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A laboratory experimental system for infiltration studies

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ABSTRACT

The investigation of a few hydrological processes under natural conditions can be distorted by their interactions. In this context, a laboratory system that allows a few mechanisms of the infiltration process to be studied univocally is presented. The core component of the system is a physical model consisting of a soil tank with slope angle, γ, adjustable from 1 ° to 15 °. A generator of artificial rainfall can produce rainfall rates up to 50 mm h^{-1}. Surface runoff and deep flow, Q_d, are continuously monitored. An overall analysis of three previous investigations performed by the physical system and directed to clarify the infiltration process is also briefly reported. These investigations, that concerned the validation of a local conceptual model for erratic rainfalls, the role of run-on and the effects of sloping soil surfaces, were all carried out by using different configurations of the system. Great slope effects in bare soils were observed. For example, under steady conditions, a ratio $Q_d(\gamma = 1^\circ)$ / $Q_d(\gamma = 10^\circ)$ equal to about 4 was observed in a loam soil. Finally, on the basis of the acquired knowledge, further investigations to be realized with the same basic elements are proposed to derive a conceptual model that describes the soil surface gradient effects.

Key words | hillslope hydrology, infiltration modeling, infiltration process, physical models

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INTRODUCTION

A deep knowledge of each physical process involved in the development of a natural event is of primary importance in the formulation of event simulations for hydrological applications. Simulation models set up on the basis of experimental investigations performed under natural conditions are generally influenced by the interaction of different processes that can lead to distorted representations for each of them.

The adoption of parameterized formulations partially covers the unsuitable representation of the processes in the cases for which an accurate model calibration procedure can be applied. On the other hand, the transposition of this approach for applications in different areas represents a considerable problem, particularly in the cases of ungauged hydrological systems.

Laboratory experiments can contribute to the solution of the aforementioned issues through the validation of theoretical approaches previously developed and/or their reformulation by mathematical models closer to the physical reality. Recently, many laboratory physical models have been set up with the aim to investigate both surface and subsurface flow processes (e.g., Suski *et al.* 2004; Jakovovic *et al.* 2011; Jomaa *et al.* 2013; Lv *et al.* 2013; Oz *et al.* 2015; Shoushtari *et al.* 2016).

Jomaa *et al.* (2013) investigated the effects of antecedent conditions and specific rock fragment coverage on soil erosion dynamics for multiple rainfall events and fixed slope angle. The results of the experiments performed by a laboratory system were also used to validate a soil erosion model previously developed by Hairsine & Rose (1991). The performance of the model was found to be acceptable for simulating erosion in soils not undergoing compaction.

Chen *et al.* (2015) examined the rill erosion process at the hillslope scale. They realized laboratory experiments with different gradients and flow rates, comparing also the

doi: 10.2166/nh.2016.066

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behavior of erosion in two soils widely distributed in many geographic areas.

Lv *et al.* (2013) studied the conditions of occurrence of lateral downslope unsaturated flow and the effects of slope angle on soil moisture movement. They conducted laboratory experiments in a homogeneous and isotropic soil by a tank with changing slope angle.

Shoushtari *et al.* (2016) studied the effects of a simple harmonic forcing representing oceanic oscillations on groundwater waves dispersion in a sandy unconfined aquifer. According to the laboratory experiments performed in two rectangular sand flumes, they obtained results in contrast with the theoretical dispersion relations and the discrepancy remained unexplained.

Oz *et al.* (2015) investigated the density-driven dispersive circulation flow patterns along the freshwater–saltwater interface in a homogeneous and phreatic coastal aquifer. They realized a laboratory physical model by a two-dimensional rectangular flow tank and combined laboratory tracer experiments and numerical simulations.

Jakovovic *et al.* (2011) considered the process of vertical upward movement of saltwater induced by pumping freshwater in coastal aquifers. They analyzed observations earlier carried out in four laboratory sand-tank experiments through numerical modeling, obtaining a partial agreement that suggested the model extension by incorporating an additional effect.

