Journal of Arid Environments 152 (2018) 69–74

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

An experimental study to assess the effect of the energy and the electrolyte concentration of rain drops on the infiltration properties of naturally crusted soils

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ARTICLE INFO

Keywords:
Rainfall simulator
Soil crust
Infiltration
Drop energy
Electrolyte concentration
Runoff

ABSTRACT

The main objective of the study was to assess the relative importance of the electrolyte concentration of rain drops and their kinetic energy on the infiltration rate of naturally crusted loess soil. A highly accurate portable rainfall simulator was used in this study. The effect of electrolyte concentration on infiltration rates was studied by comparing the runoff patterns observed using distilled or tap water. Similar infiltration curves were obtained for both treatments indicating that the effect of the electrolyte concentration of the applied water on infiltration was negligible.

The effect of raindrop energy on infiltration rate was assessed by comparing the runoff characteristics of three treatments: fog, plot covered with dense mesh and no-surface protection. No runoff was observed in the fog treatment and the infiltration rates in the protected treatment were significantly higher than those of the unprotected treatment.

The results of this study suggest that the momentum of drops hitting a naturally crusted loess soil significantly affect the infiltration process while the electrolyte concentration of the rain water does not meaningfully contribute to further crust development. Runoff coefficients derived from studies carried out with rainfall simulators that do not mimic the natural distribution of drop size and energy should be viewed with care.

1. Introduction

Rainfall generated floods are not very frequent occurrences in arid regions, but are of great consequence as they have a major impact on the environment (Sponseller et al., 2013) and can also be used for the irrigation of agricultural fields using appropriate water harvesting systems (Ben Asher and Berliner, 1994, Carmi and Berliner, 2008). Linking rainfall characteristics to runoff generation for catchments of varying sizes has been an elusive goal of dryland hydrologists for decades (Beven et al., 1988; Kirkby et al., 2005; Mirus and Loague, 2013). The generation of floods is affected, amongst others by the size of the watershed, the fraction of the watershed that was affected by the storm, topography, cover, etc. (Mirus and Loague, 2013). The main driver for large-scale process is however the local generation of runoff at micro-scale that commences when the rainfall intensity is higher than the absorption capacity of the soil; the latter being frequently the result of the presence of a raindrop-induced structural crust. Structural crust is a term used for a type of crust that results from the breakdown of aggregates due to the impact of drops and the colloidal dispersion that may follow in its wake (Carmi and Berliner, 2008).

Crust development and its effect on the infiltration process have been described in detail during the last decades (McIntyre, 1958; Römkens et al., 1990; Shainberg, 2000; King and Bjorneberg, 2012). Crusts are usually the result of the combined effect of raindrop momentum and the subsequent chemical dispersion of clays (Valentin and Bresson, 1992, Singer and Shainberg, 2004), the latter affected by the salt concentration of the soil solution, which is strongly influenced by the chemical composition of the applied water (Agassi et al., 1981, 1985, 1994; Morin et al., 1989).

The interaction of the raindrop momentum, the electrolyte concentration of the soil solution and the different physico-chemical characteristics of the soil matrix (clay content and type, presence of soluble and non-soluble salts, etc.) is complicated and most of the studies mentioned previously were carried out using laboratory rainfall simulators in which the effect of the various parameters could be separated and studied with more ease (Agassi et al., 1981; Morin et al., 1989; Singer and Shainberg, 2004; Mamedov et al., 2000; Neave and Rayburg, 2007). One of the salient results of these studies was that the

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https://doi.org/10.1016/j.jaridenv.2018.01.009
Received 4 December 2016; Received in revised form 14 December 2017; Accepted 15 January 2018

electrolyte concentration of the water drops dramatically affects the crusting process and in order to simulate natural events distilled water should be used (Agassi et al., 1981, 1985; Singer et al., 1982).

We hypothesize that for crusted soils the ionic composition of the rainfall will have no effect on the infiltration rate of water into the soil because no further clay dispersion can take place as there are no aggregates present on the soil surface. On the other hand, the momentum of the rain drops will affect the rate of infiltration on naturally crusted soils as the impact of drops on the surface can lead to the breakdown and rebuilding of the crust (Morin and Van Winkel, 1996; Mamedov et al., 2000; Fan et al., 2008).

The type of experiments described above are usually carried out in shallow trays after soil air-drying and re-packing (Bradford et al., 1987, Diekkrüger and Bork, 1994, Fox and Bissonnais, 1998, Mills and Fey, 2004; Ben-Hur et al., 1990, Morin et al., 1967, Morin and Van Winkel, 1996) and while they shed light on basic aspects of the interactions mentioned above, their direct applicability to field situations is doubtful (King and Bjorneberg, 2012). Compared to the wealth of information available for crust development processes in repacked cultivated soils under laboratory conditions, little is known about the behavior of natural non-cultivated bare soils, even though they are the main generators of runoff in natural ecosystems in arid and semi-arid regions and determine the feasibility of implementing water harvesting schemes.

