Hydrological soil behavior in areas with semi-arid vegetation (Beni Chougrane Mountains, Algeria)

Yahia BOUKHARI[1], Marta GINOVART[2], Antoni M.C. VERDÚ[3], M. Teresa MAS[3], Khalladi MEDERBAL[4], Ramon JOSA[3,*]

[1] University of Mascara, Research Laboratory for Biological Systems and Geomatics (LRSBG), 29000 Mascara, Algeria.

[2] Department of Mathematics, c/ Esteve Terradas 8. Edifici ESAB, Universitat Politècnica de Catalunya. 08860-Castelldefels, Barcelona, Spain.

[3] Department of Agri-Food Engineering and Biotechnology, c/ Esteve Terradas 8. Edifici ESAB, Universitat Politècnica de Catalunya. 08860-Castelldefels, Barcelona, Spain.

[4] University of Tiaret, Research Laboratory for Biological Systems and Geomatics (LRSBG), 14000 Tiaret, Algeria.

Personal e-mail addresses: yyahia2000@yahoo.fr, marta.ginovart@upc.edu, maite.mas@upc.edu, amc.verdu@upc.edu, kmederbal@hotmail.com, ramon.josa@upc.edu

*Corresponding author

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Abstract

In northern Algeria, the physical degradation of land by water erosion is one of the most serious forms of degradation. As is well known, vegetation plays an important role against water erosion. In the mentioned area the potential vegetation called maquis is currently characterized by an advanced stated of degradation, often ranging between sparse cover and bare soil. In the Oued Fergoug watershed belonging to the Beni Chougrane Mountains (NW of Algeria), a trial was carried out with a mini rainfall simulator designed by ORSTOM to evaluate the runoff rate and the sediment load at experimental plot scale and in a situation of bare soil. The experimental layout took into account two different surface slopes, three different rainfall intensities, and three levels of initial soil water content. The highest runoff values observed exceeded 0.50 mm min^{-1} and the maximum sediment load yield was 94.2 g L^{-1} per square meter. Summarizing, the intensity of rain is the main factor for runoff generation, independently of the slope and the initial soil water content values. Since vegetation cover is a crucial component in maintaining stable slopes and limiting soil losses, the most effective practice to protect bare soil against erosion is to provide a protective ground plant cover in this area.

Key words: ORSTOM rainfall simulator; Algeria; slope; rainfall intensity; initial soil water content

Introduction

Land degradation is recognized as the main outcome of desertification (Puigdefabregas et al. 2009). In particular, the mentioned authors highlight the importance of hydrological ratios, energy ratios, biomass, productivity and spatial patterns between the ecosystem attributes associated with land condition. Ecosystem degradation notably entails the incapacity to preserve, use and recycle local resources such as water, energy and nutrients. Koulouri & Giourga (2007) consider land abandonment and slope gradient as key factors for soil erosion in the Mediterranean region. In northern Algeria, the physical degradation of land due to water erosion is one of the most serious forms of degradation (Souidi et al. 2014).

Soil erosion is a two-phase process consisting of the detachment of individual soil particles from the soil mass and their transport by erosive agents as surface runoff. Runoff refers to the portion of rainwater that is not lost due to interception, infiltration, evapotranspiration or surface storage, and flows over the land surface to a stream channel. Interrill erosion is induced by a moving sheet of water over the soil surface. The rate at which water passes into the soil is known as the infiltration rate and this exerts a major control over the generation of surface runoff (Rickson & Morgan 1995). In the case of bare soil, rainfall is distributed between infiltration and runoff, as direct evaporation is not taken into account.

Vegetation plays an important role against water erosion in two main ways: by preventing loss of substrate and by favoring sedimentation (Rey et al. 2004). Gray & Sotir (1996) point out the beneficial effects of herbaceous vegetation in preventing rainfall erosion. Martínez Raya et al. (2005) observed that plant cover with arbustive species reduced soil loss and runoff about 90% compared to bare soil. The risk of slope failures and erosion is heightened when the vegetation cover is removed (Rickson & Morgan 1995). Coppin & Richards (1990) distinguish between (i) bioengineering, the use of vegetation for slope stabilization and erosion control, and (ii) biotechnical engineering, techniques where vegetation is combined with inert structures, in which the engineering role of the vegetation is accentuated.

