

Analysis of Saturation Risk in Sprinkler Irrigation: Case of Cherfech Irrigation Perimeter in Tunisia

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Abstract

This study is targeted to the assessment of the saturation risk in sprinkler irrigation. For this purpose, in situ field trials were carried out to infer the saturated hydraulic conductivity (K_s) and sorptivity (S) using the disc infiltrometer method. Since the measured values of K_s are very close to prescribed application rate, caution is required. In a first step, the pressure head at the wetting front (h_f) and the useful porosity ($\theta_s - \theta_i$) are assumed to be constant. Thus, the logarithmic derivation of the sorptivity provides a relation between relative variations of S and K_s . The ponding time (T_s) is estimated from Green and Ampt (1911) and Philip (1957b) infiltration equations. The risk of saturation is deemed to be inexistent inasmuch as simulated values of T_s are greater than the irrigation times practiced in the zone. In a second step, the values of the pressure head at the wetting front and saturated water content were assumed to be variable with soil texture. Simulations of the ponding time were carried out based on Rawls and al. (1981) data. For the recommended sprinkler spacing in the Cherfech perimeter (12 m \times 12 m), the simulations show a good agreement between T_s values generated from Green and Ampt and Philip equations for K_s ranging from 1.5 to 6 mm/h. Moreover, it was established that saturation risk due to a gradual texture variation is virtually inexistent in the conditions prevailing in Cherfech perimeter.

Keywords: Saturated hydraulic conductivity, Infiltration rate, ponding time, Saturation hazard, Sprinkler irrigation

1. Introduction

The fair distribution of water under sprinkler irrigation is a major concern. Irrigation network should be adapted to the soil texture, crop, available water discharge, water quality and environmental conditions. Results of Playan and Mateos (2006) show that the improvement of the irrigation efficiency depends on the appropriate choice of equipment, pedo-climatic conditions, water availability and socio-economic conditions. The assessment of sprinkler irrigation performance was widely analyzed (Merriam & Keller, 1978; Heermann et al., 1990; Keller & Bliensner, 1990; Burt et al., 1997; Pereira, 1999). Tiercelin (1998) and Keller and Bliensner (1990) emphasized that distribution uniformity is a prominent factor in the design and management of sprinkler irrigation systems. The unfair water distribution induces harmful impact on crop yield and environment. Indeed, under irrigation may induce crop yield reduction and soil salinization. Conversely, excess of irrigation may induce crop yield reduction by asphyxia as well as a leaching of fertilizers and pesticides. Solomon (1983) indicated that water stagnation and runoff has a prejudicial impact on soil and crop.

Angulo-Jaramillo et al. (2000), and Trout and Kinkacid (1987) indicated that soil water characterization is of *prima facie* importance for designing irrigation systems and modeling water movement within the soil. Li and al. (1976) stressed that the determination of the infiltration rate is essential for designing sprinkler irrigation systems. This holds true particularly for high infiltration rates and short irrigation periods. Diamond and Thomas (2003) underlined that the determination of the infiltration rate is fundamental for accurate prediction of runoff. Physically sound formulas show that runoff occurs when rainfall intensity exceeds the saturated hydraulic conductivity. In absence of a shallow water table or an underlying substratum, no runoff is expected when rainfall intensity is very low with respect to the saturated hydraulic conductivity. It is established that the higher the rainfall intensity, the shorter the ponding time. The saturation time may be straightforwardly derived from analytical and empirical infiltration equations (Slack, 1980; Broadbridge & White, 1987; Kutilek & Nilsen, 1994;

Parlange et al., 1999; Smith et al., 2002; Assouline et al., 2007). It is worthy to say that the prerequisite knowledge of the ponding time is necessary to overcome the stagnation hazard. This challenge is all the greater as sprinkler irrigation is commonly practiced on fine soils in Tunisia.

This study is devoted to (i) the estimation of the ponding time under sprinkler irrigation, (ii) the analysis of the saturation risk for gradually variable soil texture taking into account the performance of the irrigation system in Cherfech irrigation perimeter.

2. Material and Methods

Field trials were carried out in the experimental station of Cherfech located in the north of Tunisia (latitude 37° N, longitude 10.5° E, altitude 328 m). The irrigation perimeter of Cherfech covers 2022 ha.