Suski *et al.* (2004) demonstrated the possibility of using electrical potential measurements at the ground for estimating flow parameters linked with groundwater flow. To this aim, they performed a sandbox experiment involving measurements of electrical potential during a pumping test.

All the above-mentioned laboratory experiments provided new insights into the role of specific processes involved in studies of both surface and subsurface flow and indicated the main lines to be followed for the improvement of their mathematical representation.

The main objective of this paper is to present a flexible laboratory system (Essig *et al.* 2009; Morbidelli *et al.* 2015) set up to strengthen the representation of the infiltration process by simulation models. A second objective is to provide an overall analysis of the main studies on infiltration earlier performed through the system. These studies concern the validation of a model for infiltration into horizontal soil surfaces under erratic rainfalls (Corradini *et al.* 1997), the representation of run-on and the estimate of the effect of soil surface gradient. The last two factors, little considered in the partitioning of rainfall into surface and subsurface flow, could have great importance in many natural situations (Chen *et al.* 2013; Morbidelli *et al.* 2015). Finally, from the aforementioned analysis carried out to highlight the wide application field of the system, indications for further laboratory experiments are deduced.

EXPERIMENTAL SYSTEM

The basic element of the laboratory system consists of a physical model (see Figure 1) realized by a soil tank 152 cm long, 122 cm wide, and 78 cm deep, which can be adjusted with a slope gradient, γ, ranging from 1° to a maximum of 15°. The lateral and lower boundaries of the tank are not permeable. Transparent walls are used to observe the wetting front evolution during infiltration experiments. A gravel layer with a depth of 7 cm is set at the bottom of the soil tank in order to speed up the outflow of percolated water.

Rainfall is artificially produced by a generator (see Figure 2) consisting of sprinklers of water under pressure supplied by a pump. A proper choice of the sprinkler combined with an adjustment of the water pressure enables us to obtain a specific rainfall rate of interest, with values up to about 50 mm h^{-1}. Before the beginning of each experiment the average value of rainfall rate is determined through a sheet-metal pan placed on the tank. It catches the rainfall over the soil surface that generates a water flow measured at the outlet. Moreover, the spatial distribution of rainfall rate is also checked in advance by a grid of pans placed over the sheet-metal. For each sprinkler, the rain rate spatial distribution is almost uniform.

Surface runoff and percolated water are measured by two tipping bucket sensors that provide continuous data of the flow collected by two triangular metal elements. Deep flow is collected at the downstream boundary of the core, while surface flow is collected at the outlet of the soil surface exposed to rainfall during the experiments (see Figure 1). As an example, Figure 1 shows the measurement system for deep flow placed at the outlet of the soil block, while that for surface water is located upstream.

The water content profile is monitored using the time-domain reflectometry (TDR) method (TRASE-BE, Soil

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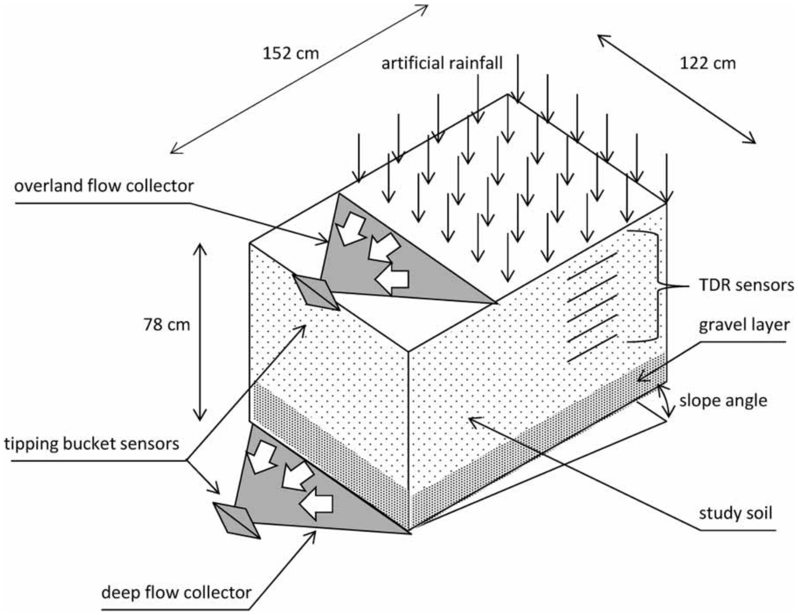

