Estimating lateral flow in double ring infiltrometer measurements


[1] Universidade Federal de Santa Maria, Departamento de Solos, Santa Maria, Rio Grande do Sul, Brasil.

ABSTRACT: The steady infiltration rate of soil profiles is commonly determined for irrigation and soil conservation planning, but the divergence of methods reduces the reliability of measurements. In this study, the steady infiltration rate measured with a double ring infiltrometer ($i_{sr-dri}$) in different layers of a soil profile was compared between layers and with the steady vertical saturated flow rate estimated by the Richards equation ($i_{sr-hy}$). The measurements of $i_{sr-dri}$ at the top of the A, E, and Bt horizons were compared to each other and also compared with the $i_{sr-hy}$ to detect the occurrence of lateral flow in double ring infiltrometer measurements. The $i_{sr-dri}$ in the A horizon (236 mm h$^{-1}$) was around 10 times higher than in the Bt horizon (20 mm h$^{-1}$), which implies in a lateral flow of almost 90% in the surface horizon. The occurrence of lateral flow in double ring infiltrometer measurements was also shown by comparing $i_{sr-dri}$ with the vertical saturated flow rate estimated with the Richards equation, $i_{sr-hy}$. The main conclusion is that $i_{sr-dri}$ measured at the soil surface overestimates the steady infiltration rate of soil profiles when underlying horizons are less permeable and more restrictive to water flow. In these cases, the use of an effective saturated hydraulic conductivity of the soil profile would imply inaccurate planning of drainage, irrigation, and soil conservation designs.

Keywords: steady infiltration rate, modeling, hydru-1D.
INTRODUCTION

Infiltration of water into the soil is limited by a dynamic threshold rate termed infiltration capacity \( i_c \) (Hillel, 2004). A water supply rate from precipitation or irrigation exceeding \( i_c \) cannot fully infiltrate and will partially turn into a runoff. Thus, soil use and irrigation management should consider \( i_c \) to prevent runoff and the consequent erosion and environmental degradation (Youngs, 1991; Liu et al., 2019; Miyata et al., 2019).

The time-space variability of \( i_c \) is due to its dependence on the intrinsic soil permeability and gradients of energy acting on water, which are time-space variables as well. Methods using devices such as tension infiltrometer, permeameter and/or pressure infiltrometer, rainfall simulator, and double ring infiltrometer can be used to evaluate \( i_c \) and its variability. Due to its low cost and ease of use, the double ring infiltrometer is a frequently used method (Pott and De Maria, 2003; Arriaga et al., 2009; Fatehnia et al., 2016; Minosso et al., 2017; Silva et al., 2017; Owuor et al., 2018; Bonetti et al., 2019; Fernández et al., 2019; Liu et al., 2019; Schwartz et al., 2019; Sithole et al., 2019).

When a double ring infiltrometer (DRI) field test is performed on an initially unsaturated soil, \( i_c \) tends to decrease exponentially over time and asymptotically reaches a quasi-steady rate \( i_{sr-dr} \) (ASTM, 2009). A similar infiltration rate curve can be simulated with the one-dimensional form of the Richards equation for variably-saturated water flow in an initially unsaturated vertical soil column by maintaining a water layer with a negligible hydraulic pressure on its surface and allowing a free drainage at its bottom. This kind of simulation shows that the water flow rate entering the surface of the soil column decreases exponentially over time and asymptotically reaches a steady rate when the entire soil column becomes saturated (Šimůnek et al., 2012). In this condition, the matric gradients of energy become zero, and the steady flow rate in any cross-section area along the soil column is the same and numerically equal to the hydraulic conductivity of the saturated soil column. Furthermore, if several simulations are performed in a same soil column with different initial water contents, all infiltration rate curves will converge to the steady rate which is numerically equal to the saturated hydraulic conductivity (Hillel, 2004).