Among the various factors for controlling soil erosion related with the vegetation cover, the growth of the roots and their persistence play a significant role in semi-arid areas (Himmelbauer et al. 2013). Coppin & Richards (1990) underline the engineering role of vegetation and particularize water uptake by roots, reinforcement of soil by roots, and anchoring and buttressing by taproots.

Rainfall simulation, used for many years, is still one of the most used and most successful tools to study soil erosion by water (Martínez-Murillo et al. 2013).

One application of a rainfall simulator in Algeria concluded that soil tillage on marls in a semi-arid condition could be an excellent tool to diminish runoff and control soil erosion (Prinz et al. 1994).

Therefore, the main objective of this paper is to characterize the runoff and sediment load yield on bare soils of a region located in Beni Chougrane Mountains (one of the most erodible countries in the world) by means of small-scale rainfall simulation. This information would be useful to assess future restoration projects using vegetation for the area understudied.

Material and methods

The experiment was carried out in the Oued Fergoug watershed (122 km^2) in the Beni Chougrane Mountains (NW of Algeria). This area forms part of the great Oran-Chott Chergui watershed belonging to the Oran Tell, which in turn covers an area of 2860 km^2. The UTM coordinates of the mouth of Oued Fergoug are: 31S 232440 mE 39394850 mN.

Average monthly temperatures (series from 1993 to 2012) show two different seasons: a cold season (from November to April) with an absolute minimum of 3°C recorded in January, and a hot season (from May to October). The absolute maximum temperature in this period was 41°C (August). Average annual rainfall at three stations located around the study area- Mascara, Ain Farès and Bouhanifia- were 402, 428 and 281 mm respectively. The maximum and minimum mean monthly rainfalls recorded between 1980 and 2000 were 62.8 mm (December) and 2.4 mm (August). The rainfall distribution throughout the year is highly variable and it is concentrated during the cold season (Bouchetata & Bouchetata 2006). It should be noted that the rainiest season is between October and December and the wettest months are December and January. Rainfall intensity is also very variable and heavy rainfalls occur from late November to February, but secondary maximums are obtained in September or October and in April or May. Extreme values of rainfall intensity reach 900 mm h^{-1} (December or January) for periods of 5 to 10 minutes.

The Beni Chougrane Mountains are characterized by an extremely abrupt relief (peaks from 300 to 800 m) and large hills alternate with high plateaus and deep valleys. Slopes are very variable. Nearly 20% of the soil surface has a slope of more than 50%, and 26% of the soil surface has a slope of between 25% and 12.5%.

The soils of the experimental area are developed on marl and sandstone and colluviums. Climatic aridity and soil erosion prevent soil development and poorly developed soils are common. Very often the soils retain characteristics of the bedrock. Inceptisols and entisols are the main soil orders in the region. Analytical data of the topsoil in the experimental area show 60.2% clay, 22.1% fine silt, 7.5% coarse silt, 5.5% fine sand, 3.1% coarse sand, and 1.7% organic matter. Calcium carbonate is present in large proportions.

In accordance with the semi-arid Mediterranean bioclimate of the area, the maximum expression of the potential vegetation in the area is a particular maquis dominated by *Callitris articulata* (Vahl.) Link. (called *thuya de Barbarie* in French). This is a scrubland or shrubland of greater or lesser density depending on the conditions, with the presence of a diverse assortment of plant species sharing the common physical characteristic of dominance by shrubs (*Olea europaea* L., *Rosmarinus officinalis* L., *Calycotome spinosa* (L.) Lamk., *Artemisia herba-alba* Asso, etc.). Evergreen oak (*Quercus ilex* L.) and pine (*Pinus halepensis* Mill.) forests can appear in some specific sites forming sparse stands (Zahira et al. 2009; Haddouche et al. 2011; Tayeb & Kheloufi 2014).

