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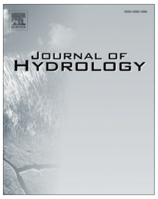

Technical Note

Laboratory investigation on the role of slope on infiltration over grassy soils

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ABSTRACT

Even though natural surfaces are rarely horizontal, infiltration modeling has been primarily confined to horizontal surfaces, and there are not enough studies to clarify the effects of slope on the partition of rainfall into surface and subsurface water. Besides, previous experimental results on the effects of slope provide conflicting conclusions perhaps because of the existence of erosion and crust formation. In this study, new laboratory experiments, performed in the absence of the last two processes, highlight the effect of the slope angle, γ, on infiltration into a grassy soil. The results are compared with those from previous experiments performed on a bare soil and interpreted in terms of an effective soil saturated hydraulic conductivity, K_e (γ). The grassy soil dampens the variation of K_e with γ compared to bare soil. For example, for $\gamma = 10°$, the reduction of the gravitational infiltration with respect to the saturation condition was ~80% for the bare soil, while we find it to be ~20% for the grassy soil. Finally, we point out that the presence of grass does not affect the results through the development of a two layered soil, but through a substantial variation of roughness.

1. Introduction

Rainfall infiltration influences surface runoff production from the local (point) to field scale, playing a significant role in the hydrological responses of hillslopes and watersheds as well as in the generation of water flow and transport of pollutants in subsurface layers. It is widely recognized that the process is mainly governed by rainfall rate, r, soil hydraulic properties and antecedent soil moisture content, θ_i, while the role of soil slope has not been fully understood.

At the local scale many infiltration models have been proposed for regular storms and immediate ponding. The approach formulated by Green and Ampt (1911) extended for applications involving pre-ponding and post-ponding conditions (Mein and Larson, 1973; Chu, 1978), the extended Philip equation (Philip, 1969; Chow et al., 1988) and the Smith and Parlange (1978) approach then reformulated by Parlange et al. (1982) are examples of widely-used models. A simplified technique based on the time compression approximation was also proposed to extend the application of these approaches to complex rainfall patterns (Mls, 1980; Péschke and Kutílek, 1982; Verma, 1982). More comprehensive formulations were presented by Dagan and Bresler (1983) and later by Corradini et al. (1997) who realized a model describing successive infiltration-redistribution cycles determined by any erratic rainfall.

Some models representing infiltration at the field scale have been more recently proposed for saturated hydraulic conductivity, K_s, assumed as a random variable at the soil surface and homogeneous (Smith and Goodrich, 2000; Govindaraju et al., 2001) or not homogeneous (Corradini et al., 2011; Govindaraju et al., 2012) in the vertical direction. Further, models were developed to describe the effects of a joint horizontal variability of K_s and r (Wood et al., 1986; Castelli, 1996; Govindaraju et al., 2006; Morbidelli et al., 2006), and of the spatial variability of θ_i (Smith and Goodrich, 2000). The role of the heterogeneity of θ_i combined with uniform values of K_s and r or with K_s randomly variable has been widely analyzed for different spatial scales (Bronstert and Bardossy, 1999; Morbidelli et al., 2012; Hu et al., 2015).

In most real situations, infiltration occurs over sloping surfaces, while all the aforementioned models were developed for horizontal surfaces. Therefore, they need to be properly adapted for applications where surface slope has a significant influence on the partitioning of rainfall into surface and subsurface flow. This is still

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an open issue because of the limited and inconclusive results obtained from both theoretical and experimental investigations.

Poesen (1984), through laboratory experiments, observed that infiltration increased in steeper slopes for heavy rainfall rates and attributed this result to the processes of surface crust formation, more pronounced in flatter slopes, or rill erosion, that occurs more quickly on steeper slopes. This interpretation was also supported by the fact that for light rainfall events, infiltration was found to be unaffected by variations in the slope angle, γ. Chen and Young (2006) adapted the Green–Ampt approach for applications to sloping surfaces under the condition of identical slope horizontal projection lengths used to have equivalent rainfall input to different slope cases. They obtained an increase of infiltration with γ that could be neglected for $\gamma < 10°$.

However, from previous field studies, Nassif and Wilson (1975) and Sharma et al. (1983) deduced a decrease of infiltration with increasing slope angle. A similar trend was obtained on the basis of laboratory experiments by Fox et al. (1997), who examined the infiltration process in an interrill area with a vertical soil profile characterized by a thin sealing layer at the soil surface. Their results also indicated that the crust permeability was independent of the slope. Furthermore, a negative relationship between infiltration rate and γ was proposed by Philip (1991) through a mathematical approach. It involves a reduction of the gravitational effect on the infiltration rate by a factor of $\cos\gamma$, which implies a decrease of 13% from $\gamma = 0°$ to $\gamma = 30°$.