If the water from the inner ring infiltrates vertically without lateral deviations in any part of the soil profile during the DRI test, the flow conditions in the soil profile would be equal to those in the simulations. Based on these assumptions, it is considered that \( i_{sr-dr} \) is an estimate of the hydraulic conductivity of the saturated soil profile (Bouwer, 1986; Sales et al., 1999; Reynolds et al., 2002; Bodhinayake et al., 2004). Thus, \( i_{sr-dr} \) is supposed to be the lower limit of \( i_c \) in the soil profile (Mbagwu, 1997) and would represent the most restrictive condition to water infiltration. Consequently, it is considered that runoff and erosion are avoided if irrigation rates do not exceed \( i_{sr-dr} \) (Chowdary et al., 2006; Vilarinho et al., 2013). Drainage systems (Stovin et al., 2015) and floodwater containment terraces (Kovář et al., 2016) are also planned considering that \( i_{sr-dr} \) corresponds to the hydraulic conductivity of the saturated soil profile. Furthermore, \( i_{sr-dr} \) has been also used to indicate the potential runoff and erosion risk associated with different soil use and management (Sidiras and Roth, 1986).

However, the occurrence of lateral flow of water infiltrating from the inner ring is almost never evaluated in DRI tests in the field (Zhang et al., 2016). If \( i_{sr-dr} \) is biased by a significant amount of lateral flow, \( i_{sr-dr} \) overestimates the saturated soil profile hydraulic conductivity and the minimum value of \( i_c \) in a soil profile. Lateral flow of water infiltrating from the inner ring is expected to occur: (i) if the water infiltrating from the outer ring is insufficient to supply the lateral flow demand of the infiltration bulb (Ahuja et al., 1976; Wu et al., 1997); under this condition, some water from the inner ring would also be driven laterally in the soil profile (Wu et al., 1997); or (ii) if less permeable subsurface layers favor the occurrence of lateral flow on their upper surface (Bouwer, 1986). A more permeable layer overlying a less permeable one is common in naturally layered
soils such as Ultisols and Alfisols with a clay illuviation horizon (B) (Franco, 2010). The presence of compacted and less permeable subsurface layers is also widely reported in soils managed under no-till (Drescher et al., 2011; Bonini et al., 2011) or with a plow layer compaction (Håkansson, 1990).

Nevertheless, a hypothesis stating the presence of lateral flow in DRI tests is difficult to be evaluated in the field. In situ quantification of lateral flow from the inner ring is challenging. Although it is possible to install probes and automated systems to measure water content and propagation of the infiltration front, it is not easy to determine the contribution of each ring (inner and outer) to the lateral flow. This difficulty implies in the complexity of precisely quantifying saturated flow exclusively in the vertical direction. A field strategy to investigate lateral flow in DRI tests could be by measuring \(i_{sr-dr}\) at different depths in the soil profile and comparing their values. If the water from the inner ring infiltrates vertically without lateral deviations in any part of the soil profile during the DRI test, the value \(i_{sr-dr}\) should be the same at the different depths. However, if \(i_{sr-dr}\) is greater at the soil surface than the \(i_{sr-dr}\) measured at a greater depth, it should contain lateral flow. An additional way to investigate if \(i_{sr-dr}\) contains lateral flow could be by evaluating if the \(i_{sr-dr}\) measured at different depths are greater than the steady, vertical flow rate of the entire saturated soil profile estimated with the one-dimensional form of Richards equation. Combining these two strategies, relevant information can be retrieved about the occurrence of lateral flow in DRI measurements. In this study, we aimed to test the hypothesis that \(i_{sr-dr}\) measured at the surface with DRI can contain a significant amount of lateral flow. We used both mentioned strategies to do so.

**MATERIALS AND METHODS**

**Study site**

Experimental determinations were performed at an experimental area of the Federal University of Santa Maria - RS (29° 43’ 14” S and 53° 42’ 18” W; altitude 110 m a.s.l.). The soil is a Typic Paleudult (Soil Survey Staff, 2014), which corresponds to an Argissolo Vermelho Distrófico arênico according to Brazilian Soil Classification System (Santos et al., 2013), under no-till management for approximately 7 years. The site was especially suitable because it features a soil profile with a more permeable layer overlying a less permeable one.