In most of the area, due to several causes (erosion, fire and overgrazing), the vegetation is characterized by an advanced state of degradation. At best a sparse vegetation cover is observed and surfaces with bare soil in higher areas are common. In particular, we can see the rapid progress of land degradation by comparing the map provided by Benchetrit (1966) showing the situation of the vegetation of the Beni Chougrane area in 1953 (the author used a legend with 8 categories: forest, degraded forest, maquis, scrublike matorral or garrigue, vineyards, European crops, Algerian crops, and bare soil) with the information obtained by remote sensing (Zahira et al. 2009; Haddouche et al. 2011; Tayeb & Kheloufi 2014). Nowadays Beni Chougrane is included in the southern edge of the olive-growing area (Zdruli 2014), and is considered a good grazing area (FAO 2005).

A mini rainfall simulator designed by ORSTOM (Asseline 1981; Casenave 1982) was used in this experiment. A total of 18 rainfall simulations were carried out on regular square plots of 1 m^2. An adjustable lever system made it possible to vary the oscillation angle of the nozzle and the wet the surface of the soil. Consequently, the rainfall intensity in the plot ranged from 30 to 150 mm h^{-1}. The nozzle was supplied with water at constant pressure. It produced a flat stream of water in a fan shape.

An experimental area located on the same parent material, with similar soils and covers (bare soil), was selected on two different surface slopes. Nine plots were established in each area, distributed in a 3 by 3 matrix of plots, with the three different rainfall intensities, and three levels of initial soil water content (Table 1). Water runoff and sediment load were measured with a test tube at 1 minute intervals. Each rainfall simulation experiment was carried out until 10 consecutive sediment samples were collected. The length of the simulations ranged between 15 (moister plots) and 108 (dry plots) minutes.

The statistical analysis of data was first conducted using a set of exploratory techniques to investigate the relationship between time, runoffs and sediment loads of various groups of data according to the combinations of the three factors considered (Table 1). Row data and transformations of the data by logarithm function were investigated. Regression models were performed with the sediment load as the response variable to explain or predict, the runoff as a continuous predictor and the three factors as categorical predictors, jointly with their interactions. In order to establish comparisons between the runoffs when the stabilization took place, data were analyzed grouped into subsets according to the factors described above. General linear models (GLM) and variance tests (ANOVA) were used to evaluate the influence of the three factors (surface slope, initial soil water content and rain intensity) and their interaction on the final stabilized runoff. In order to complete this data analysis, and taking into account the variability of the data and the small sample sizes, a nonparametric alternative to a one-way ANOVA, the Kruskal-Wallis test, was also used to rank data values. The separation of means was evaluated using the Tukey-Kramer procedure and Games-Howell pairwise comparisons. Data were analyzed using Minitab software (2007). The probability level of significance was set at 0.05.

Results and discussion

Fig. 1 shows the results of the evolution of the runoff (mm min^{-1}) in the course of the experiment for the 18 simulations carried out. In the initial dry soil condition, water infiltrated across the soil surface and no runoff was observed independently of slope. Then the runoff rate stabilized (a maximum runoff rate was reached) over time. However, runoff acquired rising importance from the beginning of the simulation under more intense rainfall (RI-50 and RI-80). Runoff in moister soils (FC and SAT) started from the first moments of the simulation and increased until a stable rate was achieved. This maximum runoff rate was not assumed conclusively in the most favorable set of conditions to erosion (RI-50 or RI-80 and 25% slope), but we can consider the runoff values to be very near to stability.

Fig. 2 depicts the relationships between stable runoff rate (mm h^{-1}) and sediment load yield (g L^{-1}) per square meter. This figure shows that when the soil is dry (DS) the sediment load concentration does not increase when maximum runoff increases; our interpretation of this is that the soil mass susceptible to erosion tends to be exhausted during the experiment. This does not mean that the total (per square meter) quantity of sediment exported was the same over both slopes (12.5% and 25%). A similar behavior can be observed in the case of the rainfall simulations with RI-30 mm h^{-1}. In this case the largest quantity of exported soil (in terms of sediment load yield) would correspond to dry soil (DS). In other combinations of factors, the regression model suggests that the maximum concentration of sediment exported was not reached. When the intensity of rainfall is maximum, the behavior varies according to slope. An overall view of all the graphs suggests a complex relationship between these variables, possibly related to the energy balance (Chaplot & Le Bissonnais 2003). The maximum value of sediment load yield, which reached 94.2 g L^{-1} m^{-2}, was generated by interrill erosion. The stable (maximum) runoff values obtained with the rainfall simulator should be considered only as indicative of soil behavior in actual field conditions, among other reasons due to the large variety of simulators that can be used (Martínez-Murillo et al. 2013) and the wide variety of environmental factors that may be involved (Casenave 1982). Consequently, the interpretation should be considered in relative terms and in relation to the trends suggested by the results.

