Impact of Evaporation on Field Capacity during Water Drainage Redistribution in a Soil

Ali Aldrees[1] and Amine Hafsi[2]

[1]Prince Sattam bin Abdulaziz University College of Computer Science and Engineering
[2]John Wood Group Plc

May 7, 2020

Abstract

To this day, field capacity (FC) is rarely defined in the context of soil properties, and the use of non-physical simplistic models is the common way to normalize water content at FC. In this study, the problem of water drainage redistribution in a soil water column with and without the presence of Evaporation (EV) was extensively studied. Analytical solutions for Richard's equation were established for the case of water drainage redistribution through a deeply wetted soil column with and without EV at Field Capacity (FC) conditions while water retention and depth evolution curves were plotted first, using different EV values of 2 mm/day, 5 mm/day and 8 mm/day and second, for different drainage redistribution durations of 1 day, 4 days and 6 days where EV was set to zero for the case with no EV or to a fixed value of 5 mm/day for the case with EV. The results suggest that EV plays a significant role in soil water drainage suggesting that, in the presence of EV, the FC drying front reaches much higher depths in the soil water profile than if EV is turned off. It was also concluded that FC reaches deeper depths faster the stronger EV is acting AT the surface of A soil water column.

Evaporation plays an important role in soil water drainage redistribution

Field capacity drying front reaches deeper in a soil due to evaporation

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Ali Aldrees[1] and Amine Hafsi[2]

[1]Department of Civil Engineering, Prince Sattam Bin Abdulaziz University, AlKharj, Saudi Arabia.

[2]Senior Engineer, Wood Environment & Infrastructure Solutions, Inc, Tampa, Florida, USA

Abstract

To this day, field capacity (FC) is rarely defined in the context of soil properties, and the use of non-physical simplistic models is the common way to normalize water content at FC. In this study, the problem of water drainage redistribution in a soil column with and without the presence of Evaporation (EV) was extensively studied. Analytical solutions for Richard's equation were established for the case of water drainage redistribution through a deeply wetted soil water column with and without EV at Field Capacity (FC) conditions while water retention and depth evolution curves were plotted first, using different EV values of (2 $\frac{\text{mm}}{\text{day}}$, 5$\frac{\text{mm}}{\text{day}}$ and 8 $\frac{\text{mm}}{\text{day}}$) and second, for different drainage redistribution durations of (1 day, 4 days and 6 days) where EV was set to zero for the case with no EV or to a fixed value of 5 $\frac{\text{mm}}{\text{day}}$ for the case with EV. The results suggest that EV plays a significant role in soil water drainage suggesting that, in the presence of EV, the FC drying front reaches much higher depths in the soil water profile than if EV is turned off. It was also concluded that FC reaches deeper depths faster the stronger EV is acting at the surface of a soil water column.

Introduction

Evaporation (EV) is one of the main stages in the hydrological cycle and an essential physical process extensively studied in agricultural engineering, irrigation management, soil physics and climatology (Salvucci 1997). Soil evaporation is the process responsible for converting soil water content at the ground surface from the liquid state to the vapor state. According to Allen et al. (2005) and Monzón et al. (2006), soil evaporation process depends on several climatological parameters such as solar radiation, wind speed, humidity, air temperature, and on soil characteristics in addition to qualitative and quantitative in-situ conditions which include soil type, frequency of irrigation, frequency of rain, soil cover, and depth to the groundwater.