**Double ring infiltrometer tests**

The DRI tests (0.20 m inner ring diameter and 0.40 m outer ring diameter) were performed on the nine experimental plots between May 31, 2018 to June 22, 2018, at the top of A, E, and B horizons. All tests were performed when soil water content was around field capacity (two to four days after rainfall). Initially, the two rings were inserted into the soil surface to a depth of 0.10 m, and the infiltration rate was determined maintaining a constant head of 0.05 m, according to the methodology described by Reynolds et al. (2002). The amount of infiltrated water was recorded at intervals of 5 min. The duration of each test was between 1.0 and 1.75 h, and they were concluded when at least five successive readings indicated that the infiltration rate had approached its quasi-stead rate \(i_{sr-dr}\). The average of the five final observed rates was considered an estimate of \(i_{sr-dr}\). To install the DRI in underlying E and B horizons, trenches were manually opened some days after the previous infiltration measurement. As the water drained from the A horizon increased the water content in the underlying horizons (E and B), the soil profile was left to drain this exceeding water for two to three days. After that, the soil was removed until the bottom of the trench reached the top of the next soil horizon. During the excavation, the bottom surface of the trench was not trampled to avoid soil compaction. The DRI tests in the E and B horizons were performed as aforementioned. The relatively long time to perform the
measurements (May 31 to June 22, 2018) was due to the time needed to allow the soil to dry between tests, sometimes delayed by rainfall.

**Soil analyses**

The soil horizons were identified by morphological observation, considering color change (visual), texture (sensitivity to touch), and perceived resistance when introducing a knife tip. Soil physical properties were determined in three subdivisions of the A horizon (A₁, A₂, and A₃), two of the E horizon (E₁ and E₂), and on the top of the B horizon. In each of these horizons, two undisturbed soil samples were collected in September 2018 with metal rings (0.04 m high, 0.057 m diameter). A disturbed sample was collected as well. The undisturbed samples were saturated by capillarity for 48 h and weighed. Subsequently, the saturated hydraulic conductivity (Kₛ, mm h⁻¹) was determined with the use of a constant head permeameter, setting the hydraulic head to 2.52 cm. After determining Kₛ, the samples were oven-dried at 105 °C for 48 h. Total porosity (TP, m³ m⁻³) was considered equal to the measured volumetric water content at saturation, and soil bulk density (BD, Mg m⁻³) was calculated dividing the sample dry mass by the ring volume. For these properties, its average from the two samples of each horizon was considered. Particle size distribution (clay, silt, and sand contents) was determined with 20 g of sieved (2 mm screen) air-dried disturbed samples, using the pipette method according to Suzuki et al. (2015).

**Process-based numerical simulation of infiltration**

Infiltration was simulated applying the one-dimensional form of the Richards equation with the software Hydrus-1D (Šimůnek et al., 2013). Hydrus-1D numerically solves the Richards equation for variably-saturated water flow in one-dimension (Equation 1), assuming that the atmospheric phase and water flow by thermal gradients are insignificant.

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K \left( \frac{\partial h}{\partial x} + 1 \right) \right]
\]

**Eq. 1**

In this equation, θ is the volumetric water content (m³ m⁻³); h is the soil pressure head (m); t is time (h); x is the vertical spatial coordinate (m); and K is the hydraulic conductivity (m h⁻¹).

The van Genuchten-Mualem soil hydraulic model without hysteresis was selected in Hydrus-1D to describe the θ-h-K relation in equation 1. Thus, parameters of the van Genuchten water retention curve [saturated and residual water contents (θₛ and θᵣ, m³ m⁻³), α (m⁻¹), and n], the pore-connectivity parameter (dimensionless) l, and the saturated hydraulic conductivity Kₛ are the soil hydraulic parameter required in Hydrus-1D. The measured Kₛ values were used, but the value of the other parameter was defined by pedotransfer function as described below.