Table 2 shows the maximum runoff values of the 18 treatments arranged in descending order and significant differences have been stated for medians and means with the two statistical tests (Kruskal-Wallis and one-way ANOVA tests).

In each of the three data sets corresponding to each level of initial soil conditions, for the stabilized runoff variable, the two-way ANOVA tests performed with the factors slope and rain intensity revealed that their interaction was significant (the three p-values < 0.01). For the three initial soil conditions, according to the Tukey-Kramer procedure, the higher means of runoff corresponding to the combinations 25%_RI-80 and 12.5%_RI-80 were significantly different, but no significant differences were detected between the pairs 12.5%_RI-50 and 25%_RI-50, or between 12.5%_RI-30 and 25%_RI-30. In turn, for each data set corresponding to the different levels of rain intensity, the two-way ANOVA tests carried out with the factors slope and initial soil water content for the runoff variable showed that the interaction of these two factors was not significant (p-values of 0.599, 0.755 and 0.825 for RI-30, RI-50 and RI-80 respectively). Thus, the two main factors, the slope and the initial soil water content- showed an additive effect on runoff. Both factors were significant in each of the three rain intensities (all p-values<0.01). According to the Tukey-Kramer procedure, in the case of the lowest rain intensity no significant difference was detected for the means corresponding to FC and DS, while for the other two rain intensities no significant differences were detected between the means of FC and SAT.

The results conclusively showed that the rainfall intensity is the main factor for runoff generation independently of slope value and initial soil water content. Both slope value and initial soil water content are factors that are uncontrollable by man, but their geographical distributions are usually known on different scales. The maximum concentration of sediment load yield tends to decrease with time over shallowly sloping surfaces and when rainfall intensity is low. In other cases the sediment load yield can increase with time. This suggests that it is necessary to protect the soil surface under any conditions of slope and initial moisture level in areas with more intense rainfall (> 80 mm h^{-1}). The most effective practice for protecting the soil against erosion is to implement an adequate vegetal cover, because vegetation is a critical component in maintaining stable slopes and thus limiting erosion.

The importance of the soil surface protective (vegetation) cover is well known. Subsequently, more field research and acquired knowledge would be necessary to design a detailed project for the bare soil areas in the Beni Chougrane Mountains favoring long-term restoration of spontaneous vegetation. The different factors involved in this land degradation and the present success of some bioengineering techniques to obtain ground cover vegetation should be taken into account in this context. Moreover, rainfall simulations would be an adequate technique to evaluate the abovementioned restoration work.

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FIGURES AND TABLES

Figure 1. Runoff values obtained from the 18 rainfall simulations (mm min^{-1}). Slopes (%): 12.5 and 25; Initial soil water content: DS = dry soil, FC = near field capacity, Sat = near soil saturation. Rainfall intensity: RI-30, 30 mm h^{-1}; RI-50, 50 mm h^{-1}, and RI-80, 80 mm h^{-1}.

Figure 2. Chart showing the relationship between sediment load (g L^{-1}) and maximum runoff rate (mm h^{-1}). Slopes (%): 12.5 and 25; Initial soil water content: DS = dry soil, FC = near field capacity, Sat = near soil saturation. Rainfall intensity: RI-30, 30 mm h^{-1}; RI-50, 50 mm h^{-1}; and RI-80, 80 mm h^{-1}.

