

## Thematic Issue on Soil Water Infiltration

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“Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface” (Hillel, 1998). Studying infiltration is central in hydrological and agricultural sciences since this process governs the stock of available water for plants and groundwater recharge and also controls surface water runoff and soil erosion (e.g., Angulo-Jaramillo et al., 2016; Green et al., 2003).

Scientific understanding of infiltration processes has greatly improved, over the past 30 years, and new insight has been given into modelling of non-uniform flow (e.g., Gerke, 2006; Jarvis, 2007; Köhne et al., 2009). Indeed, structural porosity and reduced soil wettability can lead to significant lateral and vertical redistribution of water including transport of pollutants that cannot be described by the traditional Darcian-based Richards’ equation. Despite the enormous effort and number of various methods for determining soil water infiltration (e.g., Angulo-Jaramillo et al., 2016; Lassabatere et al., 2006; Reynolds et al., 2000), the determination of water infiltration for the characterization of the soil hydraulic properties is hampered by effects of spatial and temporal variability (e.g., Green et al., 2003; Nielsen et al., 1973). Directly linked to both, the smaller- and the larger-scale heterogeneities, is the recognition that under natural conditions, infiltration is characterized by the spatial variability observed at the mm-scale (e.g., Hallett et al., 2004), the aggregate scale (e.g., Gerke and Köhne, 2002; Leeds-Harrison et al., 1994), the pedon scale and up to the field scale (e.g., Haws et al., 2004). Thus, local infiltration experiments are sensitive to space-time variability of the unsaturated soil properties. High resolution infiltration measurement, both in space and time, is therefore crucial to properly describe and analyse soil water properties needed to model water flow. In particular, the investigation of preferential flow requires experimental and numerical approaches that span over scales (e.g., Clothier et al., 2008; Gerke et al., 2010; Lin et al., 2010).

Over the past couple of decades, we have seen the development of many new measurement techniques that consist in infiltrating water under controlled conditions (i.e., water pressure head and initial water content) and the creation of innovative devices (ponded or tension infiltrometers, infiltration pits, etc.) for this purpose (Angulo-Jaramillo et al., 2016). These methods have improved our ability to estimate soil hydraulic characteristics directly in the field and are resulting in better enhanced prediction of the flow of water and the transfer of solutes through the vadose zone.

This thematic issue collects 11 original contributions presented during the session “Infiltration: measurements, assessment and modelling” at the General Assembly of European Geosciences Union (EGU), being held on 17–22 April, 2016, Vienna, Austria. Contributions presented at the session focused

on the principles, capabilities and applications of both infiltration techniques and models at different scales.

Soil hydraulic properties controlling infiltration generally exhibit a dynamic nature, being influenced by different interrelated factors including soil nature and stability, climate, land use, dynamics of plant canopy and roots, or tillage operations (Jarvis et al., 2013) as well as measurement techniques (Bagarello et al., 2014). The spatial and temporal variability of ponded infiltration was measured in a long-term experiment on a grid of 18 permanent measurements points established in a coarse sandy loam soil prone to preferential flow paths (Votrubova et al., this issue). Substantial interannual changes of infiltration rate were observed. However, in the first four years of the study, the temporal variability did not exceed the spatial variability. Then, a shift to extremely high infiltration rates was observed. The increase was not monotonous but the infiltration curves in successive years switched up or down between apparently stable infiltration modes. The authors hypothesized that the detected behaviour was related to structural changes of the soil profile possibly due to combined effects of soil biota activity, climatic conditions and experimental procedure. Indeed, the activation of preferential pathways within the soil profile may strongly depend on time-variable meteorological conditions and animal activity.

Air entrapment in soil pores during an infiltration process can explain temporal variability of soil hydraulic properties (Císlarová et al., 1988; Dohnal et al., 2013). The volume of entrapped air bubbles as well as air solubility is related to water temperature. Temperature changes are expected to affect the soil hydraulic properties and thus water flow to a greater extent than that induced by changes in water viscosity. Sobotkova et al. (this issue) conducted isothermal and non-isothermal infiltration experiments on intact laboratory soil columns to assess temperature effects on water infiltration and tracer breakthrough. The soil intrinsic permeability was generally higher when cold water was infiltrated in initially warm soil (non-isothermal infiltration). The authors hypothesized that air bubbles initially trapped in the pore system gradually shrank in response to cooling, thus opening the flow channels initially blocked by the air bubbles. Despite these differences in the continuity of water-filled porosity, the tracer transport was not affected by temperature.

The amount of entrapped air depends essentially on the nature of the wetting; more air is trapped when the soil surface is wetted extensively (Sněhota et al., 2010). However, most of the existing investigations were conducted on laboratory samples or in the field at point scale, whereas the extension of infiltrating surface could have a marked influence on air entrapment given that the larger the ponded surface is the lower is the op-

portunity for air to escape. Water infiltration experiments were performed in a large infiltration basin (dedicated to groundwater recharge) to investigate how air-entrapment at the beginning of the experiment and temperature difference between infiltrating water and groundwater affected infiltration rate (Loizeau et al., this issue). In initially dry soil conditions, infiltration rates increased by 78 and 43% of the initial value with warm and cold water, respectively. In initially saturated soil conditions, infiltrating water with approximately the same temperature as groundwater allowed a perfect stability of infiltration rate with time. The increase in flow rate could be explained by the dissolution of entrapped air or the increase in water temperature. It was concluded that the effect of entrapped air was more important than that of temperature.