2.1 Characterization of the Experimental Site

The climate of the studied zone is semi-arid. It is characterized by a hot summer and moderated and rainy winter. The mean values of annual rainfall and reference evapotranspiration are 443 mm and 1112 mm, respectively. Table 1 summarizes the values of the soil bulk density (ρ_d), volumetric soil water contents at the field capacity and at wilting point (θ_{fc} and θ_{wp}) as well as granulometric fractions over 1 m soil depth.

Table 1. Soil water characteristics and granulometry in Cherfech station

Depth (cm)	ρ_d (g/cm ³)	θ_{fc} (cm ³ /cm ³)	θ_{wp} (cm ³ /cm ³)	Clay (%)	Loam (%)	Sand (%)
0-20	1.48	0.426	0.267	28	53	19
20-40	1.60	0.419	0.260	26	55	19
40-60	1.56	0.423	0.245	22	47	31
60-80	1.51	0.448	0.262	21	52	27
80-100	1.53	0.386	0.262	17	47	36

According to the United States Department of Agriculture [USDA] classification, the soil is a fine loam over the depth 0-40 cm and loamy over the remaining soil depth. The mean electrical conductivity of the water irrigation, supplied by Medjerda Channel, is equal to 2.6 dS/m.

2.2 Determination of the Soil Infiltrability

The infiltration law was established using the infiltrometer disc method (Peroux & White, 1988). Contrariwise to the double ring method of Muntz (Maheshwari, 1996), the disc infiltrometer method has the merit to provide hydraulic conductivity at the saturation and also hydraulic conductivities for very low soil water pressure heads (Coquet et al., 2000). The estimation of K_s by the disc infiltrometer is based on the Wooding (1968) equation:

$$q_{\infty}(h_0) = K(h_0) + \frac{4\Phi(h_0)}{\pi r} \quad (1)$$

where, q_{∞} , h_0 , K , Φ and r refer to the infiltration density rate [LT^{-1}], imposed potential at the soil surface [L], soil water conductivity [LT^{-1}], Kirchhoff potential [L^2T^{-1}] and the radius of the infiltrometer disc [L].

Equation (1) was derived from steady state regime under axisymmetric flow from a surface point source. Assuming that soil water conductivity varies exponentially with soil water pressure head (Gardner, 1958, $K(h) = K_s e^{\alpha h}$), the infiltration density rate may be written as:

$$q_{\infty}(h_0) = K(h_0) \left(1 + \frac{4}{\pi r \alpha}\right) \quad (2)$$

The approach of multi-potential disc infiltrometer developed by Reynolds and Elrick (1991) and by Ankeny et al. (1991) allow the inference of the parameters of $K(h)$ law from the knowledge of two pairs of discharge-soil water pressure head.

$$\begin{cases} Q_{\infty}(h_1) = \pi r^2 K_s e^{\alpha h_1} \left(1 + \frac{4}{\pi r \alpha}\right) \\ Q_{\infty}(h_2) = \pi r^2 K_s e^{\alpha h_2} \left(1 + \frac{4}{\pi r \alpha}\right) \end{cases} \quad (3)$$

The sorptive number α (L^{-1}) is straightforwardly derived from solving the above equation system.

$$\alpha = \frac{\ln[Q_{\infty}(h_2)] - \ln[Q_{\infty}(h_1)]}{h_2 - h_1} \quad (4)$$

The knowledge of α allows the inference of K_s from one equation of equation system (3). At the opposite, the mono-potential method developed by White and Sully (1987) has the advantage to be applicable for only one pair of emitter discharge-soil water pressure head:

$$\Phi(h_0) = \frac{bS^2}{\theta_s - \theta_i} \quad (5)$$

where, S , θ_s and θ_i refer to the soil sorptivity [$L/T^{1/2}$], saturated and initial soil water contents respectively.

The parameter “ b ” depends on the shape of $K(h)$ and $\theta(h)$ curves. According to Warrick and Broadbridge (1992), the value of b ranges from 0.5 to 0.8 and may be assigned to 0.55. Combining Equations (2) and (5) leads to:

$$q_{\infty}(h_0) = K(h_0) + \frac{4bS^2}{\pi(\theta_s - \theta_i)} \quad (6)$$

The soil sorptivity depends on the hydraulic soil diffusivity, initial and saturated water contents. It may be derived from the infiltration law at short times. Indeed, Philip (1957a) established the following infiltration law when water movement is only governed by capillary forces:

$$I(t) = S\sqrt{t} \quad (7)$$

where, I and t refer to the cumulative infiltration and elapsed time, respectively. The saturated hydraulic conductivity may be inferred from infiltration law of Philip (1957b):

$$I(t) = S\sqrt{t} + At \quad (8)$$

where, the term A accounts for gravitational effect. It is tantamount to the saturation hydraulic conductivity.