Figure 1 | Laboratory physical model with adjustable slope angle. The sensors for surface and deep flow as well as the probes for soil moisture content measurements by TDR method are also indicated.

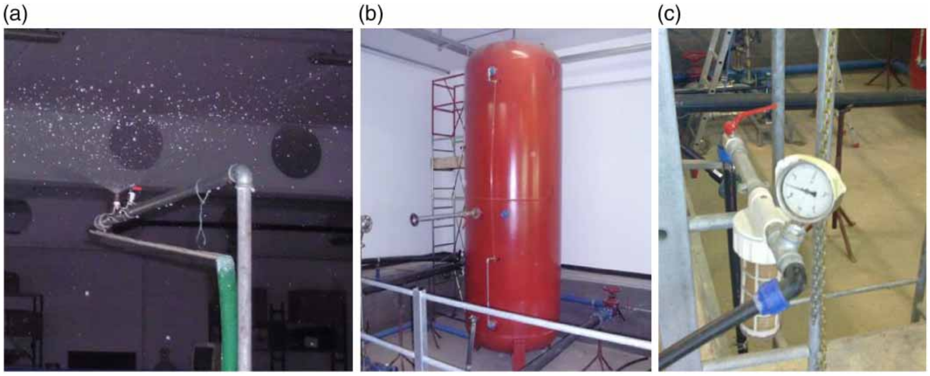

Figure 2 | Generator of artificial rainfall: (a) water sprinklers; (b) and (c) water pressurization system.

Moisture Equipment Corp., Goleta, CA, USA). Up to five buriable three-rod waveguides with wire-to-wire spacing of 1.25 cm and length 8 cm can be inserted horizontally at different depths (see Figure 1), taking care that the metal rods are in close contact with soil. Each probe provides measurements of soil moisture associated with the corresponding depth, but in any case the zone of influence is a small soil volume around itself. Zegelin *et al.* (1989) showed that three-wire probes embedded horizontally in a field profile during a rainfall event can be used to follow the wetting front and water redistribution, as well as to estimate the amount of infiltrated water with error less than 10%. The probes are interrogated at intervals of 5 min and the universal calibration curve of Topp *et al.* (1980) (relationship between volumetric water content and apparent dielectric constant) is used to calculate soil moisture content from the TDR signal.

The porous medium for the experiments is taken from a natural soil divided into different diameter classes. Then, by recombining fixed quantities of material of each class a homogeneous soil is obtained. Some soils selected on the basis of the USDA soil classification are used for the laboratory experiments. These soils, characterized by saturated

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hydraulic conductivities, K_s, less than the maximum rainfall rate, r, available from the artificial rainfall generator, enable us to perform experiments in a range of r/K_s values that is sufficiently wide for investigating the main aspects of the infiltration process. The duration of each experiment is usually larger than 15 h and in the period between two successive experiments the value of moisture content in the uppermost part of soil is kept high in order to avoid the formation of cracks. Experimental investigations can be realized for infiltration into both bare soils and grassy soils. In the last case, an artificial generation of grass is obtained through a lamp producing radiation with a wavelength spectrum fairly similar to that of solar radiation.

MAIN INSIGHTS ON THE INFILTRATION PROCESS DERIVED BY THE LABORATORY EXPERIMENTAL SYSTEM

Simulation of hydrological response to rainfall requires the estimate of areal-average infiltration that, in principle, could be performed through the representation of the local infiltration into a horizontal surface gradient effect and the run-on process. These three elements are analyzed here on the basis of separate laboratory experiments that avoid a misinterpretation of their specific role. A summary of the experiments carried out for each investigation is shown in Table 1.