Essig et al. (2009) and Morbidelli et al. (2015) reported results from controlled laboratory experiments under conditions of dominant gravitational effects using bare soils. In the absence of sealing and erosion of top soil, they showed that infiltration decreased with increasing γ and overland flow was generated even for $r < K_s$. The observed trends agreed with those showed by Sharma et al. (1983) and Philip (1991), but the magnitudes of the reduction in infiltration with slope were much larger than expected from the earlier studies. Furthermore, Essig et al. (2009) and Morbidelli et al. (2015) examined the possibility of representing the infiltration process through an effective saturated hydraulic conductivity depending on soil roughness and to be used in the models set up for $\gamma = 0°$.

The main objective of this paper is to address this last issue by providing experimental evidence on the role of roughness in the determination of the relation between infiltration and slope angle. In this context new laboratory experiments involving infiltration into a grassy soil have been performed, and a comparison of the results with those obtained earlier on bare soils using a similar experimental apparatus is provided.

2. Laboratory experimental system

The basic element used for the experiments is a physical model (Fig. 1) consisting of a soil tank 152 cm long, 122 cm wide and 78 cm deep with impermeable sides and slope angle that can vary in the range 1–15° (1.8–26.8%).

A natural soil with vertically uniform grain size distribution corresponding to loam soil according to the USDA classification was selected. It was carefully packed to a thickness of 67 cm and was placed on a gravel layer 7 cm deep to speed the drainage process. Furthermore, a natural grassy soil (see Fig. 1b) was realized with the aid of a lamp producing artificial radiation characterized by a wavelength spectrum similar to that of solar radiation.

Artificial rainfall of almost uniform intensity was produced by pressurized water sprinklers. The characteristics of the rainfall fields were checked before the beginning of each experiment by a grid of pans placed on a metal sheet. Rainfall rates fairly different from the soil saturated hydraulic conductivity and well representative of many real situations were produced, considering also the importance to obtain infiltration results for r significantly larger than K_s as well as for r comparable to K_s.

The moisture content, θ, was monitored by a Time Domain Reflectometer (TDR) sensor used with a vertically oriented probe that provided continuous average measurements associated with the uppermost part of the soil (0–20 cm deep).

Continuous measurements of surface runoff and deep flow were carried out by tipping bucket sensors through triangular metal collectors, both placed at the outlet of the physical model. This solution to measure surface runoff was adopted considering that a comparison of the results earlier obtained by Essig et al. (2009) and Morbidelli et al. (2015) for bare soils indicated that the downstream boundary of the physical model did not influence significantly the partitioning of rainfall into surface and subsurface flow. More specifically, the trend of the infiltration observed in bare soils as a function of γ when the surface flow collector was placed at the lower tank side (Essig et al., 2009) or 50 cm upstream (Morbidelli et al., 2015) was identical.

3. Experiments and analysis of results

Many experiments were carried out for different γ and r values that varied in the range 1–15° and 7–30 mm h^{-1}, respectively. The whole soil surface was subject to uniform rainfall of 8 h-duration, while surface and deep flow were continuously measured up to 14 h. Twenty-eight experiments were performed, each starting from a soil moisture vertical profile close to saturation. This condition was reached by application of a long duration rainfall before the beginning of each experiment. The grassy soil allowed us to set-up experiments with tank angles greater than 10°, which was the maximum angle for the experiments with bare soils carried out by Morbidelli et al. (2015) without causing surficial landslides. In each experiment, the long duration of steady rainfall generated surface (if any), and deep steady flows. The discharges observed at this stage represent the primary quantities for the analysis of the slope effects on infiltration and surface flow production.

Table 1 summarizes the steady flows obtained for different values of γ and r. We note that different equipment was used in the artificial rainfall generation. Most experiments were performed using the same sprinkler, while those with water pressure denoted by $1.0^{\wedge}$ bar and 1.0^{*} bar were realized using one larger sprinkler and two sprinklers, respectively. As it can be seen, the rainfall rates associated with a given value of water pressure and the same sprinklers characteristics are not the same in the four experiments performed for $\gamma = 1°, 5°, 10°$ and $15°$, however the variability in r is less than 10%. These differences were due to the fact that no more than one experiment per day could be carried out and the pressurized water sprinkler system was turned off and switched on for the successive experiment. This procedure, coupled with the limited resolution in the selection of water pressure, did not allow us to exactly obtain a fixed value of r. We chose the lowest value of γ equal to 1° because it was the minimum value that enabled us to carry out accurate measurements of flow. The deep flow observed for $\gamma = 1°$ should be representative of the infiltration process into a horizontal soil surface.

An analysis of the data of Table 1 for $\gamma = 1°$ allows us to identify the deep flow observed under the rainfall rate of 29.9 mm h^{-1} as the soil saturated hydraulic conductivity (i.e. $K_s = 28.7$ mm h^{-1}) because the production of surface runoff indicates surface saturation. The achievement of steady conditions, with equality in the sum of surface and deep flow rates with the rainfall rate, indicates that the soil moisture vertical profile is uniform and time invariant with water content equal to the saturation value, θ_s. These deductions are confirmed by the results shown in Fig. 2 for the same