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The effect of sorptivity on cumulative infiltration

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ABSTRACT

Hydraulic parameters of the soil play a considerable role in the hydrological cycle, irrigation planning, drainage, groundwater recharge, and water resources management. One of the most important hydraulic parameters of the soil is sorptivity (S), yet there is insufficient research on how it affects the mechanism of infiltration. The main scope of this study is to investigate the effect(/significance) of sorptivity on the mechanism of infiltration of water, through various types of soil medium, from both mathematical and experimental perspectives. For this scope, the absolute sensitivity analysis factor of sorptivity was obtained, while two experimental procedures were carried out in the laboratory. Each soil sample was packed into a vertical column, while a constant head of 2 mm was applied at the surface of the soil. The incoming water was measured volumetrically and at the same time, soil moisture, at certain locations, was measured using the TDR method. Sorptivity of each soil was calculated using Parlange's equation. Absolute sensitivity analysis factor of sorptivity showed that for a longer duration/period of cumulative infiltration, sorptivity strongly affects the phenomenon the more synectic the soil type. Thus, estimating sorptivity of the soil could lead to better solutions for irrigation planning, flood prediction and water saving.

Key words | cumulative infiltration, diffusivity, soil column, sorptivity

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HIGHLIGHTS

- Three soil samples sand (S), sandy loam (SL) and loamy sand (LS) were used.
- Hydraulic conductivity at saturation of each soil was measured in the laboratory.
- Large time of cumulative infiltration influences the sorptivity.
- Equations of diffusivity (D) were obtained using using analytical and arithmetic methods.

INTRODUCTION

Infiltration is the vertical movement of water from the surface of the earth into the soil mass through the pores of the soil, while cumulative infiltration is the total amount of water that crosses the soil surface. Hydraulic parameters of the soil play a considerable role in the hydrological cycle, irrigation planning, drainage, groundwater recharge, dam and all water-related agricultural and hydrological studies. It is crucial to estimate the hydraulic parameters of the soil, because of their importance in the above procedures. Cumulative infiltration (I) is a variable that is affected by soil sorptivity (S) and hydraulic conductivity at saturation (K_s). Sorptivity (S) is a soil characteristic to sustain water, due to capillary forces, and it is a function of the initial soil moisture and the applied boundary condition. Sorptivity is one of the most important hydraulic parameters, which affects infiltration as it is included in most infiltration models, yet there is insufficient research in this field of hydraulics.

Many researchers have worked on sorptivity equations or on ways to estimate soil sorptivity. Philip (1957a, 1957b, 1957c, 1958, 1969) was the first researcher who introduced

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sorptivity as a new parameter in the infiltration equation that he derived, using soil moisture profiles. Afterwards, many researchers showed an interest and worked on this subject and various equations of sorptivity were extracted. Dirksen (1975) proposed the use of an experimental setting (USD) to estimate soil sorptivity in the field. Later, this method was improved by Clothier & White (1981) to estimate diffusivity as well. Bouwer (1976) considered that soil sorptivity depends on two elements: soil structure and initial soil moisture. Youngs (1981) derived an equation for estimating sorptivity, according to which sorptivity depends on hydraulic conductivity as well as initial soil moisture. Chong & Green (1983) compared various methods of estimating soil sorptivity and showed that the relation between sorptivity and initial soil moisture is nonlinear. Poulovassilis et al. (1989) extracted an equation of sorptivity and introduced the time-variant sorptivity (S(t)). Minasny & McBratney (2000) estimated soil sorptivity with the aid of a parameter. They also used Philip's equation for the early times of infiltration. Argyrokastritis & Kerkides (2003) developed a simplified equation for the sorptivity equation that comes from the Poulovassilis et al. (1989) proposal. They showed that one can simplify the Poulovassilis equation by eliminating one of the parameters, without losing its applicability. Zhou (2014) found that initial diffusivity is proportional to the square of the ratio of sorptivity to the water content difference between saturated and initial states, using Boltzman transformation. Latorre et al. (2015) found, under field conditions, a new numerical procedure (NSH) to estimate the soil sorptivity from the cumulative infiltration curve obtained by a disc infiltrometer using the analytical equation developed by Haverkamp et al. (1994). Alagna et al. (2016) tested via the infiltrometer method factors such as initial soil water content, the height from which water is poured onto the soil surface, and the duration of the infiltration run and showed that sorptivity was less affected by the thickness of the soil medium through which water is pouring in since this property depends more than K_s on the soil matrix, which does not change with the water application procedure. Moret-Fernández et al. (2017) compared five different methods to estimate S from a single upward infiltration curve and found that the complete-time (CIM) upward infiltration method that uses the quasi-analytical Haverkamp et al. (1994) function was the most accurate method to estimate S in both clean and noised theoretical and experimental upward infiltration curves. Their research demonstrated that the simplest Philip (1957a, 1957b, 1957c) equation for infiltration allows good approaches of S, and the CIM procedure, which calculates S from the best fitting between the experimental upward infiltration and the quasi-exact Haverkamp et al. (1994) model, allowed the best estimation of S for all types of soils.

