Technology 8, pages 109-117
[9] Liu. G, F. X. Tian, D. N. Warrington, S. Q. Zheng, Q. Zhang, (2010) efficacy of grass for mitigating runoff and erosion from an artificial loessial earthen road. American Society of Agricultural and Biological Engineers Vol. 53(1): 119-125
[10] Morgan, R.P.C. (1986). Soil erosion and conservation. Longman Group Limited.
[11] Morgan. R.P.C and R.J.Rickson (1995). Slope stabilization and erosion control: a Bioengineering approach
[12] Morgan, R.P.C. (2007). Vegetative-based technologies for erosion control, The Use of Vegetation to Improve Slope Stability) 265–272.
[13] Moussouni, A., Mouzai L. and Bouhadef M. (2012). Laboratory experiments: Influence of rainfall characteristics on runoff and water erosion, Waset, 68. 1540-1543.
[14] Nearing, M.A.,Norton, L.D., Bulgako, D.A., Larionov, G.A., West, L.T., Dontsova, K.M., (1997). Hydraulics and erosion in eroding rills. Water Resources Research 33 (4), 865–876.
[15] Pan Chengzhong., Zhouping Shangguan. (2006). Runoff hydraulic characteristics and sediment generation in sloped grassplots under simulated rainfall conditions. Journal of Hydrology (331), 178– 185.
[16] Tollner, E.W. Barfield, BJ., and Hayes, JC., (1982). Sedimentology of erect vegetal filters. J. Hydr. Eng. Div-ASCE (108), 1518–1531.