2.3 Experimental Layout

Three infiltration trials were carried out on a bare soil at the Cherfech station. The method of disc infiltrometer was used with 20 cm as disc diameter. Two trials were performed with the mono-potential method at soil suctions equal to -5 and -2 cm. The third trial was carried out using the multi-potential method with a pair of soil suction (-16 cm, -6 cm). For all the trials, a thin sand layer was placed at the interface between the disc and the soil surface to mitigate the effect of asperities and ascertain a good contact between the soil and the membrane. Initial and final water contents were measured by sampling soil beneath and at the vicinity of the disc. Figure 1 displays the experimental device used for measuring the saturated hydraulic conductivity by the disc infiltrometer method.



Figure 1. In situ measurement of the saturated hydraulic conductivity using the disc infiltrometer method at Cherfech station

2.4 Estimation of the Ponding Time

In this study, two well-known physically sound equations were used for modelling soil water infiltration: Green and Ampt (1911) and Philip (1957b). Following Kutilek and Nielsen (1994), the ponding time may be written as following for constant rainfall intensity:

2.4.1 Green and Ampt Equation

$$T_s = \frac{S^2}{2K_s(i - K_s)} \ln\left(\frac{i}{i - K_s}\right) \quad (9)$$

Where, i refers to the rainfall intensity [LT^{-1}]. It is worth to remind that Green and Ampt equation holds true when soil hydraulic diffusivity obeys a Dirac function.

2.4.2 Philip Equation

$$T_s = \frac{S^2(2i - K_s)}{4i(i - K_s)^2} \tag{10}$$

By comparing Green and Ampt (1911), and Philip (1957b) equations at short times, one can deduce:

$$S = \sqrt{2K_s (h_0 - h_f)(\theta_s - \theta_i)} \tag{11}$$

where, h_0 and h_f refer to the water depth at the soil surface and the soil suction at the wetting front, respectively. It should be highlighted that h_f is assumed to be soil depth independent in the theory of Green and Ampt (1911).

Considering the dimensionless variables:

$$\left\{ \begin{array}{l} T^* = \frac{2(i - K_s)K_s T_s}{S^2} \\ i^* = \frac{i}{K_s} \end{array} \right. \tag{12}$$

Equations (9) and (10) may be written as following:

Green and Ampt:

$$T^* = \ln\left(\frac{i^*}{i^* - 1}\right) \tag{13}$$

Philip:

$$T^* = \frac{2i^* - 1}{2i^*(i^* - 1)} \tag{14}$$

In the same site, Yacoubi et al. (2012) have shown that sprinkler spacing of $12\text{ m} \times 12\text{ m}$ and a pressure head of 3 bars at the nozzle provide the better distribution uniformity ($76.8\% \leq CU \leq 86.1\%$) for wind speeds less than 4 m/s. Under these circumstances, the recommended application rate is equal to 9 mm/h.

3. Results and Discussion

3.1 Infiltration and Hydraulic Conductivity

Recorded infiltration data under a soil suction of -2 cm were used to establish the infiltration equation. Figure 2 illustrates the relationship between the cumulative infiltration depth and the elapsed time.

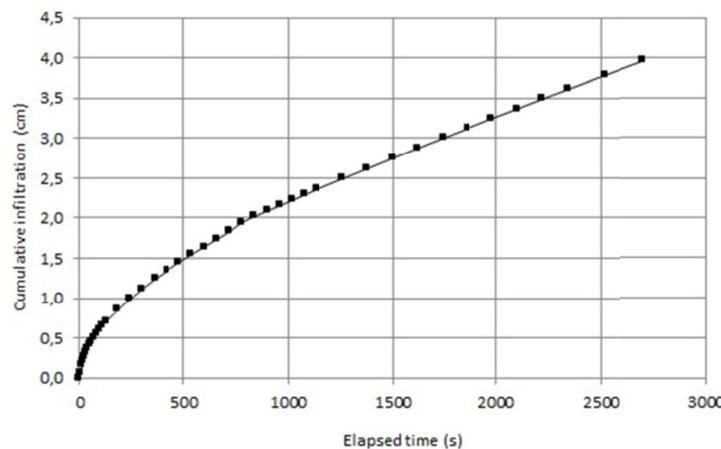


Figure 2. Cumulative infiltration versus elapsed time under -2 cm soil suction (mono-potential trial)

Fitting the scattered data according to Philip (1957b) equation leads to:

$$I(t) = 0.059\sqrt{t} + 0.000314t \quad (R^2 = 0.99) \tag{15}$$

where, I and t are expressed in cm and s, respectively.