Table 1 | Summary of the experiments performed for the analysis of three elements of the infiltration process

Validation of the conceptual model by Corradini *et al.* (1997)	
Number of experiments	4
Artificial rain rate interval (mm h^{-1})	15–24
Slope angle (°)	0
Infiltration by the run-on mechanism	
Number of experiments	24
Artificial rain rate interval (mm h^{-1})	8.83–14.18
Slope angle interval (°)	1–15
Infiltration into sloping soil	
Number of experiments	65
Artificial rain rate interval (mm h^{-1})	4.6–32.4
Slope angle interval (°)	1–15

Validation of a conceptual model for local rainfall infiltration

Many models of local infiltration into vertically homogeneous soils for constant initial soil water content and rainfall over horizontal surfaces have been proposed in previous works (e.g., Mein & Larson 1973; Parlange *et al.* 1982; Corradini *et al.* 1997). Most of them are not suitable for continuous applications to real rainfall patterns which generally involve periods of significant redistribution of soil moisture content. A conceptual model with a more extended field is that proposed by Corradini *et al.* (1997) for erratic rainfalls.

Some laboratory experiments were realized (see Table 1) to test the last model using different soil types (Melone *et al.* 2006, 2008). Both fine-textured and coarse-textured soils were used. In each experiment the artificial rainfall, selected by the system in Figure 2, was characterized by stepwise pulses separated by no rainfall periods, with values of r independent of time and r/K_s in the range 0.6–3.7. A nearly horizontal position of the tank ($\gamma = 1°$) was fixed. The structure of the simulation model relies upon the following ordinary differential equation:

$$\frac{d\theta_0}{dt} = \frac{(\theta_0 - \theta_i)\ \beta(\theta_0)}{I'\left[(\theta_0 - \theta_i)\dfrac{d\beta(\theta_0)}{d\theta_0} + \beta(\theta_0)\right]} \left[q_0 - K_0 - \frac{(\theta_0 - \theta_i)\ G(\theta_i, \theta_0)\ \beta(\theta_0)\, p\ K_0}{I'}\right] \tag{1}$$

where the subscript 0 denotes quantities at the soil surface, θ is the soil moisture content with initial value θ_i, β denotes a shape factor for the dynamic wetting profile, q is the vertical water flux, K is the soil hydraulic conductivity, I' is the cumulative dynamic infiltration depth at time t, p is a quantity depending on the profile shape and linked with β, and $G(\theta_i, \theta_0)$ is the net capillary drive at the wetting front depending on the suction head and hydraulic conductivity.

In the derivation of Equation (1) (Appendix, available with the online version of this paper) the initial soil moisture content was considered invariant with depth, z, and the dynamic wetting profile was approximated by a distorted rectangle through the factor β (≤ 1). Then, a combination of the continuity equation with a depth-integrated form of the Darcy law was developed. This equation was also

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extended to represent successive cycles of infiltration-soil moisture redistribution through the adoption of compound profiles and consolidated profiles. Thus, it can simulate infiltration and $\theta(z)$ for any real pattern of r.

The laboratory experimental system enabled us to highlight the performance of the conceptual model by comparing the $\theta(z)$ values continuously monitored and those estimated in the different stages of infiltration, redistribution, and reinfiltration. As can be seen in Figure 3, obtained for two pulses of rainfall ($r = 15\ \mathrm{mm\ h^{-1}}$, duration 4 h) separated by a rainfall hiatus of 20 h, the conceptual model was found to be substantially appropriate in the simulations of the experimental vertical profiles of soil moisture, particularly during the infiltration and reinfiltration stages. The small errors at the depth of 35 cm in the reinfiltration stage derive from the simulations in the previous redistribution stage and can be, in any case, considered of minor importance in the estimate of infiltration rate and cumulative infiltration.

