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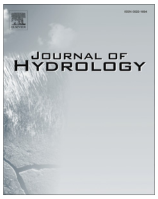

Infiltration on sloping surfaces: Laboratory experimental evidence and implications for infiltration modeling

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SUMMARY

Infiltration on sloping surfaces occupies an important role in our understanding of surface and subsurface hydrology. Previous studies have provided conflicting results about the role of slope on infiltration. Here, our main objective is to highlight, by well-controlled experiments, the slope role in the absence of the conflicting contributions generated by other physical processes observed in previous studies under natural or laboratory conditions. The experimental program was designed to resolve some of the confounding factors such as lower impermeable boundary condition, range of rainfall rates relative to soil saturated hydraulic conductivity, surface sealing, and erosion of top soil. The experimental apparatus consists of a box containing a natural bare soil with slope angle γ chosen between 0° and 10°, two sensors of surface and deep flow, one probe for moisture content and an artificial rainfall generator. The primary experimental results suggest that under steady conditions and rainfall rate, r, greater than saturated hydraulic conductivity, K_s, the deep flow, Q_d, decreases with increasing slope angle, γ, up to a value leading to $Q_d(\gamma = 1^\circ)/Q_d(\gamma = 10^\circ)$ equal to ≈ 4 which is in contrast with the results provided in a few earlier papers. Furthermore, in sloping bare soils surface runoff is produced even for $r < K_s$. Finally, we discuss the link between $Q_d(\gamma)$ and the shear stress at the soil surface as a guideline in the determination of an effective saturated hydraulic conductivity to be incorporated in the existing horizontal infiltration models.

1. Introduction

Partitioning of rainfall into surface and subsurface flow components is an important element in our understanding of the hydrologic cycle, and influences many events of major hydrologic interest such as runoff generation, aquifer recharge, and transport of pollutants in the vadose zone and aquifers. This partitioning is achieved through the process of infiltration that has been widely investigated at the local scale, and more recently also at the field scale, by models that were primarily designed for horizontal surfaces. For local infiltration, the extended Philip equation (Chow et al., 1988), the Green–Ampt model extended by Mein and Larson (1973) and the Smith and Parlange (1978) model are the classical formulations typically used when isolated storm events are considered, while in the case of complex rainfall patterns with successive infiltration-soil water redistribution cycles an appropriate model was proposed by Corradini et al. (1997). Extensions of infiltration modelling from the local to the field scale were developed for vertically homogeneous soils by Smith and Goodrich (2000) and Govindaraju et al. (2001), while for two-layered soils formulations with a more permeable upper layer were proposed by Corradini et al. (2011a,b).

However, infiltration, overland flow, and deep flow in most real situations are generated by rainfall over surfaces with different gradients (see also Beven, 2002; Montgomery and Dietrich, 2002; Fiori et al., 2007). Therefore, the aforementioned models have to be adapted to account for the effects of surface slope. Some investigations to address this issue have been performed, for example, by Poesen (1984) and Sharma et al. (1983) through laboratory and field experiments, respectively, by Philip (1991) developing a theoretical formulation for the dynamics of infiltration, by Chen and Young (2006) extending the Green–Ampt approach and by Essig et al. (2009) comparing numerical and laboratory experimental results. However, conflicting results have been reported in the literature on the role of surface slope on infiltration. In a few papers, a decrease of infiltration with increasing slope angle was observed. Sharma et al. (1983) performed field experiments in a

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bare loamy sand soil under natural rainfall rates and ascribed this trend to the reduction in the time available for rainfall to infiltrate into steeper slopes. On the other hand, Poesen (1984) set up laboratory experiments and observed that for light artificial rainfall rates, infiltration and overland flow were not affected by variations in the slope angle, while for heavy rainfall rates the results showed a positive relationship between infiltration and slope. Poesen ascribed the results to either the formation of a sealing layer, or the increase of rill erosion on the steeper slopes, suggesting that variations in the slope angle should not significantly affect the infiltration rate and surface runoff quantity in the absence of erosion and a sealing soil layer.

Philip (1991) proposed an extension of the classical infiltration theory that was earlier developed for horizontal land surfaces (Philip, 1957,1969) considering a long planar sloping surface with infinite extent of a homogeneous isotropic soil characterized by uniform initial moisture content. By using the Richards equation for the flow both normal and parallel to the slope, an analytical solution in the form of a series solution and two simplified relations for different time intervals were obtained. Philip showed that the gravitational effect decreases by a factor $\cos\gamma$, where γ is the angle of the sloping surface with the horizontal, that implies a reduction of about 13% from $\gamma = 0°$ to $\gamma = 30°$. Chen and Young (2006) modified the Green–Ampt approach to represent the physical effects of γ on infiltration and surface runoff generation under the condition of identical slope horizontal projection lengths. The Richards equation was used as a benchmark for applications of both steady and unsteady rainfalls. Their results showed a positive relation between infiltration and γ, which is significant at small times or low rainfall depths and can be neglected for $\gamma < 10°$.