A soil domain with six materials and 1.8 m length was defined, according to the six horizons of profile (A₁, A₂, A₃, E₁, E₂, and B) and respective depths (0.00-0.20, 0.20-0.43, 0.43-0.64, 0.64-0.86, 0.86-1.12, and 1.12-1.80 m). Considering the measured values of sand, silt, clay, and BD of the six horizons, the parameters θₛ, θᵣ, α, and n of each layer were estimated for the nine plots using the software Rosetta Lite v. 1.1 (Schaap et al., 2001) available in Hydrus 1D. The default value 0.5 suggested in Hydrus-1D for the pore-connectivity parameter l was used for all horizons.

Simulations were performed setting the initial water condition at field capacity, which was defined automatically in Hydrus 1D as a function of van Genuchten water retention parameters and Kₛ, using the equation of Twarakavi et al. (2009). A permanent positive pressure head of 5 cm was defined as the upper boundary condition and free drainage as the bottom boundary condition. A duration of 30 h was used in all simulations to ensure that the entire domain was saturated and the steady infiltration rate, i_{stbyr}, was achieved.
Under steady vertical flow in a saturated, layered soil column, the solution of Richards equation becomes the serial Darcy flow equation for $N$ layers according to $i_r = (h+Z)/(L_1/K_{s_1} + L_2/K_{s_2} + \cdots + L_N/K_{s_N})$. Note that the infiltration rate ($i_r$) is a function of thickness (L) and saturated hydraulic conductivity ($K_s$) of each layer, the hydraulic head (h) at the soil surface, and the length of the soil column (Z). The Hydrus steady infiltration rate ($i_{sr-hy}$) in our study is the steady vertical flow after the soil column became saturated. Thus, $i_{sr-hy} = i_r$, and then the parameters $\theta_s$, $\theta_r$, $\alpha$, and $n$ were needed just for running Hydrus, but they were irrelevant for determining the $i_{sr-hy}$. The initial condition (field capacity based on Twarakav proposition) is irrelevant as well. The water retention curve parameters affect the shape of infiltration rate curves until the onset of steady infiltration rate and the time infiltration rate become steady. For not estimating inconsistent shaped infiltration rate curves, we estimated the $\theta_s$, $\theta_r$, $\alpha$, and $n$ parameters according to the texture and bulk density of each horizon, using the software Rosetta. However, Hydrus was used to solve a specific problem in our study: to estimate the steady vertical flow in a saturated, layered soil column. Thus, $i_{sr-hy}$ was our target. In this case, $K_s$ was the mandatory parameter, and $K_s$ was measured in all soil profiles and horizons.

Values of $i_{sr-hy}$ and $i_{sr-dr}$ were compared, and their difference was considered an estimate of the lateral flow contained in $i_{sr-dr}$. The effect of soil horizons on $i_{sr-dr}$ was tested by analysis of variance. Tukey test was used to identify significant differences in the means of $i_{sr-dr}$, considering $p<0.05$.

### RESULTS

#### Profile characterization

The E horizons had a lower clay content (about 0.10 kg kg$^{-1}$) than the A horizon (about 0.20 kg kg$^{-1}$) (Table 1). A large increase in clay content (increasing to 0.63 kg kg$^{-1}$) and a decrease in sand and silt contents is observed in the B horizon. These differences in texture implied in step transitions in the profile permeability when the saturation front entered the E and B horizon, as shown in the next sections. The low $K_s$ of the E horizons indicates a restriction on water entering from the A horizons (Table 1). The E horizons are sandy, which could suggest a higher permeability, but their total porosity (TP) was lower, and bulk density (BD) was higher than that of the B horizon and E$_2$. Also, their $K_s$ was lower than in the A$_1$ horizon, where $K_s$ was much higher than in any of the other horizons. According to the standard deviation, variability in TP and BD was low in each horizon, and they did not correlate clearly with $K_s$.