FC is a significant concept in soil hydrology used for crop growth modelling, irrigation planning, as well as water and chemical leaching characterization in a profile, as stated by Reynolds (2018). Twarakavi et al. (2019) also described FC as the approximate quantity of water permanently retained in the soil in opposition to the downward pull of gravity. Although there is a general consensus that FC implies a near-hydrostatic hydration state that prevails after gravity drains the profile, there is no unified method to define this state or at least to estimate FC. Yet, an accurate definition of FC can most certainly be established through better understanding of the effects of EV during soil water drainage which is an important player in how water drains inside a soil column and given that EV will always be present and in effect in the same time as any soil water redistribution (Sun and Yang 2013; Aldrees and Nachabe 2019). During the process of soil water drainage redistribution for the case of deeply wetted profile and where the soil cover is minimal (i.e., majority of the soil surface is directly exposed to the atmosphere), evaporation becomes an essential factor that accelerates drying front from the soil depth, especially very close to the surface (Black et al. 1969; Allen et al. 2011). This is due to the factor that the roots of the crops uptake the water from the horizon.

In this paper, the problem of water drainage redistribution in a soil water column with and without the presence of EV was extensively examined both analytically and numerically to better grasp the direct impact of EV on soil water redistribution and on FC in particular.

ANALYTICAL SOLUTION

Richards, L. A. (1931) has established a general equation that describes the flow in the vadose zone by combining Darcy's law and the law of conservation of mass As a result, Richards has established an equation to describe flow as follows:

$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D_\theta \frac{\partial\theta}{\partial z}\right] - \frac{\partial K_\theta}{\partial z}(1)$

where D_θ is the soil water diffusivity which is a parameter that depends on the diffusivity the time scaled with capillary time $t_s = \frac{\Delta\theta\lambda_s}{k_s}$ and the microscopic capillary length λs and K_θ is the hydraulic conductivity as function of volumetric water content.

The pressure gradient is determined as a function of soil depth and time which was analytically developed by Parkin et al. (1995) as follows:

$$\frac{\partial\psi}{\partial z}\ (z,t) = \frac{(C-\theta *\ )^2}{\theta *^2}\ u^{\ -1}.\ \left\{u^{\ -1}\ \left(\frac{\partial u}{\partial \xi}\ \right)^2\ -\ \frac{\partial^2 u}{\partial \xi^2}\right\}\ \ (2)$$

For the case of drainage redistribution of water in a deeply wetted soil water profile, Aldrees, A., & Nachabe, M. H. (2019) proposed the use of near unity of pressure gradient distribution during drainage redistribution as a condition of the attainment of FC in the soil profile (equation 3).

$\frac{\partial\psi}{\partial z}\ \ (z_{\mathrm{FC}}, t_{\mathrm{FC}}) \approx 1(3)$

Broadbridge and White (1988) presented an analytical solution to Richard's equation which was used to solve equation 3 while the pressure gradient was set to 0.95 so that the drainage redistribution gradient is close enough to 1 to ensure attainment of FC without using a value 1 that can only be reached asymptotically in time, in addition to a negative flux flow that was added to the system to simulate evaporation, an upward pressure force exerted at the surface of the soil water column.

The analytical solution of $u\left(\zeta,\tau\right)$ for the case of drainage redistribution with deeply wetted profile and using a negative evaporation flow at the surface (Warrick et al. (1990)) is as follows:

$u\left(\zeta,\tau\right)\ =u_1+u_2$ (4)

$R_*=\frac{R}{K_s}$ (5)

$\rho=R_*\left[4C\left(C-1\right)\right]^{-1}$(6)

$\lambda=\rho\left(\rho+1\right)$ (7)

The value of R_* is negative, as a result, U_1 will be a complex argument as follows:

$u_1=0.5e^{\left(\frac{-\xi^2}{\tau}\right)}\left[w\left(\text{iZ}\right)+w\left(iZ\right)\right]$(8)

$u_2=0.5\exp\left(-\zeta^2/\tau\right)\left\{f\left(-0.5A\tau^{0.5}-\zeta\tau^{-0.5}\right)-f\left(-0.5A\tau^{0.5}+\zeta\tau^{-0.5}\right)\right\}$(9)

$Z=\xi\tau^{-0.5}+\iota\mu\tau^{0.5}$ (10)

$w\left(\text{iZ}\right)+w\left(iZ\right)=2\ \sum_{n=0}^{\infty}\frac{-r^n}{\Gamma(0.5n+1)}\cos\left(n\arg Z\right)$(11)