Anisotropy in saturated soil hydraulic conductivity,  $K_s$ , influences hydrological processes such as runoff generation (Beven and Germann, 2013). Measurements of  $K_s$  anisotropy can be conducted in laboratory or in the field by a combination of infiltrometer experiments establishing either vertical and radial flow (Angulo-Jaramillo et al., 2016). However, the possibility to estimate both the vertical and the horizontal components of  $K_s$  from a single infiltration experiment is still a challenging issue. A large (1 m in diameter) single-ring infiltrometer experiment was conducted by Réfloch et al. (this issue) to estimate the  $K_s$  anisotropy in a heterogeneous alluvial deposit. Experimental data included cumulative volume of infiltrated water and extension of the moisture stain around the ring. A simple numerical inversion of the Richards' equation for axisymmetric flow allowed the authors to show that an accurate fitting of the stain extension was only possible by considering anisotropy of hydraulic conductivity. Their results also showed that horizontal  $K_s$  was 125-times higher than vertical one.

The lateral saturated soil hydraulic conductivity,  $K_{sl}$ , determined with large-scale experiments can be expected to allow an improved representation of the effects of heterogeneity on the hillslope hydrological response as compared with near-point measurements (Brooks et al., 2004). However, large scale experiments are rare in the scientific literature. Lateral subsurface flow processes were investigated by Pirastru et al. (this issue) in a semiarid Mediterranean climate hillslope with different vegetation covers. For this kind of environments, subsurface flow has traditionally been considered less important than surface flow for discharge production. The authors monitored water table levels and subsurface flow under both natural and artificial rainfall for determining the relationship between  $K_{sl}$  and the thickness of the water table above the impeding layer. A sharp increase of  $K_{sl}$  was observed when the water table level was close to the soil surface, suggesting that high water table levels were necessary to make large-scale hydraulic connection of the macropore system effective. Higher  $K_{sl}$  values were obtained under the Mediterranean maquis than in the grassed hillslope probably because the macropore network was better connected in the former land cover.

Water movement through an unsaturated fractured aquifer combines flow in the porous matrix with that in the fracture or preferential flow domain. The two-domain character of such dual-porosity and dual-permeability systems greatly increases the difficulty of predicting water infiltration and groundwater recharge (e.g., Gerke et al., 2010). Pastore et al. (this issue) developed a kinematic diffusion approach to model the concomitance of matrix flow and preferential flow in fractures and their effects on water table fluctuation. They investigated the specific case of the fractured chalk aquifer of Picardy, France. The kinematic diffusion approach was able to reproduce water

table fluctuation with a proper simulation of both rise and fall, with rise being explained by preferential flow and smooth fall by matrix flow. The authors concluded that the applied approach was valuable for prediction of the aquifer recharging when preferential flow occurs.

Water infiltration into the soil profile may be strongly affected by the presence of macropores and cracks (e.g., Lassabatere et al., 2014). Besides structural singularities of the porous media, non-uniform flow may also be triggered by heterogeneous lithology, specifically when lithofacies with contrasting properties form inclusions in the soil profile. Insights on the effects of heterogeneous lithology on flow patterns and wetting fronts were given by the numerical study conducted by Ben Slimene et al. (this issue) for a glaciofluvial heterogeneous deposit (Goutaland et al., 2013). Multiple scenarios based on different levels of heterogeneity were simulated with HYDRUS-2D (Šimůnek et al., 2016) considering a range of assumed infiltration rates at the soil surface. Spatial flow variability and preferential flow decreased as flow rate increased. Indeed, at low flow rates sand and gravel lenses acted as capillary barriers deviating water fluxes between the inclusions and thus triggering funnelled flow. At high flow rates, the capillary barrier effect was lessened because pressure heads in the deposit profile increased and reversed the difference in hydraulic conductivities between the lenses and the main body of the porous media. Geometry of lithofacies was identified as a critical factor in enhancing the flow of water and the transport of pollutants towards groundwater.