Recently, several researchers used soft computing techniques for the prediction of infiltration rate and cumulative infiltration and compared the outcomes with conventional models (Mishra et al., 2003; Vand et al., 2018). Angelaki et al. (2018) used the Support Vector Machine (SVM), artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) to estimate the cumulative infiltration of soil. Results showed the superiority of ANFIS among other models, while sensitivity results suggest that time (t) is the most effective parameter for the particular modelling methods that were used. Sihag et al. (2019) used adaptive neuro-fuzzy inference system (ANFIS), support vector machine (SVM) and random forest (RF) models to determine cumulative infiltration and infiltration rate in arid areas in Iran. Comparison of these models showed that the C10 SVM_RBF model, with the combination of time, sand, clay, silt, soil density and soil moisture, could estimate cumulative infiltration with much less error than the other models. The results of the performance assessment showed that the M4 SVM_RBF model, with the combination of time, sand and soil density, performed better than other models for estimating infiltration rate. Quaintly, although infiltration is a significant procedure, there is a vacuum regarding how specific hydraulic parameters, such as sorptivity, depend on soil structure and affect the phenomenon.

Absolute sensitivity analysis factor of S

Philip (1958, 1969) derived Equation (1) of sorptivity using soil moisture profiles. In this equation, K_s is hydraulic conductivity at saturation, θ_o is initial soil moisture, θ_1 is the applied boundary condition, H_o is the pressure head on the soil surface and H_f is active suction at the wet head.

$$S^2 = 2K_s(\theta_1 - \theta_0)(H_0 - H_f) \quad (1)$$

Sorptivity can also be estimated experimentally using Equation (2) (Philip 1969):

$$I = St^{1/2} \tag{2}$$

where S is sorptivity of soil, I is cumulative infiltration and t is time. Equation (2) is valid for very small times, when infiltrability is high and gravity forces have not yet been active.

Parlange (1975) gave Equation (3), which leads to an optimum value of soil sorptivity,

$$S^2 = \int_{\theta_i}^{\theta_s} (1+\theta)D(\theta)d\theta, \tag{3}$$

where θ is soil moisture and $D(\theta)$ is diffusivity.

Parlange (1971a, 1971b, 1972, 1975) also derived a cumulative infiltration model, which is:

$$K_s t = I + \frac{S^2}{2K_s}\left[\exp\left(-\frac{2K_s}{S^2}I\right) - 1\right] \tag{4}$$

Equation (4) includes two parameters: soil sorptivity (S) and hydraulic conductivity at saturation (K_s). In this study, the main objective of the research is to determine soil sorptivity, which affects cumulative infiltration in different soil types.

Vauclin & Haverkamp (1985) gave Equation (5) to estimate sorptivity:

$$S^2 = 2\int_{\theta_i}^{\theta_s} \theta D(\theta)d\theta \tag{5}$$

Mualem (1976) and Mualem & Dagan (1978) gave a prediction model (Equation (6)) to estimate characteristic curves of a soil.