$r=\sqrt{\left(\frac{\xi^2}{\tau}-\lambda\tau\right)}$ (12)

$\Gamma\left(n\right)=\left(n-1\right)!$ (13)

$\lambda=-\mu^2$ (14)

$\mu=\sqrt{-\lambda}$ (15)

RESULTS AND DISCUSSION

SOIL WATER DRAINAGE ANALYSIS WITH DIFFERENT EV VALUES

The analytical solution for drainage redistribution with deeply wetted homogeneous soil profile in the presence of evaporation is applied to the soil with parameters as follows:$k_s=10^{-6}ms^{-1}$, $\theta_s=0.4$, $\theta_r=0.1$ and $\lambda_s=1m$. In the literature, evaporation flux values vary considerably. Allen et al. (1998) suggested ranges for evaporation fluxes based on different agro-climatic regions (i.e., regions where the mean daily temperature is about $10C$ (cold temperatures), regions where the mean daily temperature is around $20C$ (moderate temperatures) and regions where the mean daily temperature is beyond$30C$ (warm temperatures)) and this range of values is between a minimum value of 1 mm/day which corresponds to the coldest regions and a maximum value of 9 mm/day which corresponds to the warmest regions.**Figure 1** illustrates the soil water redistribution curves for different values of evaporation flux chosen from the EV range of values$\left(2\frac{\text{mm}}{\text{day}},\ 5\frac{\text{mm}}{\text{day}}\text{ and }8\frac{\text{mm}}{\text{day}}\right)$ in the literature after exactly two days.

It can be seen in **Figure 1** that, as the evaporation flux increases at the soil surface, the soil water content decreases. For example, the amount of soil water content at the surface (i.e., soil depth = 0) is 0.282 when evaporation flux equal to 2 $\frac{\text{mm}}{\text{day}}$, while it is 0.269 when evaporation flux is equal to 8 $\frac{\text{mm}}{\text{day}}$.

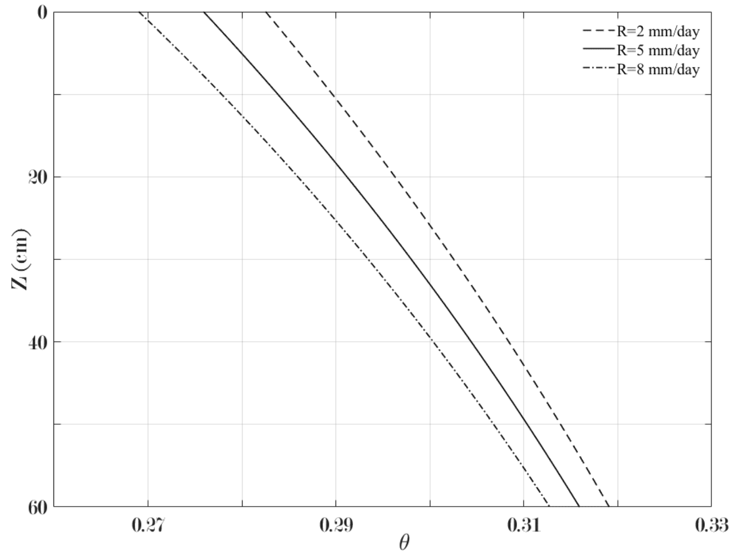

Figure 1. Example of drainage redistribution with deeply wetted homogeneous profile and EV solved analytically using different values of EV (2, 5 and 8 mm/day).

In their studies, Nachabe (1998) and Warrick et al. (1990) also used an evaporation value of 5 mm/day, which represents an average value of evaporation flux. Therefore, in the next analysis, EV was set to 5 mm/day.