Water repellency can slow down the infiltration process and increase the variability as compared to infiltration in a more wettable soil. A quantitative characterization of soil water repellence can be obtained by the Water Drop Penetration Time (WDPT) test (Letey et al., 2000). An alternative approach relies on the adjusted ratio, RI, between the soil-ethanol and soil-water sorptivities determined by infiltration experiments (Tillman et al., 1989). However, there are still issues that need further investigations such as the kind of water application for the infiltration experiment (ponded or tension) to estimate RI and the method for the comparison between RI and the traditional WDPT test data. Soil water repellency, aggregate water-stability and both unsaturated and saturated soil hydraulic conductivities were determined in a Mediterranean oak forest with the aim to assess the impact of thinning on soil hydraulic properties (Di Prima et al., this issue). Thinning had no implication on saturated and unsaturated hydraulic conductivities. However, both the WDPT and RI tests suggested that the soil was more water repellent at the thinned site as the consequence of increased microbial activity and, consequently, production of water repellent substances. Due to the presence of macropores, saturated soil hydraulic conductivity,  $K_s$ , measured with the single ring infiltrometer with a small ponded head of water ( $\leq 10$  mm) was two orders of magnitude greater than unsaturated hydraulic conductivity measured at a small suction head of  $-20$  mm,  $K_{-20}$ , by using a minidisk infiltrometer. A negative correlation with both WDPT and RI that was found for  $K_{-20}$  but not for  $K_s$  thus suggested that water repellency only affected unsaturated soil hydraulic properties.

Hydrophobicity can be extreme when soils are dry; it is declining and eventually disappearing as soils become wet (Buczko et al., 2005; Vogelmann et al., 2013). In addition to the temporal variability, the spatial (i.e., vertical) distribution of hydrophobicity within soil profiles can be highly variable (Buczko et al., 2002; Dekker and Ritsema, 1994). With the aim to better understand temporal and vertical variation of soil

water repellency in two Mediterranean forest soils, Alagna et al. (this issue) applied the WDPT test and compared the data with those obtained from alternative approaches based on minidisk infiltration tests, namely the repellency index (RI) (Tillman et al., 1989), the water repellency cessation time (WRCT) (Lichner et al., 2013) and a specifically proposed modified repellency index ( $RI_m$ ) derived from the hydrophobic and wettable stages of a single water infiltration experiment. All indices unanimously detected the severe water repellency in the duff of the pine forests that resulted from high amounts of organic matter. The mineral subsoils in the two forests showed wettability patterns that corresponded with the hydraulic conductivity of the duff layer that influenced leaching of hydrophobic compounds. Indices gathered from the minidisk infiltration tests were able to signal sub-critical repellency conditions that were not detected by the traditional WDPT test. The  $RI_m$  index was in reasonable agreement with the more cumbersome RI index.

The lack of representative data for soil hydraulic properties, i.e., the relationships between soil water pressure head,  $h$ , water content,  $\theta$ , and hydraulic conductivity,  $K$ , constitute the main limitation to larger-scale applications of deterministic models for predicting water infiltration and the fate of pollutants in unsaturated soils. A lot of effort has been put in developing pedotransfer functions (PTFs) to predict the soil hydraulic properties from more easily measurable or routinely surveyed soil data (e.g., Jarvis et al., 2002; Wosten et al., 2001). Most of the  $\alpha(h)$  estimating PTFs were developed for temperate soils and great caution is needed for application in tropical regions (Minasny and Hartemink, 2011). Ten point PTFs and two continuous PTFs developed for tropical regions were tested by Rustanto et al. (this issue) for the upper Bengawan Solo catchment in Java island, Indonesia. Direct application of point PTFs was not successful but reasonable results were obtained with the continuous PTF proposed by Hodnett and Tomasella (2002). The study also suggested that, instead of developing new PTFs, recalibration of existing ones, even with a relatively limited dataset, could successfully improve the  $\alpha(h)$  predictions.

Applicability of distributed hydrological models at regional scale needs large datasets of saturated hydraulic conductivity,  $K_s$ , values, which are most frequently based on infiltration measurements but may rely on different methods. However, the use of different methods may yield substantially dissimilar  $K_{fs}$  values with values spanning over three to four orders of magnitudes, because this parameter is extremely sensitive to sample size, flow geometry, sample collection procedure and various soil physical and hydrological characteristics (Alagna et al., 2016; Reynolds et al., 2000; Verbist et al., 2013). An original procedure to pool the data from infiltration measurements performed with Guelph permeameter, double ring infiltrometer, single ring Beerkan infiltrometer and tension infiltrometer was outlined by Braud et al. (this issue). An equivalent set of  $K_s$  data was built by statistical tests and simple regressions between data obtained by the different devices. Geology and land cover were found to be significant discriminating factors, and therefore were used to aggregate  $K_s$  for the aim of mapping this property at regional scale. For the study case of the Cévennes-Vivarais region, France, a PTF based on soil texture yielded much lower  $K_{fs}$  values than observed equivalent ones showing that a PTF that does not consider land cover information is not a good predictor of the spatial variability of  $K_{fs}$ .

In conclusion, the combined use of water infiltration experiments and numerical or analytical models presented in the papers of this thematic issue on "Soil Water Infiltration"

provide an insight into some of the most challenging problems in water infiltration research and for the prediction of water and solute movement in the vadose zone at different scales, from the soil profile to the watershed, and under different climatic, edaphic and geo-pedological conditions. This research is part of the enormous efforts performed by the soil science community to develop better techniques for soil hydraulic characterization and better understand and model of water flow in the vadose zone and hydrological processes (Angulo-Jaramillo et al., 2016). However, more research is needed on these topics to better understand and implement effects of the dynamic nature of the soil surface structure on infiltration.

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