Infiltration by the run-on mechanism

The generation of Hortonian overland flow at a point starts from the time to ponding and continues as long as the rainfall intensity remains greater than the infiltration rate. Owing to the spatial variability of soil hydraulic properties (Nielsen *et al.* 1973; Sharma *et al.* 1987), the infiltration of surface water moving downslope over permeable areas (run-on mechanism) can occur. Infiltration is therefore determined by rainfall and run-on with the latter that in some cases can have a significant role (Saghafian *et al.* 1995; Woolhiser *et al.* 1996; Nahar *et al.* 2004).

The effects of run-on on infiltration and Hortonian runoff production were investigated through numerical simulations in which the basic element was the representation of the interaction between overland flow and local infiltration rate over the permeable cells (Corradini *et al.* 1998).

Many trials were carried out in the laboratory experimental system to clarify this crucial interaction (Morbidelli *et al.* 2008). Specifically, two adjacent bare soils with rather different hydraulic properties were used in the experiments: a loam soil ($K_s = 6\ \mathrm{mm\ h^{-1}}$) in the upstream half of the tank and a sandy loam soil ($K_s = 11\ \mathrm{mm\ h^{-1}}$) in the lower part. An appropriate packing mechanism was used to enhance contact at the interface and to minimize preferential flow

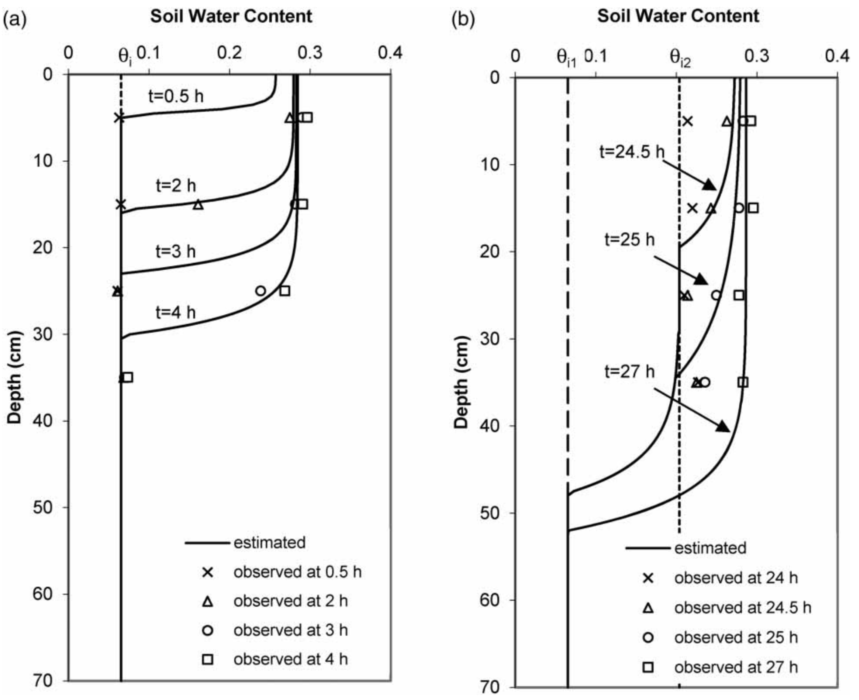

Figure 3 | Comparison of simulated and observed soil water content profiles for a representative event at different times, *t*: (a) infiltration stage; (b) reinfiltration stage. Two rainfall pulses with duration of 4 h, separated by a rainfall hiatus of 20 h, were used.

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along the lateral walls. The trials were performed with $\gamma = 1^\circ$, 5°, and 10° and $r = 10$ mm h^{-1} and 15 mm h^{-1}. During each experiment the upper soil was exposed to a constant rainfall (duration 6 h) while the lower soil was covered by a waterproof sheet. For this investigation the soil moisture vertical profile was monitored in each soil. Two groups of similar experiments were realized, the first group with surface flow measurements performed at the tank outlet and the other with surface flow collected at the downstream end of the upper soil.