The high value of the correlation coefficient R indicate a very good agreement between fitted and observed results. The value of A provides a saturated hydraulic conductivity equal to 11.3 mm/h. Subsequently, application rates should be fixed less than this threshold to prevent ponding and runoff. Table 2 summarizes the values of S and K_s measured by the mono-potential (2a) and multi-potential methods (2b).

Table 2. Soil water characteristics using the disc infiltrometer

2a. mono-potential method

h_0 (cm)	θ_i (cm ³ /cm ³)	θ_s (cm ³ /cm ³)	S (cm/s ^{1/2})	$K(h_0)$ (mm/h)	K_s (mm/h)
-5	0.074	0.497	0.0712	5.8	10.7
-2	0.157	0.500	0.0615	8.2	11.3

2b. multi-potential method

h_0 (cm)	$Q_{\infty}(h_0)$ (cm ³ /h)	α (cm ⁻¹)	K_s (mm/h)
-16	70	0.118	7.1
-6	227		

It should be emphasized that the two trials were performed in different points. According to Nielsen et al. (1973) and Vauclin et al. (1994), the saturated hydraulic conductivity is widely affected by the spatial soil variability. Therefore, we can assume that K_s values presented in tables (2a) and (2b) are virtually of the same order of magnitude. These values are in a good agreement with K_s values reported by Hillel (1974) for loamy textured soils (K_s ranging from 5 to 10 mm/h).

3.2 Saturation Risk Analysis for on Sprinkler Spacing of 12 m × 12 m

For a given pressure head at the sprinkler nozzle, the discharge is constant. Therefore, the decrease of the sprinkler spacing induce an increase of the application rate. Consequently, caution is required to avoid saturation and runoff hazards when sprinklers are close to each other. The narrow gap between saturated hydraulic conductivity (11.3 mm/h) and suitable application rate (9 mm/h) incited us to investigate the risk of soil saturation. Assuming that $(h_0 - h_f) (\theta_s - \theta_i)$ is constant, the logarithmic derivation of Equation (11) leads to the following expression:

$$\frac{\Delta S}{S} = \frac{\Delta K_s}{K_s} \quad (16)$$

It should be stressed that Green and Ampt (1911) and Philip (1957b) equations assume a uniform soil texture and constant initial water content all over the soil depth. It is obvious that perfect uniformity is an idyllic schematization of the reality. This is why we investigated the impact of an eventual texture change on the ponding time. Hereinafter, we assumed that soil texture varies from clay loam to silt loam. For these soil types, K_s varies from 1.5 to 7.6 mm/h according to the National Engineering Handbook (1991). The sorptivity values were calculated using an incremental approach based on Equation (16). The derived ponding times were determined for a constant application rate of 9 mm/h.

Figure 3 displays the evolution of the ponding time with respect to K_s for the two aforementioned equations.

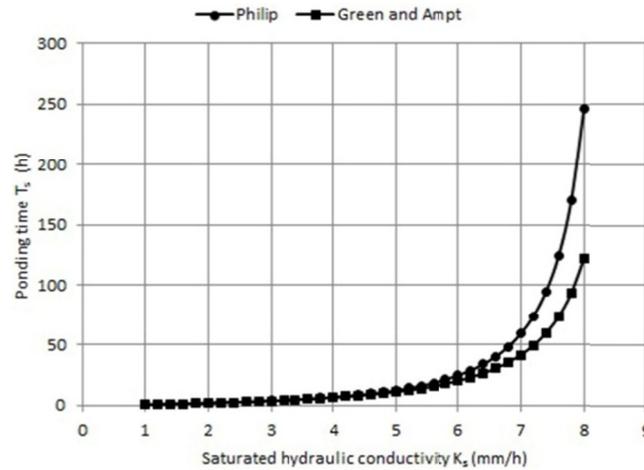


Figure 3. Ponding time versus K_s for the two infiltration equations in the Cherfech station