#### Quasi-steady infiltration rate of infiltration curves measured with DRI

The quasi-linear slope of the end of measured cumulative infiltration curves corresponds to the quasi-steady infiltration rate $i_{sr-dr}$, which normally occurred after one to two hours, but earlier in some of them (Figure 1). Empirical infiltration models were not fitted because

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Layer</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>$K_s$ (mm h$^{-1}$)</th>
<th>BD (Mg m$^{-3}$)</th>
<th>TP (m$^3$ m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A$_1$</td>
<td>0.00-0.20</td>
<td>0.18</td>
<td>0.16</td>
<td>0.66</td>
<td>136 ± 175</td>
<td>1.59 ± 0.06</td>
<td>0.37 ± 0.04</td>
</tr>
<tr>
<td>A$_2$</td>
<td>0.20-0.43</td>
<td>0.21</td>
<td>0.18</td>
<td>0.61</td>
<td>9 ± 5</td>
<td>1.65 ± 0.09</td>
<td>0.35 ± 0.03</td>
</tr>
<tr>
<td>A$_3$</td>
<td>0.43-0.64</td>
<td>0.19</td>
<td>0.19</td>
<td>0.62</td>
<td>36 ± 21</td>
<td>1.60 ± 0.07</td>
<td>0.39 ± 0.05</td>
</tr>
<tr>
<td>E$_1$</td>
<td>0.64-0.86</td>
<td>0.12</td>
<td>0.24</td>
<td>0.64</td>
<td>10 ± 9</td>
<td>1.73 ± 0.02</td>
<td>0.36 ± 0.02</td>
</tr>
<tr>
<td>E$_2$</td>
<td>0.86-1.12</td>
<td>0.10</td>
<td>0.26</td>
<td>0.64</td>
<td>4 ± 2</td>
<td>1.84 ± 0.06</td>
<td>0.34 ± 0.04</td>
</tr>
<tr>
<td>B</td>
<td>1.12+</td>
<td>0.63</td>
<td>0.10</td>
<td>0.27</td>
<td>4 ± 3</td>
<td>1.55 ± 0.06</td>
<td>0.42 ± 0.02</td>
</tr>
</tbody>
</table>
$i_{sr-dr}$ was calculated as average infiltration rate of the five final measurements. Despite the high variability between replication, a notable decrease in the slope of cumulative infiltration curves occurred in curves of $E_1$ and $B$ horizons.

The average value of infiltration rate of the five final measurements of each infiltration curve, considered an estimate of $i_{sr-dr}$ of each plot, is shown in figure 2. The average values $i_{sr-dr}$ of horizons were statistically different according to the Tukey test ($p = 0.05$). At the top of the $A_1$ horizon, $i_{sr-dr}$ was an order of magnitude higher than at the top of the $E_1$ and $B$ horizons (Figure 2).

Quasi-steady infiltration rate of infiltration curves simulated with Hydrus-1D

The nine infiltration rate curves simulated with Hydrus-1D decreased exponentially toward a steady rate, $i_{sr-hy}$, observed between 7 and 23 h in all simulations (Figure

Figure 1. Cumulative infiltration rate versus time measured with a double ring infiltrometer at the top of $A_1$, $E_1$, and $B$ horizons of nine plots of a Typic Paleudult.
The highest \( i_{sr-hy} \) (10 mm h\(^{-1}\)) was 50% of \( i_{sr-dr} \) of the B horizon (20 mm h\(^{-1}\)), and about 4% of \( i_{sr-dr} \) of the A\(_1\) horizon (236 mm h\(^{-1}\)). An abrupt decrease of the infiltration rate in some curves indicates a restriction to water flow after the saturation front entered the horizons with lower permeability (E and B) (Table 1). To evaluate the advance of the wetting front, the abrupt change from initial to saturated water content in E and B horizons was shown for the soil profile with the lowest water flow when completely saturated (line converging to \( i_{sr-hy} \) of 0.6 mm h\(^{-1}\) in figure 3a).