Through a mass balance it was deduced that disregarding the run-on mechanism, the surface runoff could be considerably overestimated. Furthermore, the effect of run-on increased with the increase of rainfall rate, because the latter led to a greater quantity of surface water available for infiltration into the downstream soil. A very similar effect was observed with the increase of the slope angle. Figure 4 supports the above results showing the locations of the wetted surface in the downstream soil at the end of the rainfall period, as deduced by photographs and visual observations of the surface and along the transparent sides.

The laboratory experimental system allowed us to point out the significant role of run-on in the estimate of surface runoff. In many cases this mechanism cannot be disregarded and, in the hydrological modeling, the surface flow generated upslope has to be represented by a corresponding flow depth per unit time, then used as an additional rainfall rate over the study cells.

Infiltration into sloping soils

In spite of most watersheds including soil surfaces with appreciable gradient, the existing local infiltration models have been generally formulated for horizontal surfaces even though it is not yet sufficiently clear what is the role of the slope angle. In fact, a few conflicting studies are available in the hydrologic literature (Sharma *et al.* 1983; Poesen 1984; Philip 1991; Chen & Young 2006; Essig *et al.* 2009; Morbidelli *et al.* 2015). The last two papers investigated this issue for bare soils by the laboratory experimental system, in the limits of experiments carried out under conditions of a dominant role of gravitational effects which were obtained working with a soil moisture close to saturation at any depth. Essig *et al.* (2009) realized experiments for $r > K_s$ with rainfall over the entire soil surface and overland flow measured at the tank outlet. Later, Morbidelli *et al.*

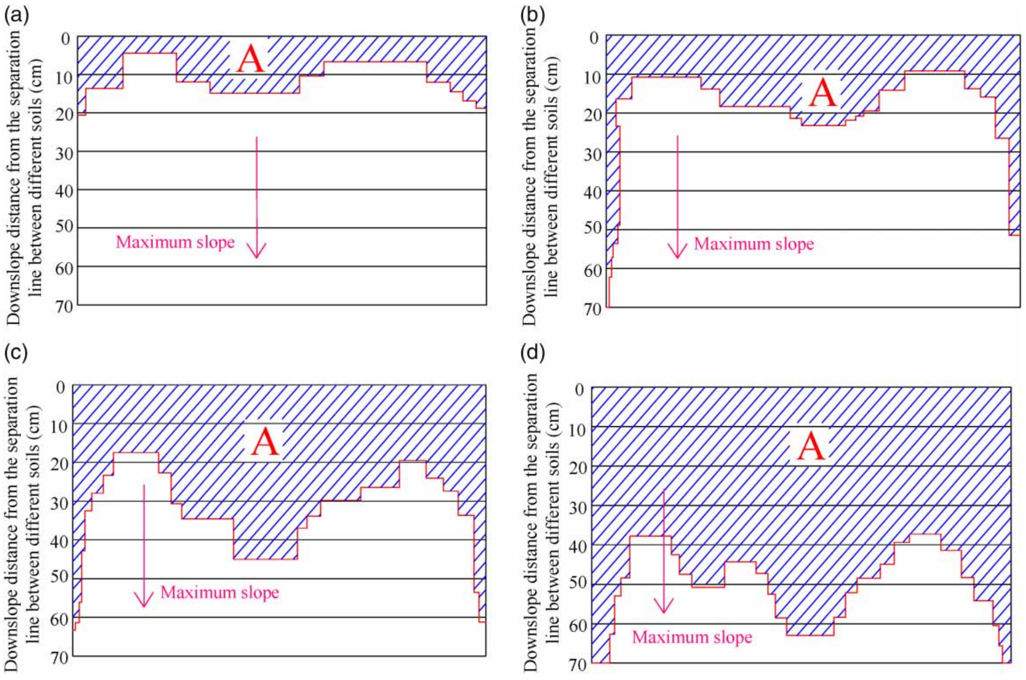

Figure 4 | Influence of slope angle and rainfall rate: (a) 1°, 10 mm h^{-1}; (b) 10°, 10 mm h^{-1}; (c) 1°, 15 mm h^{-1}; (d) 10°, 15 mm h^{-1}. Shaded areas represent the wetted surfaces in the lower soil.

