EGU General Assembly #EGU24 14 -19 April 2024

Comparing Hydrus-2D/3D and Philip (1984) models to assess wetting bulb expansion from buried source

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Summary and objective

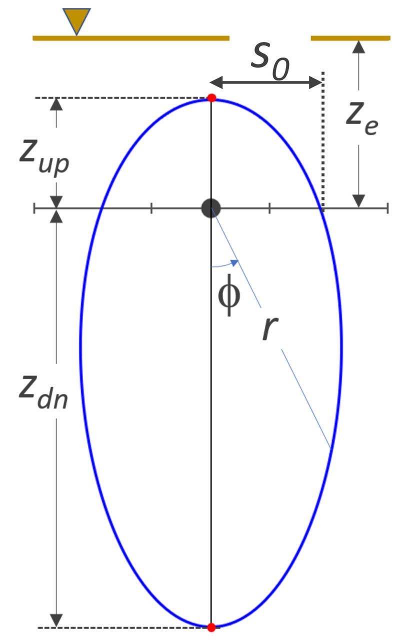
In surface and subsurface drip irrigation systems, predicting the size of the wetting bulb is crucial for their design and management, with the aim of water conservation. Various hydrological models have been proposed for predicting the wetting bulb expansion from buried and surface point sources. Considering the hydraulic parameters ensuring correspondence of the soil hydraulic conductivity function according to van Genuchten-Mualem and Gardner models, the primary objective of this study was to compare the estimated bulb dimension using the Philip (1984) model and Hydrus 2D/3D software, for buried source. This comparison aims at understanding any differences between the two models and their practical implications in drip irrigation.

Theoretical Background - Philip 1984 Model

In 1984, Philip proposed exact solutions for travel times, *T*, for three-dimensional steady-state infiltration into homogeneous soils, from buried and surface point sources. To detect the impact of soil hydraulic properties on wetting patterns, Baiamonte et al., (2024) reformulate the dimensionless solutions of wetting front travel time relationships for the vertical bulb lengths z_{dn} and z_{up} in dimensional terms.

$$q\,t = V = \frac{4\,\pi\,\Delta\theta}{\alpha_{Gar}^{3}}\, e^{\frac{\alpha_{Gar}\,z_{up}}{2}\left(2+\alpha_{Gar} z_{up}(\alpha_{Gar}\,z_{up}-2)\right)-2} \qquad (1)$$

$$q\,t = \frac{4\,\pi\,\Delta\theta}{\alpha_{Gar}^{3}}\left[\alpha_{Gar}\,z_{dn}(\alpha_{Gar}\,z_{dn}-2) + 2\,ln(1+\alpha_{Gar}\,z_{dn})\right] \qquad (2)$$



where: α_{Gar} [cm^{-1}] is the shape parameter of the Gardner (1958) hydraulic conductivity function, q [cm^3 hour^{-1}] is the emitter discharge, t [h] is the irrigation time, and $\Delta\theta = \theta_{avg} - \theta_i$ in which θ_{avg} [cm^3 cm^{-3}] is the average volumetric soil water content in the soil behind the wetting front, and θ_i [cm^3 cm^{-3}] is the initial volumetric water content before wetting.

The above dimensional relationships also allow practical applications, as determining the water volumes required to achieve an assigned vertical bulb length. To calculate the horizontal ($\varphi = \pi/2$) bulb expansion from the source, S_0, Thorburn et al. (2003) obtained the following equation

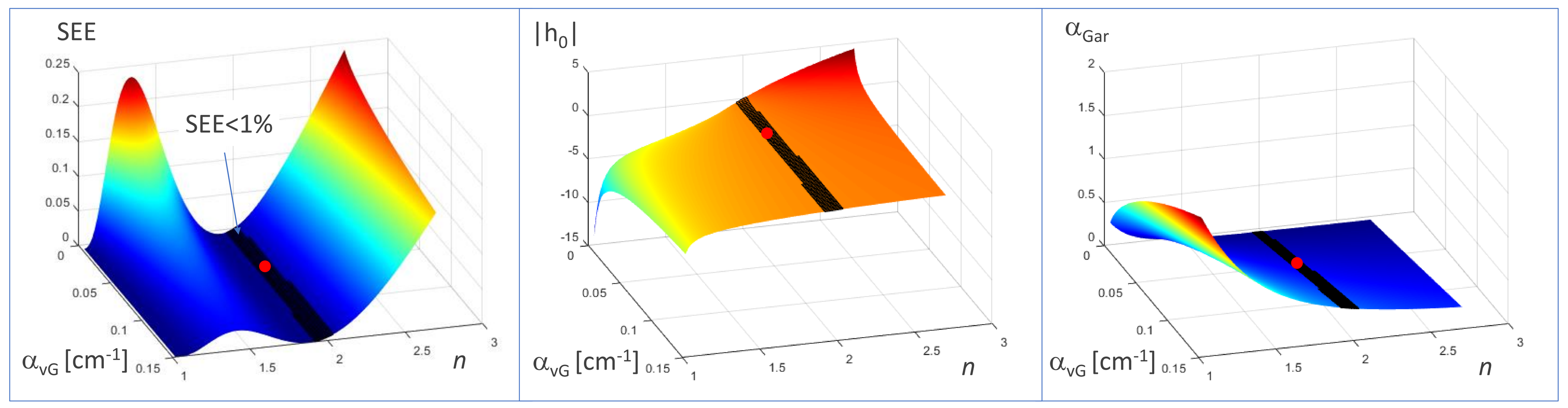
$$T\left(\frac{\pi}{2}, S_0\right) = e^{S_0}\left\{S_0^2 - S_0 + \frac{1}{2}[1 - S_0 - ln(2)]\; ln(2\,e^{S_0} - 1) + \frac{1}{2}L(2\,e^{S_0}) - \frac{\pi^2}{24}\right\} \qquad (3)$$