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1+(\alpha\psi)^n]^m}, \tag{6}$$

where θ is soil moisture, ψ is suction, θ_r is residual moisture and θ_s is soil moisture at saturation. Also a, m, n are parameters and $m = 1 - 1/n$, $0 < m < 1$.

Diffusivity of soil can be estimated by the equation below:

$$D(\theta) = -\frac{K(\theta)}{C(\theta)}, \tag{7}$$

where:

$$K(\theta) = K_s\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{1}{2}}\left\{1-\left[1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{1}{m}}\right]^m\right\}^2 \tag{8}$$

$K(\theta)$ is hydraulic conductivity and $C(\theta)$ is a specific water capacity, which is equal to:

$$C(\theta) = \frac{d\theta}{d\psi} \tag{9}$$

Parlange infiltration Equation (4) can be written as below:

$$I = K_s t - \frac{S^2}{2K_s}\left[\exp\left(-\frac{2K_s}{S^2}I\right) - 1\right] \tag{10}$$

Setting $S^2 = \alpha$, Equation (10) becomes:

$$I = K_s t - \frac{\alpha}{2K_s}\left[\exp\left(-\frac{2K_s}{\alpha}I\right) - 1\right] \tag{11}$$

The derivative of Equation (11) functional to S^2 is:

$$\begin{aligned}\frac{\partial I}{\partial \alpha} &= -\frac{\partial}{\partial \alpha}\left\{\frac{\alpha}{2K_s}\left[\exp\left(-\frac{2K_s}{\alpha}I\right)-1\right]\right\} = \\ &-\left\{\frac{1}{2K_s}\left[\exp\left(-\frac{2K_s}{\alpha}I\right)-1\right]+\frac{\alpha}{2K_s}\frac{\partial}{\partial\alpha}\left[\exp\left(-\frac{2K_s}{\alpha}I\right)-1\right]\right\} = \\ &-\frac{1}{2K_s}\left\{\left[\exp\left(-\frac{2K_s}{\alpha}I\right)-1\right]+\alpha\frac{\partial}{\partial\alpha}\left[\exp\left(-\frac{2K_s}{\alpha}I\right)-1\right]\right\}\end{aligned} \tag{12}$$

The second provision of the above sum is

$$\frac{\partial}{\partial\alpha}\left[\exp\left(-\frac{2K_s}{\alpha}I\right)-1\right]=\exp\left(-\frac{2K_s}{\alpha}I\right)\frac{\partial}{\partial\alpha}\left(\frac{-2K_sI}{\alpha}\right)=$$
$$\exp\left(-\frac{2K_s}{\alpha}I\right)\left[-2K_s\frac{\partial}{\partial\alpha}\left(\frac{I}{\alpha}\right)\right]=\exp\left(-\frac{2K_s}{\alpha}I\right)(-2K_s)\frac{\frac{\partial I}{\partial\alpha}\alpha-I}{\alpha^2} \tag{13}$$

Using Equation (13), Equation (12) becomes:

$$\frac{\partial I}{\partial\alpha}=\frac{-\alpha\exp\left(-\frac{2K_s}{\alpha}I\right)+\alpha-2K_sI\exp\left(-\frac{2K_s}{\alpha}I\right)}{2K_s\alpha\left[1-\exp\left(-\frac{2K_s}{\alpha}I\right)\right]} \tag{14}$$

Replacing α with S^2, Equation (14) can be written:

$$\sigma=\sigma(S^2)=\frac{\partial I}{\partial S^2}=\frac{-S^2\exp\left(-\frac{2K_s}{S^2}I\right)+S^2-2K_sI\exp\left(-\frac{2K_s}{S^2}I\right)}{2K_sS^2\left[1-\exp\left(-\frac{2K_s}{S^2}I\right)\right]} \tag{15}$$