Figure 2. Steady infiltration rate measured with a double ring infiltrometer (\( i_{sr-dr} \)) at the top of A\(_1\), E\(_1\), and B horizons in nine plots of a TYPIC Paleudult. Small circles represent individual measurements, larger circles the average value per horizon.

Figure 3. Infiltration rate simulated by Hydrus-1D for all plots and the average of \( i_{sr-dr} \) measured with double-ring infiltrometer at top of A\(_1\) and B horizons (a); the upper and lower colored lines correspond to the soil profile less and more restrictive to water infiltration. Water content simulated by Hydrus-1D at different depths along time (b).
when the entire profile reached saturation (Figure 3b), eliminating the pressure head of -1.13 m (corresponding to the initial water content) acting on the wetting front within the B horizon.

**DISCUSSION**

The average value of $i_{sr-dr}$ in the A$_1$ horizon was higher than in the deeper horizons (Figure 2). This result and the differences of $K_s$ values in the soil profile (Table 1) show that the soil profiles have a more permeable section overlying a less permeable one, which is a layered condition favorable to test our hypothesis. It seems not to be plausible to attribute the high difference of $i_{sr-dr}$ in the A$_1$ horizon when compared to the E$_1$ and B horizons ($\Delta i_{sr-dr} = 216$ mm h$^{-1}$) to factors other than the occurrence of lateral flow in the soil profile (Figure 2). In other words, it is reasonable to assume that $i_{sr-dr}$ measured on top of A$_1$ horizon largely overestimated the vertical flow in the soil profile. These results are part of the evidences supporting our hypothesis that $i_{sr-dr}$ measured on the soil surface with DRI may contain a significant amount of lateral flow.

Further support to our hypothesis was provided by the Hydrus-1D simulations (Figure 3). A boundary condition for Hydrus-1D simulations is that its steady infiltration rate, $i_{sr-hy}$ in a saturated soil profile is the saturated vertical flow given by Darcy equation $i_{sr-hy} = q = -K_s \frac{dH}{dx}$, which is the solution of equation 1 for a saturated media (Šimůnek et al., 2005). In a saturated media, the parameter governing water flow is $K_s$. The lowest values of $K_s$ occurred in the E$_2$ and B horizons (Table 1), which caused some step-decrease in infiltration rate curves (Figure 3a) when the saturation front entered these horizons (Figure 3b). Thus, the range of $i_{sr-hy}$ from 0.6 to 10.2 mm h$^{-1}$ (Figure 3a) is in agreement with the $K_s$ range of 4 ± 3 mm h$^{-1}$ in the B horizon (Table 1), and simulated $i_{sr-hy}$ seems consistent. All estimated $i_{sr-hy}$ were lower than the measured $i_{sr-dr}$, which shows that lateral flow in DRI tests must have occurred in all horizons. In the A$_1$ horizon, the magnitude of lateral flow was at least 226 mm h$^{-1}$.

Although the duration of DRI measurements (between 1.0 and 1.75 h) was different and much shorter than the duration of Hydrus-1D simulation (30 h), the target information in DRI tests is the quasi-steady infiltration rate (Reynolds et al., 2002). Frequently, this target is achieved in DRI tests with a duration shorter than 3.5 h (Uloma et al., 2014; Cunha et al., 2015; Silva et al., 2017; Aboukarima et al., 2018; Zhang et al., 2019). Furthermore, the verification of saturation of the soil profile when infiltration rate approaches quasi-steady rate flow is not mandatory. Taking these considerations into account, the target $i_{sr-dr}$ as a flow rate that tends to a quasi-steady flow rate was satisfactorily met in our experiment (see the quasi-linear slope at the end of the measured cumulative infiltration curves shown in figure 1). Then, even considering long duration infiltration measurements in field conditions in which an additional small reduction in $i_{sr-dr}$ might be observed, the estimated lateral flow would not significantly change.