Figure 1

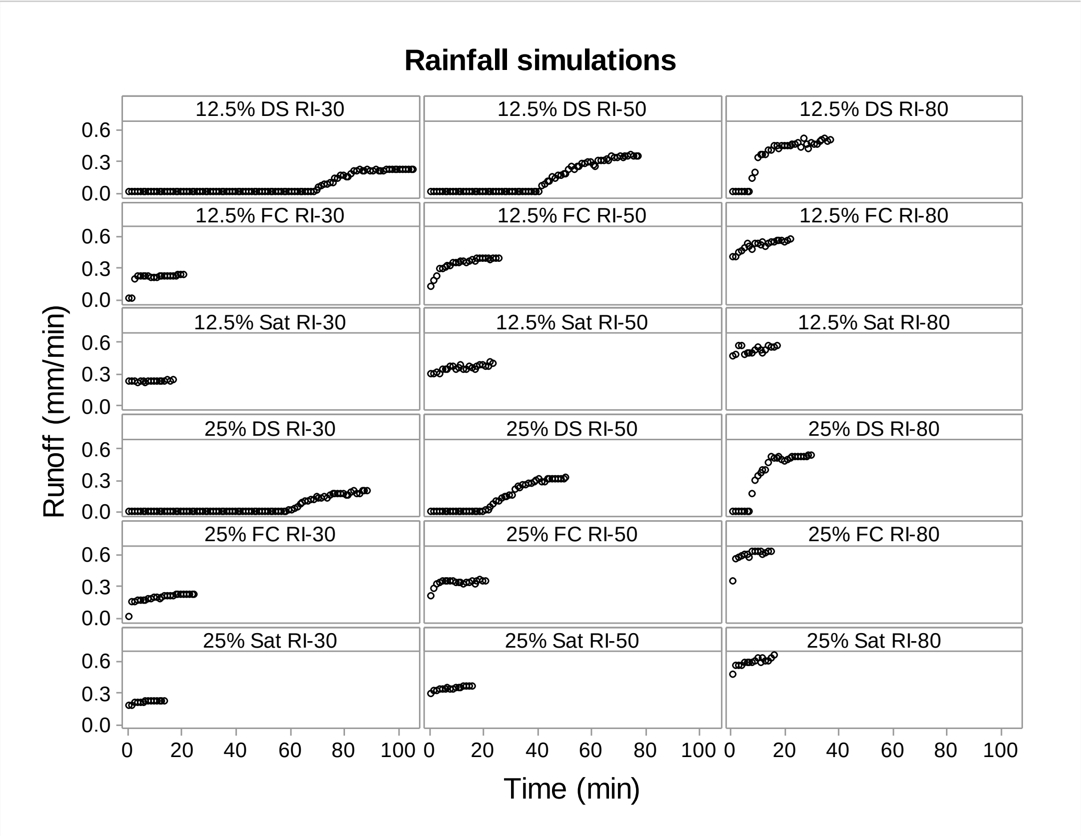
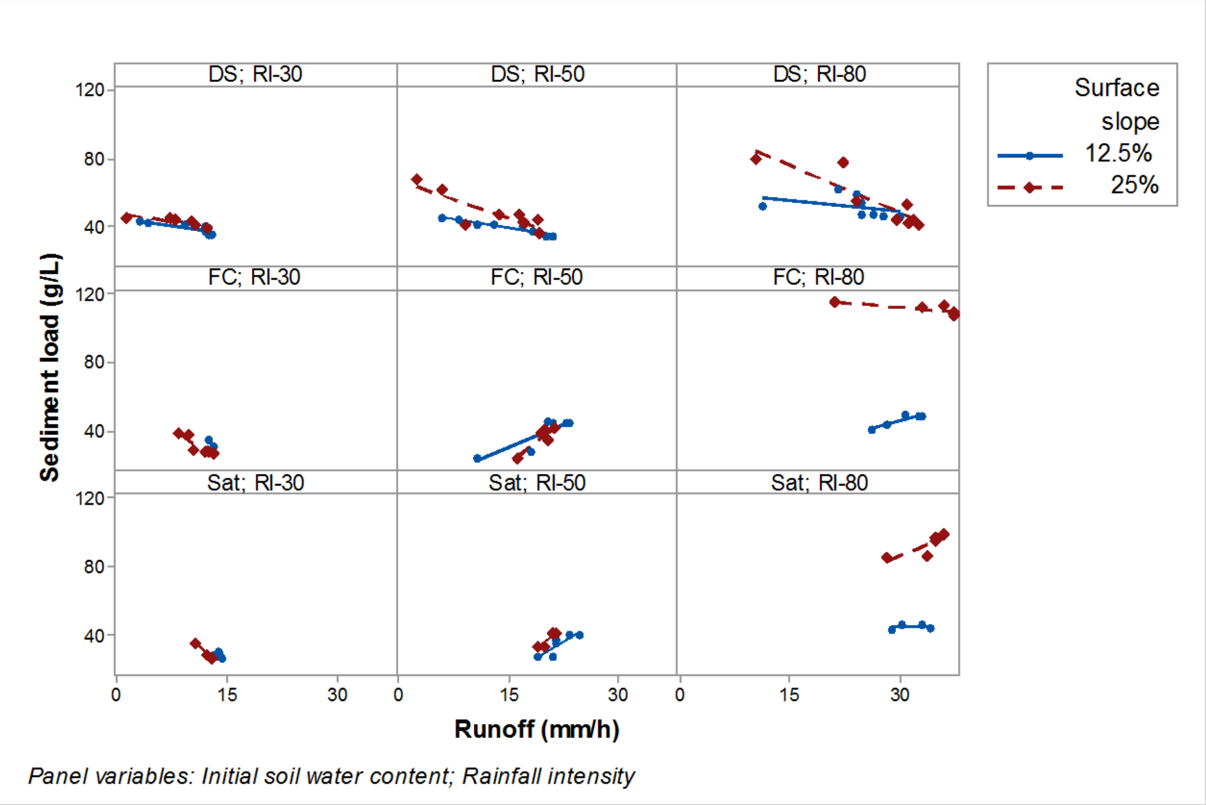