Equation (15) is named absolute sensitivity analysis factor of S parameter [$\sigma=\sigma\ (S^2)$]. Dividing Equation (15) with 2 K_sS^2:

$$\sigma=\sigma(S^2)=\frac{\partial I}{\partial S^2}=\frac{-\frac{1}{2K_s}\exp\left(-\frac{2K_s}{S^2}I\right)+\frac{1}{2K_s}-\frac{I}{S^2}\exp\left(-\frac{2K_s}{S^2}I\right)}{1-\exp\left(-\frac{2K_s}{S^2}I\right)} \tag{16}$$

Setting $a=\frac{1}{2K_s}$, $b=\frac{I}{S^2}$, $\frac{b}{a}=\frac{2K_sI}{S^2}$, Equation (16) becomes:

$$\sigma=\sigma(S^2)=\frac{a-(a+b)e^{-b/a}}{1-e^{-b/a}} \tag{17}$$

Postulating that $S^2\to 0$, then: $b\to\infty$, $e^{-b/a}\to 0$, so the limit of absolute sensitivity analysis factor is:

$$\lim_{S^2\to 0}\sigma=\alpha=\frac{1}{2K_s}, \tag{18}$$

so absolute sensitivity analysis factor is equal to a finite value when soil sorptivity converges to zero.

Postulating that: $S^2\to\infty$, then: $b\to 0$, $e^{-b/a}\to 1$ and the limit of σ is:

$$\lim_{S^2\to\infty}\sigma=\frac{0}{0} \tag{19}$$

and

$$\lim_{S^2\to\infty}\sigma=\left(\frac{a-(a+b)e^{-b/a}}{1-e^{-b/a}}\right)'=\frac{-e^{-b/a}+(1/a)(a+b)e^{-b/a}}{(1/a)e^{-b/a}}=\frac{1-1}{1/a}=0 \tag{20}$$

so the absolute sensitivity analysis factor is zero when soil sorptivity converges to infinity (Angelaki *et al.* 2013).

MATERIALS AND METHODS

At first, a transparent column with an inner diameter of 6 cm was used in order to accomplish three separate cumulative infiltration experiments in the laboratory. The bottom of the column was supported by a geotextile with hydraulic conductivity at saturation greater than that of the soil samples.

Each soil sample column was packed uniformly, using a soil raining method with free-falling soil passing through a sequence of sieves before reaching the surface of the soil body. This is an easy method in order to achieve good homogeneity of the soil column, which was checked by gamma-rays. Also, measuring soil moisture at several depths of the soil at saturation is a good way to confirm homogeneity of porosity. Figure 1 shows the cumulative infiltration experimental setting. A constant head boundary condition of about 2 mm was applied on the surface of each soil sample. The cumulative volume of the incoming water was obtained with the aid of two volumetric tubes and at the same time TDR unit was used in order to measure the water content at four locations of the column (where the TDR waveguides had been inserted).

In order to estimate soil sorptivity, a second experimental setting of upward infiltration was used (Figure 2). The soil

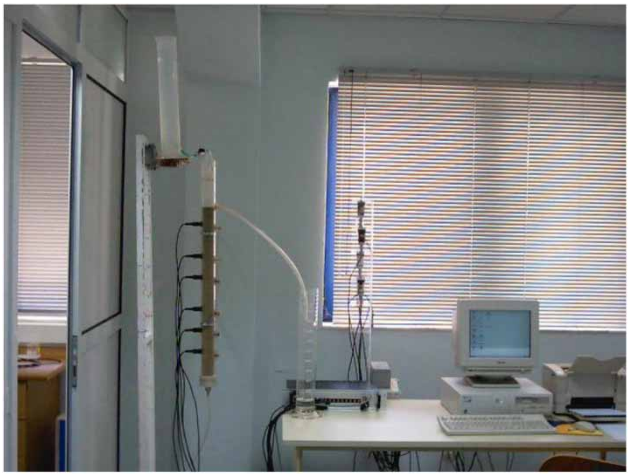

Figure 1 | The first experimental setting. (cumulative infiltration with ∼2 mm head boundary condition).