The assessment of how γ affects infiltration and overland flow generation still remained a controversial problem. Essig et al. (2009) conducted a detailed study on the effect of slope on infiltration by combining controlled laboratory experiments with different mathematical models. By using a planar slope with γ variable between 1° and 15°, they found that the increase of γ has a negative influence on infiltration and this effect becomes more pronounced with decreasing rainfall rate. Furthermore, the observed behavior of deep and overland flow for varying γ could not be appropriately simulated by the current theories. Three mathematical models of different complexity were utilized to explain the observed data. The authors proposed an effective saturated hydraulic conductivity, that empirically accounts for slope effects, to obtain reasonable agreements with measurements of overland flow, deep flow and soil moisture profile.

However, many issues about infiltration on sloping surfaces remain unresolved. An overall comparison of the aforementioned experimental and theoretical investigations indicates knowledge gaps that can be attributed to experimental site-specific conditions, and to the differences in initial and boundary conditions between theoretical and experimental investigations. The overall intent of this work is to address some of these concerns through controlled laboratory experiments, and further elucidate the role of slope on infiltration. The primary objectives of this paper are:

- to isolate the slope effects on surface runoff, infiltration and deep flow through laboratory experiments realized in the absence of the aforementioned processes of erosion and sealing layer formation;
- to perform laboratory experiments under different slopes to investigate whether the results of Essig et al. (2009) could be significantly influenced by the downstream boundary of their experimental system as speculated by the authors;
- to extend the investigation of the effects of γ to rainfall rates, r, comparable to the saturated hydraulic conductivity, K_s.

2. Experimental system

The laboratory experimental system consists of:

- a soil box with geometric features shown in Fig. 1 and the slope angle γ adjustable in the range 1–15°, the lateral surfaces are impermeable and transparent;
- a two-layered study soil obtained from natural soils with particles divided into different diameter classes that were recombined to obtain a homogeneous upper layer, with grain size distribution illustrated in Fig. 2, and a lower gravel layer of thicknesses 67 cm and 7 cm, respectively. The two layers are separated by a geotextile mesh. The upper soil, according to the USDA soil classification, is of loam type, the gravel layer acts as support and speed the drainage process;
- an artificial rainfall generator, based on sprinklers of water under pressure supplied by a pump, that produces a rainfall distributed over the soil surface of intensity chosen through the appropriate combination of a sprinkler and water pressure. The rain rate spatial distribution is almost uniform and is checked before the beginning of each experiment by a grid of pans placed over a sheet of metal that enables us to also measure the outflow produced by the sprinkler;
- a tipping bucket sensor which provides continuous surface flow data collected by a triangular metal element placed transversely on the soil surface (see Fig. 1) at the lower boundary of the area influenced by rainfall during the experiments. The same method is used to obtain measurements of deep flow at the downstream soil boundary;
- two Time Domain Reflectometer (TDR) sensors with vertically oriented probes that collect continuous observations of the average soil water content in the uppermost part between 0 and 20 cm. One sensor is inserted in the area subjected to rainfall during the experiments, while the other probe samples the portion that does not receive direct rainfall. The artificial rain falls over the entire box area, but during the experiments the downstream soil surface between 100 cm and the lower box side is covered by a sheet of metal which covers also the two flow collectors.

One of the requirements of this paper is to determine the saturated hydraulic conductivity K_s of the upper soil. As discussed in subsequent sections, this estimate is performed through the analysis of the observed temporal variability of the deep flow generated by different rainfall rates over a nearly horizontal soil surface.

3. Experimental results

Experiments were performed for different γ values, specifically 1°, 5° and 10°, under rainfall rates between 5 and 12 mm h^{-1}. The box angle was kept $\leqslant 10°$ for stability of the soil and to avoid surface landslide sites. Before the beginning of each experiment a rainfall rate of duration sufficient to lead the soil close to saturation at any depth was applied. The achievement of this stage was confirmed by the TDR sensors.

Fifteen experiments with soil surface under rainfalls of 6 h-duration and with flow measurements extended to 14 h were realized in successive days. The outflow hydrographs involve periods of steady flow, that are shown in Figs. 3a–5a each referred to a representative experiment for $\gamma = 1°$, 5° and 10°, respectively. The corresponding rainfall rates, obtained by the same water pressure of 1 bar, were 11.40, 11.59 and 11.71 mm h^{-1}, respectively. A comparison of the three surface flow hydrographs indicates that the time required to reach the steady flow condition (~2 h) is practically independent of γ, however the discharge starts to increase