Figure 2



Panel variables: Initial soil water content; Rainfall intensity

Table 1. Rainfall simulation experimental conditions.

Rainfall intensity	Slope		Initial soil water content	
mm h^{-1}	%	º	w w^{-1}	Last rain
RI-30	12.5	≈7	0.03 (DS)	25 days ago
RI-50	25	≈14	0.29 (FC)	24 h ago, 10 mm h^{-1}
RI-80			0.33 (SAT)	15 min ago, 10 mm h^{-1}

Table 2. Sample sizes, medians, average ranks and standardized values of these ranks given by the nonparametric Kruskal-Wallis test, for each combination of the three factors, slope (12.5%, 25%), initial soil water content (DS-dry soil, FC-near field capacity, SAT-near soil saturation) and rain intensity (RI-80 mm h^{-1}, RI-50 mm h^{-1}, and RI-30 mm h^{-1}). Means and grouping information using the Games-Howell method and 95% confidence (means that do not share a letter are significantly different).

		Kruskal-Wallis test			Games-Howell pairwise comparisons													
Treatment	N	Median	Ave Rank	Z	Mean	SE Mean												
25% FC RI-80	5	37.2	74.7	3.6	36.12	0.81	a											
25% Sat RI-80	4	34.8	72.4	3.0	34.80	0.49	a											
12.5% Sat RI-80	5	30.3	62.8	2.4	31.30	0.97	a	b										
25% DS RI-80	5	31.2	62.3	2.3	31.14	0.51		b										
12.5% FC RI-80	3	32.4	64.8	2.0	32.00	0.72	a	b										
12.5% DS RI-80	5	26.4	54.2	1.5	26.64	1.01		b	c									
12.5% Sat RI-50	5	21.6	46.4	0.7	22.44	0.67			c	d								
12.5% FC RI-50	5	22.8	44.5	0.5	22.08	0.58			c	d								
25% Sat RI-50	4	20.4	37.6	-0.2	20.33	0.61				d								
25% FC RI-50	4	20.1	37.0	-0.2	20.25	0.40				d								
12.5% DS RI-50	4	19.2	33.1	-0.6	19.05	0.94				d	e	f	g	h	i	j		
25% DS RI-50	4	18.0	29.1	-0.9	17.93	0.66				d	e							
12.5% Sat RI-30	5	13.9	22.7	-1.7	13.87	0.20					e		g		i		k	
25% Sat RI-30	3	12.9	13.7	-2.0	12.72	0.18							g	h	i	j	k	l
12.5% FC RI-30	5	12.6	14.1	-2.6	12.77	0.16									i	j	k	l
25% FC RI-30	4	12.3	9.5	-2.7	12.08	0.58											k	l
25% DS RI-30	3	10.8	3.7	-2.8	11.10	0.62											k	l
12.5% DS RI-30	5	12.6	10.2	-3.0	12.44	0.17						f		h		j		l