Figure 2 | The second experimental setting (upward infiltration).

column was wetted by the bottom via a Marriotte bottle and the soil moisture was measured using TDR, while water suction was measured via a ceramic capsule connected to a pressure transducer. This 'upward infiltration' method was obtained in stages, and via this method air trapping is avoided. Air trapping is a common problem that leads to 'noise' while measuring water suction. Three soil samples were used (sand (S), sandy loam (SL) and loamy sand (LS)) in both experiments. Hydraulic conductivity at saturation of each soil was measured in the laboratory, using the constant head method. The three values of K_s of each soil sample are shown in Table 1.

Table 1 | Hydraulic conductivity at saturation for the three soil samples

	S	SL	LS
K_s (cm/min)	0.9721	0.1027	0.2265

RESULTS AND DISCUSSION

Table 1 shows the measured values of hydraulic conductivity at saturation for the three soil samples.

Parameters *a*, *m* and *n* of Mualem–Van Genuchten's model (Equation (6)) were estimated using experimental points of the 2nd infiltration for each soil sample (second experimental setting) and RETC model. Table 2 shows the values of the parameters for the three soil types.

Using Equations (6)–(9) and the values of Table 2, the diffusivity of each soil sample versus soil moisture was figured (Figures 3–5). The points of the above figures were approximated by exponential equations, shown in Table 3.

Using Parlange's Equation (3) sorptivity was estimated, for all soil samples. Integrals of Equation (3) did not lead to analytical solutions for the equations of diffusivity of sandy (S) and sandy loam (SL) soil samples. Arithmetic methods (trapezoidal and 1/3 Simpson) were applied in order to solve the integrals. Equation of diffusivity of loamy sand (LS) led to the analytical solution of Equation (3). Table 4 shows the values of the estimated soil sorptivity of the three soil samples using analytical and arithmetic methods.

At the very early times of infiltration, capillary forces affect infiltration the most. Gravity forces act at larger times of infiltration, but the exact time depends on hydraulic properties of the soil. The main aim of this research was to investigate the effect/significance of sorptivity on cumulative infiltration at longer time duration of the phenomenon.

Table 2 | Parameters of Van Genuchten's model estimated using RETC model

	S	SL	LS
θ_s	0.24835	0.38182	0.28349
θ_r	0.10444	0.33585	0.19872
a	0.15041	0.16246	0.09180
n	4.91828	2.43972	2.59427
m	0.79667	0.59012	0.61454
R^2	0.9983	0.983299	0.969418

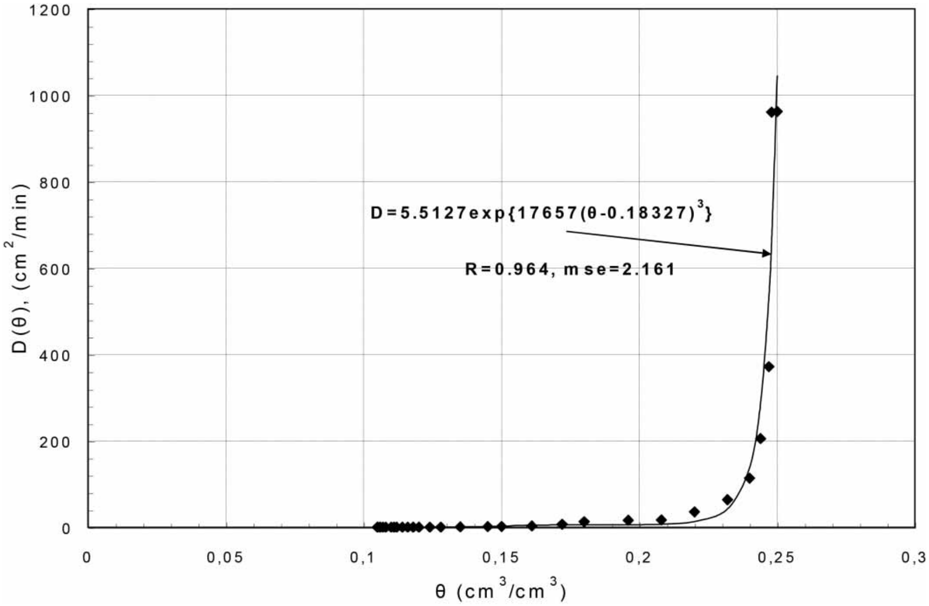

Figure 3 | Diffusivity versus soil moisture – sandy soil (S).