Figure 3 shows that the ponding times calculated by the two methods are virtually identical for K_s ranging from 1.5 to 6 mm/h. Regarding the practical irrigation times in the region (4-6 hours), Figure 3 shows that the saturation risk is quasi inexistent for K_s ranging from 4.5 to 7.6 mm/h. Inasmuch as the infiltration rate should be higher than or equal to 3 mm/h for sprinkler irrigation to be operated (Keller & Bliesner, 1990), simulation results show that ponding time is approximately equal to 4 hour.

The comparison between dimensionless ponding time Equations (13) and (14) shows a small discrepancy between Green and Ampt (1911) and Philip (1957b) formulations. For high dimensionless infiltration rates (i^*), Figure 4 shows a very good agreement between the two equation.

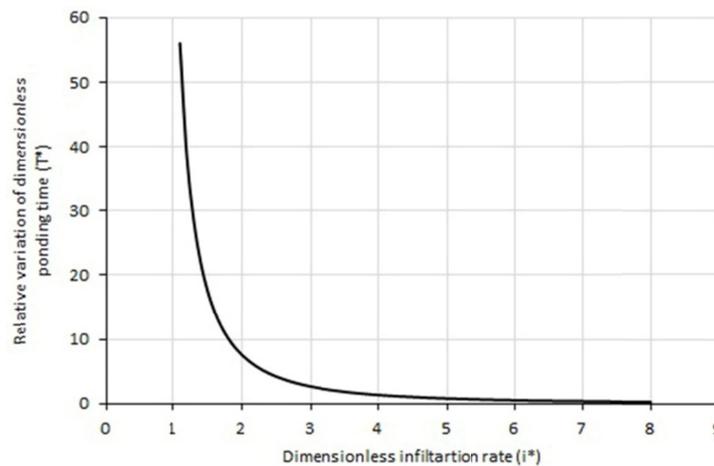


Figure 4. Relative variation of dimensionless ponding time versus dimensionless infiltration rate

In the previous simulations, the pressure head at the wetting front (h_f) was assumed to be soil depth independent. Nevertheless, results of Rawls et al. (1981) show that h_f and effective porosity ($\theta_s - \theta_f$) vary according to the soil texture. In what follows, we perform simulations of the ponding time on the basis Rawls et al. (1981) data for three soil textures: Sandy clay loam, loam and silt loam.

Table 3. Ponding time for three soil texture based on Rawls et al. (1981) data

Soil texture	Data of Rawls et al. (1981)			S (Eq. 11)	T_s	
	K_s	$\theta_s - \theta_i$	$h_f - h_0$		Philip	Green and Ampt
Sandy clay loam	1.5	0.330	218.5	14.7	1.8	1.8
loam	3.4	0.434	88.9	16.2	3.3	3.4
Silt loam	6.5	0.486	166.8	32.5	41.5	53.9

Values of $(h_f - h_0)$, $(\theta_s - \theta_i)$, K_s , S and T_s are expressed in mm, cm^3/cm^3 , mm/h, $\text{mm}/\text{h}^{1/2}$ and h, respectively. Table 3 indicated that ponding times are of the same magnitude than those depicted in Figure 3. Definitely, Figure 3 and Table 3 show that the risk of soil saturation generated by a gradual soil texture variation is virtually inexistent for the practical irrigation times in the study region. Referring to the pedology map of the zone, one can claim that it is unlikely that saturated soil hydraulic conductivity varies from 3 to 11.3 mm/h.

4. Conclusion

Field trials showed that optimal application rate is equal to 9 mm/h for a sprinkler spacing of 12 m \times 12 m. This application rate is so close to the saturated hydraulic conductivity (11.3 mm/h). To assess the soil saturation hazard due to the spatial soil variability, we compared the calculated ponding times to the irrigation times operated in the study region. It was established that Green and Ampt (1911) and Philip (1957b) methods produce similar results for K_s ranging within 1.5 to 6 mm/h. The estimated ponding times are greater than operated irrigation times in the region. Therefore, one can conclude that the saturation risk is virtually inexistent in the study area. Consequently, farmers can use the prescribed application rate without saturation hazard. This application rate is the best compromise between energy cost and water distribution uniformity.

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