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(2015) carried out further trials addressed at highlighting the influence (if any) of the downstream wall of the tank on the results earlier obtained and to extend the analysis to rainfall with $r/K_s < 1$. In this context the trials were performed using the physical model in the configuration indicated in Figure 1. Four different soils were selected for the experiments. The first soil consisted mostly of silt and clay, the second was primarily sand and silt, the third was a sandy loam, and the other was a loam. In each soil a substantial reduction of infiltration with increasing γ from 1° to 10° was observed on the basis of the deep flow data, Q_d. For example, under steady conditions, in the loam soil the ratio of $Q_d(\gamma = 1^\circ)$ / $Q_d(\gamma = 5^\circ)$ was equal to about 2.5 and that of $Q_d(\gamma = 1^\circ)$ / $Q_d(\gamma = 10^\circ)$ was approximately equal to 4. These results were very different from those obtained by other authors through theoretical and experimental studies. In fact, Sharma *et al.* (1983) and Philip (1991) pointed out the same trend but with effects much reduced in magnitude. On the other hand, for heavy rainfall rates, Poesen (1984) and Chen & Young (2006) found a positive relationship between infiltration and slope.

A preliminary conceptual and numerical analysis led to identify the use of an effective saturated hydraulic conductivity, depending on slope angle, soil type, and soil roughness, as a reasonable solution for representing infiltration in sloping soil surfaces. Along these lines, new experiments by the physical model should be made to find an explicit relation for the representation of the effective saturated hydraulic conductivity. This procedure should allow application of the local models developed for infiltration into a horizontal surface also to a sloping surface, provided the relation for the effective saturated hydraulic conductivity is explicitly known.

CONCLUSIONS

The overall analysis regarding the results of the experimental studies earlier performed by Melone *et al.* (2006, 2008), Essig *et al.* (2009), and Morbidelli *et al.* (2015) in order to improve the knowledge of different aspects of the infiltration process leads to a few important deductions:

- The laboratory experimental system set up with adjustable soil surface gradient can be considered appropriate for a variety of investigations. It allowed us: (1) to validate a local infiltration model for complex rainfall patterns over an almost horizontal soil surface; (2) to provide a direct evidence of the run-on effects; and (3) to point out the considerable role of surface slope in the infiltration process, at least if a bare soil is involved.
- The generator of artificial rainfall with uniform rain rate and the methodology used to localize rainfall over a reduced part of soil surface extend the application field of the system.
- The apparatus set up to measure surface flow with the collector placed at the downstream wall of the physical model or in the middle of the soil block allows us to examine if the downstream wall determines a distortion of results in terms of surface flow, deep flow, and soil moisture vertical profile. In the aforementioned investigations, it can be seen that the wall effect was practically insignificant.

Furthermore, the examined experimental results show the significant accuracy of the conceptual model for local infiltration into horizontal soil surfaces and indicate an appropriate approach for representing the run-on in hydrological models. On the other hand, even though the quantitative evaluation of the effects of surface slope on infiltration into bare soils is of primary importance, currently only an empirical representation of these effects can be made. The solution of the last problem requires the development of an explicit conceptual relation linking the effective saturated hydraulic conductivity with slope angle and other physical quantities such as, for example, the surface roughness. Along these lines, further experiments by the available laboratory system are required.

ACKNOWLEDGEMENT

This research was mainly financed by the Italian Ministry of Education, University and Research (PRIN 2010/2011).

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First received 19 February 2016; accepted in revised form 28 June 2016. Available online 30 July 2016

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