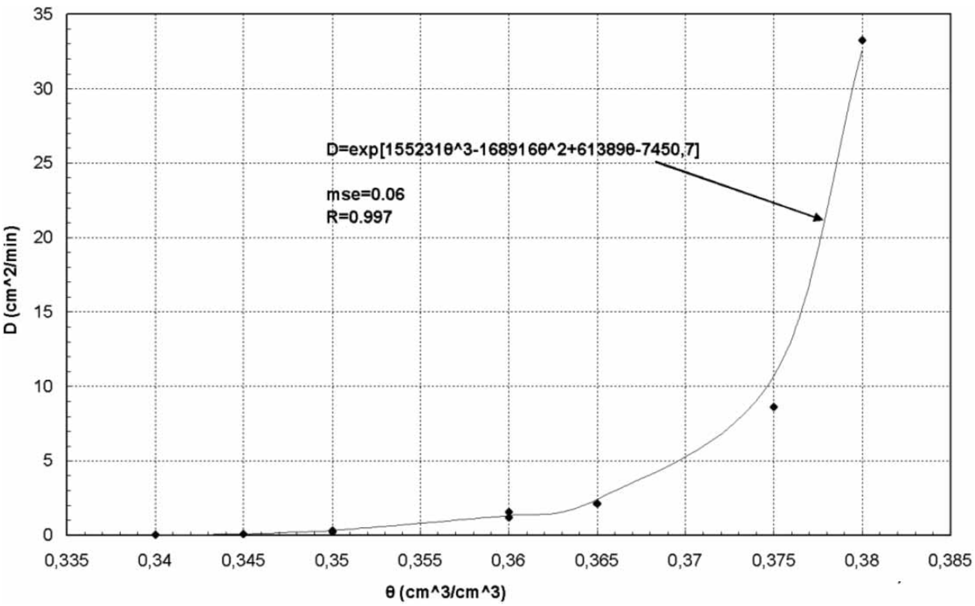

Figure 4 | Diffusivity versus soil moisture – sandy loam soil (SL).

The absolute sensitivity analysis factor of sorptivity for the three soil samples was performed, by inserting in Equation (16) the values of hydraulic conductivity at saturation (K_s) and sorptivity (S) (Tables 1 and 4), in longer time durations of cumulative infiltration. The curves of the absolute sensitivity analysis factor versus sorptivity squared are shown in Figures 6–8. The value of S^2 of each soil has been pointed out by arrows. Absolute sensitivity analysis factor of sorptivity is about 0.46, 4.6 and 2.1 for sand (S), sandy loam (SL) and loamy sand (LS) respectively. Absolute