Our results indicated that $i_{sr-dr}$ is an estimate of vertical flow that could be highly biased by the lateral flow. It is plausible to suppose that the increase in $i_{sr-dr}$ observed in several studies may be caused by an increased lateral flow rather than by an increase in vertical flow. For example, the frequently detected increase in $i_{sr-dr}$ when soil hydraulic properties are changed only in the topsoil, like when changing from conventional to no-till management (Santos et al., 2016; Alhameid et al., 2020), revolving the soil surface by fertilizer shanks (Drescher et al., 2016) and chisels (Camaro and Klein, 2005; Prando et al., 2010; Drescher at al., 2016), improvement of bioporosity by the root system (Pagliai, 1993; Azooz and Arshad, 1996; Cessa et al., 2014; Fernández et al., 2019), and reducing animal trampling in integrated crop-livestock systems (Bonetti et al., 2019), is likely a DRI measurement artifact, effect of an increase in lateral flow in the ameliorated topsoil horizon. Although a large $i_{sr-dr}$ at the soil surface favors infiltration in the ameliorated topsoil horizon until
it becomes saturated, the vertical flow after saturation of the more permeable surface layer should be lower than \( i_{sr-dr} \).

The measured value of \( i_{sr-dr} \) at the surface is frequently considered to be the effective saturated hydraulic conductivity of the soil profile, \( K_e \) (Bouwer, 1986; Reynolds et al., 2002; Bodhinayake et al., 2004). Our results show that this assumption is prone to be highly inaccurate. As a practical consequence, the purpose with projects based on \( K_e \) like drainage systems (Stovin et al., 2015) or floodwater containment terraces (Kovář et al., 2016) could not be attained if the \( i_{sr-dr} \) used for designing these systems were an inaccurate estimate of \( K_e \).

Our results suggest that \( i_{sr-dr} \) may not be considered the lower limit of soil infiltration capacity in the vertical direction nor the upper limit of precipitation rate that will not cause runoff. Hydrus-1D simulations suggested these limits may be much lower than \( i_{sr-dr} \). Using a hydrologic model based on the Richards equation to estimate the lower limit of soil infiltration capacity is a more reliable strategy than using double ring infiltrometer measurements. The latter could be used to compare the effects of soil use and management on the permeability of the surface horizons, but \( i_{sr-dr} \) is not a reliable measurement to assess saturated vertical flow in the entire soil profile.

**CONCLUSIONS**

A significant amount of lateral flow occurs during infiltration rate measurements with a double ring infiltrometer (\( i_{sr-dr} \)) at the soil surface with underlying horizons with lower permeability. In the soil used in this study, 9 of every 10 mm h\(^{-1}\) of \( i_{sr-dr} \) at the soil surface represented lateral flow.

Consequently, in layered soil profiles in which the less permeable layer is located below the surface layer, \( i_{sr-dr} \) contains a significant amount of lateral flow and overestimates the effective saturated hydraulic conductivity of the soil profile. Hence, the use of this \( K_e \) would imply in inaccurate drainage, irrigation, and soil conservation designs.

Further studies comparing infiltration rate measurements from any technique with the saturated steady vertical flow rate estimated using the Richards equation would be useful to understand to what extent the measurements of infiltration are biased by natural and anthropic profile layering factors.

**ACKNOWLEDGEMENT**

This study was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) – Finance code 001.

**AUTHOR CONTRIBUTIONS**

Conceptualization:  
- Daniel Boeno (equal),  
- Paulo Ivonir Gubiani (equal), and  
- Quirijn de Jong Van Lier (equal).

Investigation:  
- Daniel Boeno (equal) and  
- Paulo Ivonir Gubiani (equal).

Methodology:  
- Daniel Boeno (equal).

Supervision:  
- Paulo Ivonir Gubiani (lead).

Writing - original draft:  
- Daniel Boeno (equal).

Writing - review & editing:  
- Paulo Ivonir Gubiani (equal),  
- Quirijn de Jong Van Lier (equal), and  
- Rodrigo Pivoto Mulazzani (equal).
REFERENCES