The fact that it is extremely difficult (or practically impossible) to obtain undisturbed large samples for lab studies and the inherent difficulties associated with field studies during natural rain events, insights into the main mechanisms involved in generating runoff may be gained by using portable rainfall simulators in the field, provided they properly mimic the size and momentum of natural raindrops. One of their great advantages is that they can be deployed within the area of interest, the soil surface can be manipulated and quantities of interest monitored in real time. However the variety of rainfall simulators used in the field is large (Cerdà et al., 1997; Abudi et al., 2012; Iserloh et al., 2013) and researchers must often develop devices suiting their particular needs, due to a lack of a standard design (Lora et al., 2016). An analysis of available information about these simulators reveals that the characteristics of rainfall simulators used in the field are extremely varied (Abudi et al., 2012, Iserloh et al., 2013), particularly in terms of raindrop size and momentum, a fact that makes comparisons and drawing of conclusions extremely difficult.

In addition to the demand of properly mimicking the size and momentum of raindrops, a potential limitation to rainfall simulators use could be the need to use distilled water for the simulation runs, as the results obtained in laboratory tests with bare soils and mentioned above appear to imply. This would entail a very complicated logistic set-up and cast doubts on the validity of previous trials in which non-distilled water was used with the simulators. A high accuracy portable rainfall simulator providing ~76% of the energy flux of expected natural rainfall (Assouline and Mualem, 1997; Van Dijk et al., 2002; Fornis et al., 2005) was recently developed (Abudi et al., 2012) and allows studying the interactions discussed above in the field.

The objective of this study was to characterize the effects raindrop energy, as parameterized by the momentum of raindrops, and their total salt content (as parameterized by the electrical conductivity) have on the water infiltration rates of a naturally crusted loess soil during simulated rain events in the field and thus test in the field the hypothesis mentioned above.

2. Materials and methods

2.1. The soil

This study was carried out at the Wadi-Mashash experimental farm located in the Negev highlands of Israel (lat: 31.069250 long: 34.852753). The soil is sandy loess, typical of the area. The aquifer in this area is at a depth of close to 400 m. and there is consequently no contribution of upward water movement to salt concentration at the soil surface. The total annual precipitation, approximately 90 mm, is made up of series of relatively modest rainfall events (usually less than 30 mm) resulting in a very shallow water penetration.

Table 1
Some physical and chemical properties of the composite soil samples.

Soil	Mechanical composition			ESP	CEC	EC soil upper layer (dS/m)
	Sand	Silt	Clay			
		%				
Sandy loam	55	21	24	5	10.4	4.4

(standard deviation of ESP = 1.2, standard deviation of CEC = 1.3, standard deviation of EC = 5.2).

Average values of some top soil properties obtained from four composite soil samples taken from the study area are presented in Table 1. The area of approximately 10^3 m^2 with apparently uniform surface texture was selected by visual inspection. The area has not been cultivated for at least fifty years and the uppermost layer was covered by a fully developed and continuous structural crust, i.e. without visible signs of biological activity on the crust's surface. The order of magnitude of the crust's thickness was estimated from photographs obtained with scanning electron microscopes obtained in nearby plots and was 800 μm.

2.2. The rainfall simulator

A full description of the high accuracy portable rainfall simulator (RS) used in this study is presented in Abudi et al. (2012). The main features of the rainfall simulator are an upward pointing rotating nozzle set atop at 2 m high tripod (Fig. 1). The upward spray increases the wetted surface and accordingly, reduces the overall intensity. The rainfall intensity can be adjusted by periodically interrupting the high rate of flow from the nozzle with an electronically controlled pneumatic valve. The rotating of the nozzle results in very high uniformity of water depth distribution over a relatively large area, located in an annulus with radius of 1.3m–2.35 m from the nozzle. The horizontal spatial water distribution for a range of rain intensities tested was homogenous (Christiensen coefficient of 98) and similar for each of the two 1 × 2 m plots located equidistantly from the nozzle within the above mentioned area.

The rainfall simulator generates drops of $D_{50} = 1.5$ mm that reach 79–83% of their terminal velocity without the need for a high tower. The energy flux of the simulated rain is 9.89 $J\,m^{-2}\,mm^{-1}$ or ~76% of the energy flux of expected natural rainfall (Assouline and Mualem, 1997; Van Dijk et al., 2002; Fornis et al., 2005). A 4.5 m high windshield made of light metal collapsible frame over which a dense nylon fabric sheet was stretched surrounded the wetted area.

2.3. The plots

The 1 × 2m experimental plots were delimited by a 5 cm high rectangular frame made of thin aluminium sheets. The sheets were inserted into the soil to a depth of 2–3 cm by hammering delicately and with great care in order to minimize soil surface disturbance in the immediate vicinity of the sheets (Fig. 2). The soil-sheet interface was sealed with silicone rubber. The frame effectively insulates the surface of the plot from its surroundings. The two plots located side by side were exposed simultaneously to the simulated rainfall. Runoff was collected from the plot area at the lower end and conveyed through a pipe to a measuring station where the runoff water was collected in sample bottles and the latter weighed at one minute intervals with an electronic scale (precision 0.01 g).