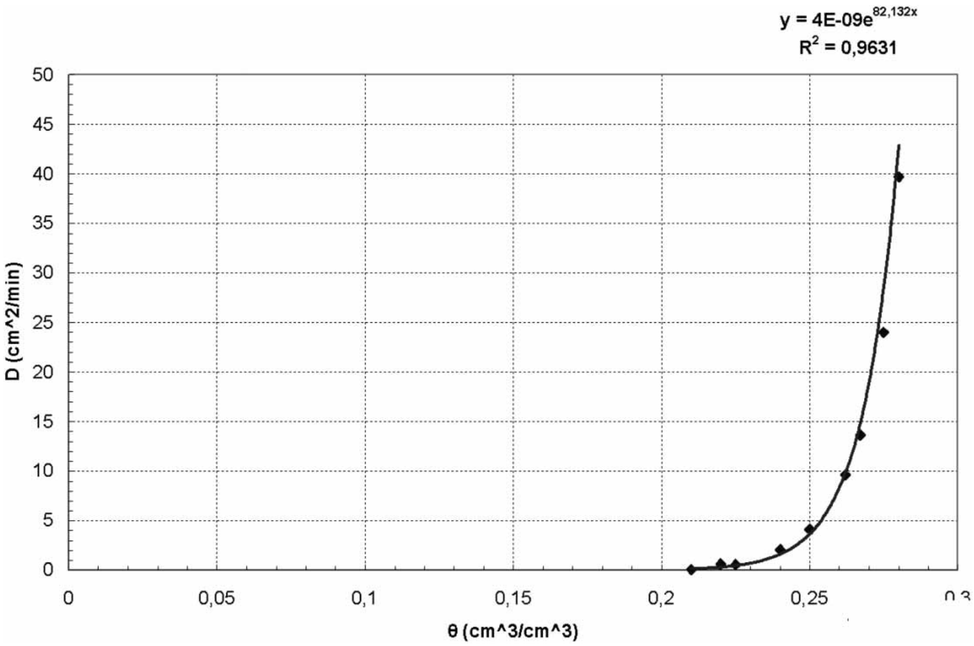

Figure 5 | Diffusivity versus soil moisture – loamy sand soil (SL).

Table 3 | Equations of diffusivity

	D(θ)
S	$D = 5.5127\exp\{17657(\theta - 0.18327)^3\}$
SL	$D = \exp[1552310^3 - 1689160^2 + 613890 - 7450.7]$
LS	$D = 4{\cdot}10^{-9}\exp(82.132\theta)$

Table 4 | Optimal sorptivity values estimated using Equation (3)

	S	SL	LS
S_{opt} (cm/min$^{1/2}$)	2.64	0.48	0.77

sensitivity analysis factor of sorptivity of sandy loam (SL) soil is twofold and more than loamy sand (LS) and it is tenfold that of sand (S). On the other hand, the converse is equally valid in the relationship between various hydraulic conductivities at saturation. Referring to the values of the absolute sensitivity analysis factor of sorptivity, it is clear that at longer time durations of cumulative infiltration, sorptivity is a significant parameter that strongly affects cumulative infiltration, which is further dependent on soil and its types. Thus, in soils with decreased hydraulic conductivity at saturation, capillary forces act not only at the very early times of cumulative infiltration but at large times as well, while sorptivity is a parameter which strongly affects the phenomenon.

CONCLUSIONS

The main objective of this study was to research the effect of sorptivity (S) in its mechanism of cumulative infiltration. For this purpose, the results of two laboratory experimental procedures for three soil samples were performed. Equations of diffusivity (D) were obtained, which led to the estimation of sorptivity (S) for each soil sample, using analytical and arithmetic methods. Absolute sensitivity analysis factor of sorptivity was performed, further demonstrating that at longer time duration of cumulative infiltration sorptivity affects to a larger extent the more synectic the soil type. In addition, results showed that the absolute sensitivity analysis factor of soil sorptivity is equal to a finite value when soil sorptivity converges to zero. This value is inversely proportional to 2 K_s. Also, the absolute sensitivity analysis factor of soil sorptivity is zero, when soil sorptivity converges to infinity. Absolute sensitivity analysis factor of sorptivity of sandy loam (SL) soil is two-fold and is more than that of loamy sand (LS). It is tenfold that of sandy (S)