SOIL WATER DRAINAGE ANALYSIS WITH AND WITHOUT EV

In order to understand the impact of EV in soil water drainage redistribution, a comparison between the same cases with and without EV was found to be very informative. Using the analytical solutions for drainage redistribution with deeply wetted homogeneous soil profile with and without EV that we developed, and for the same soil parameters used earlier, soil water contents were plotted with regards to depth for both the cases with and without EV as illustrated in **Figure 2** , and where the curves were represented with either solid lines in the case with EV and with dashed lines in the case without EV. Note that all curves were plotted following different drainage durations (after 1, 4, and 6 days).

Figure 2 exhibits depth and soil moisture results computed analytically for different

drainage durations in the cases with and without EV.

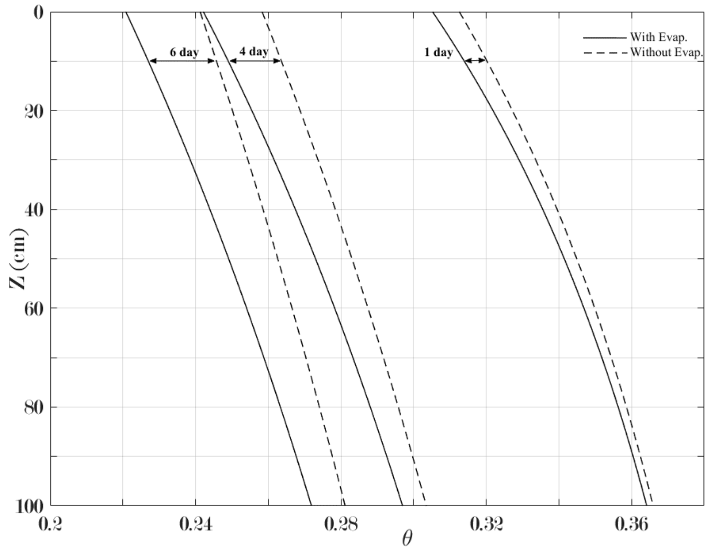

Figure 2. Comparison of soil water drainage with (solid lines) and without EV (dashed line).

As shown in **Figure 2** , EV accelerates the drying of the soil, which is apparent in all curves representing different drainage durations. This indicates that FC is reached faster for the case of soil water drainage with EV. For example, in the case of redistribution duration of 1-day, the amount of soil water content at the surface (i.e., soil depth = 0) is 0.305 for the case with EV and 0.313 for the case without EV. Furthermore, **Figure 2** shows that the difference between these soil moisture values (i.e., with and without EV for 1-day drainage duration) increases as the drainage redistribution in the soil column is tracking at longer durations. It is also apparent in this figure that as the depth of the soil column increases, the influence of EV on soil water redistribution decreases while the maximum EV impact is experienced by the soil moisture at depths very close to the surface.

Figure 3a and **Figure 3b** respectively exhibit the water retention curves and temporal evolution of depth to FC curves which represent analytically computed solutions using the previous soil parameters also used to plot **Figure 1** and **Figure 2** . As exhibited in **Figure 3a** and **Figure 3b** the EV case (represented by solid lines) show larger dry fronts as compared to the same case but without EV (dashed line). This indicates the strong impact of EV on the propagation of the drying front. For instance, after just three days of soil water drainage, water content at FC was computed as 5 cm for the case without EV and 33 cm with EV, an increase of about 560% in depth indicating that EV is an important parameter in the physics of soil water drainage redistribution. These results were predictable due to the fact that, when EV is present at the time of soil water drainage, the pressure pulls soil water content upward within the soil column. On the other hand, the drying front will propagate down faster, which also means that the depth to FC will reach lower depths within the soil column.