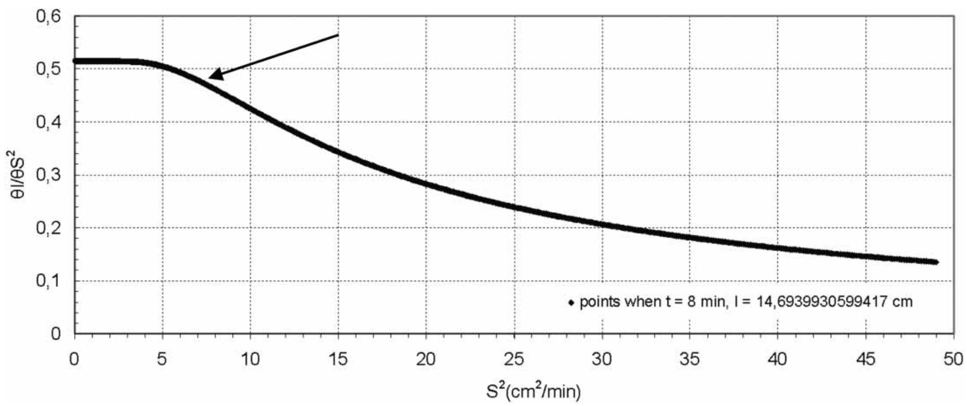

Figure 6 | Absolute sensitivity analysis factor of S vs S^2 (Sand – S).

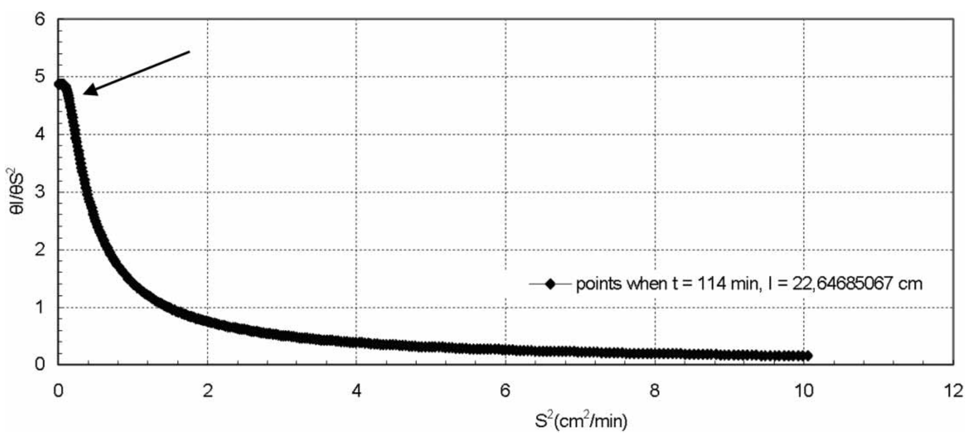

Figure 7 | Absolute sensitivity analysis factor of S vs S^2 (Sandy Loam – SL).

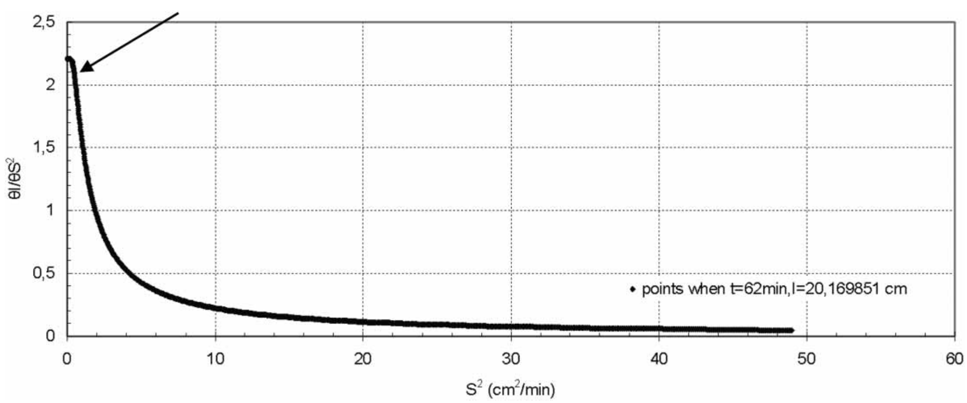

Figure 8 | Absolute sensitivity analysis factor of S vs S^2 (Loamy Sand – LS).

soil when the relationship between hydraulic conductivity at saturation of these soil samples is conversely validated. In conclusion, the knowledge of sorptivity of the soil can be significant, efficient and affects the mechanism of infiltration. Thus, this can lead to better irrigation planning, flood prediction and water saving.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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