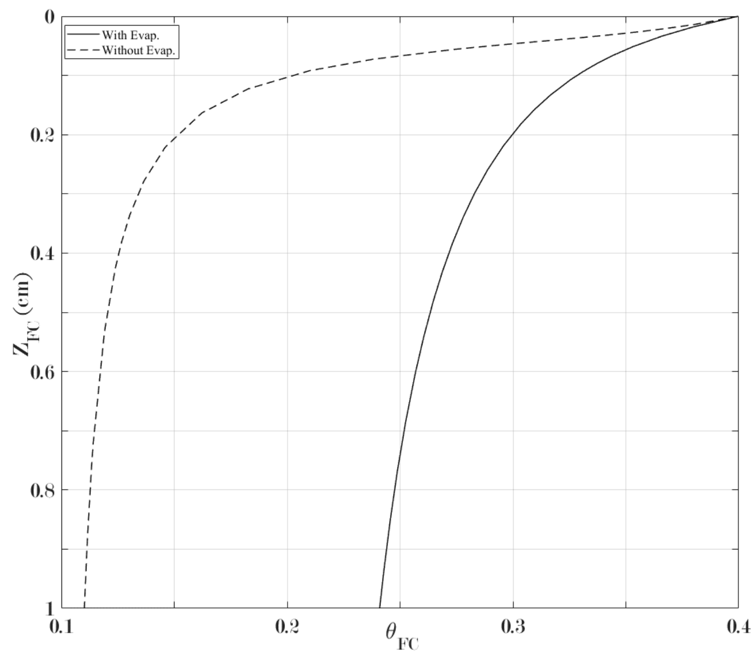

Figure 3a. Depth and soil water content at FC in case of EV (solid lines) and without EV (dashed line).

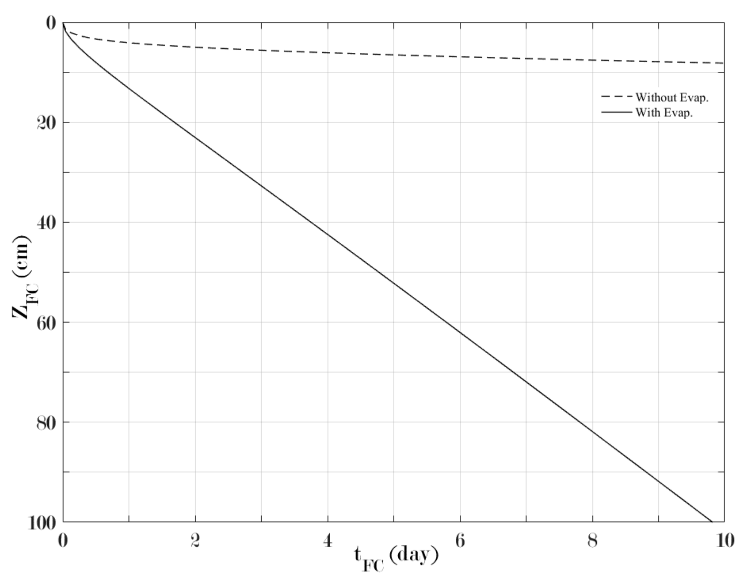

Figure 3b. Depths and times at FC in case of EV (solid lines) and without EV (dashed line).

CONCLUSIONS

Thus far, FC was rarely defined in the context of soil properties, and the use of non-physical simplistic models was often used to normalize water content at FC (e.g., using Van genuchen and Brooks and Corey models) which had many flaws. In this study, the problem of soil water drainage redistribution with and without the presence of EV was extensively studied both analytically and numerically via real intrinsic soil parameters to better understand the physics behind soil water drainage redistribution at FC. This was accomplished using analytical solutions to Richard's equations which were solved similarly to Aldrees, A., & Nachabe, M. H. (2019) but with the addition of an negative pressure force to model the upward pulling force exerted by EV on the water at the soil column surface during drainage redistribution. The results suggest that EV plays an important role in soil water drainage suggesting that, in the presence of EV, the FC drying front reaches much higher depths in the soil water profile than if EV is turned off. It was also concluded that FC reaches deeper depths faster the stronger EV is acting on the surface of the soil water column.

Data availability statement

The data that support the findings of this study are openly available in "mendeley" at http://doi.org/10.17632/5wsdtxcpdh.1

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