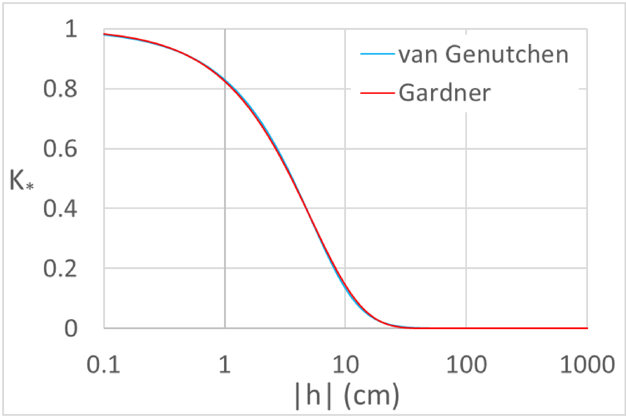
where L(x) denotes the dilogarithm function defined by: $L(x) = \int_1^x \frac{ln\,x}{x-1}dx$

Materials and Methods

First, the correspondence between the parameters of the van Genuchten-Mualem and Gardner functions was evaluated, with a Standard Error of the Estimate, SEE < 1%.

From this preliminary analysis, it was found that the van Genuchten function corresponds to the Gardner function for values of α_{vGM} ranging between 0.005 and 0.15 cm^{-1} and n values between 1.92 and 2.04.





For the purposes of this study, the values of α_{vGM} and n of the van Genuchten model were chosen as 0.0753 and 1.936, respectively, which correspond to values of the parameters α_{Gar} and h_0 of the Gardner model of 0.1945 and 0.016. To apply the Hydrus 2D/3D software, it was essential to know additional parameters of the van Genuchten-Mualem soil water retention and hydraulic conductivity function such as θ_r, θ_s, and K_s. Starting from the hydraulic parameters proposed by Carsel and Parrish (1988) for twelve soil textural classes and considering the closer resemblance between the chosen α_{vGM} and n, the sandy loam soil was chosen to obtain the parameters θ_r, θ_s, and K_s for this investigation Table 1.

Three-dimensional water flow was modeled using the axisymmetric simulation. This choice can be justified considering suggestion by Kandelous et al. (2011) that for a single emitter source the three-dimensional flow process could be well approximated by an asymmetrical two-dimensional process. The flow domain extensions were assumed to be 50 cm in radial direction and 100 cm in vertical one. A semicircular boundary of 2 cm radii was considered along the symmetrical axis, at 30 cm depth, to represent the emitter.

Table 1 -Parameters of Gardner and van Genuchten-Mualem models for the considered soil

Model	Gardner		Van Genuchten-Mualem				
Parameters	α_{Gar}	h_0	θ_r	θ_s	α_{vG}	n	K_s
	[cm^{-1}]	[cm]	[cm^3 cm^{-3}]	[cm^3 cm^{-3}]	[cm^{-1}]	[-]	[cm hour^{-1}]
	0.1945	0.016	0.065	0.41	0.075	1.936	4.42

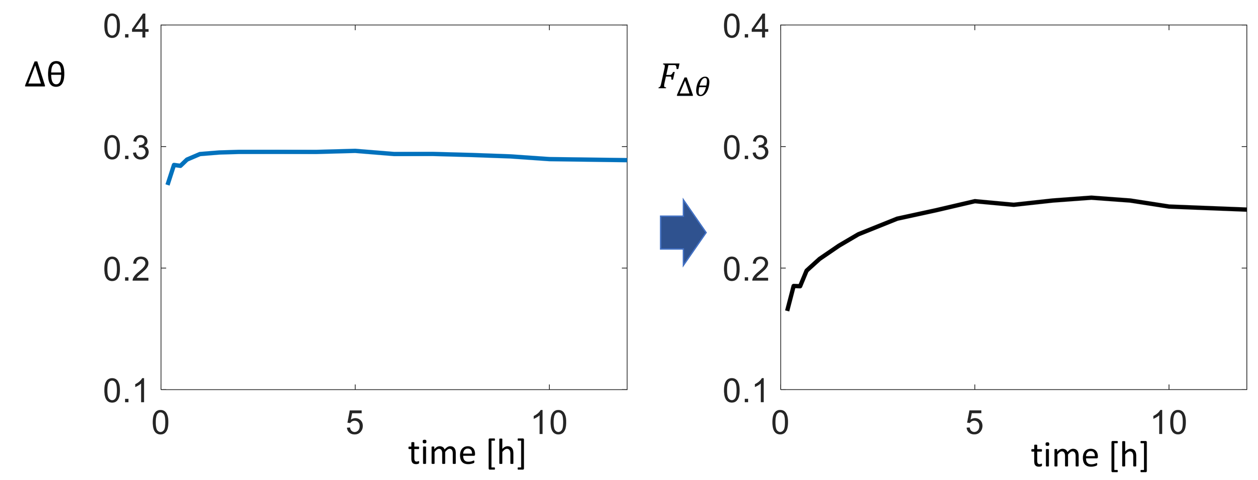
A total of 14220 nodes were used to represent the entire simulation domain. A no flux boundary condition was considered for the surface and lateral vertical boundaries and a free drainage was considered along the bottom boundary of the flow domain. A constant flux density boundary condition of 159.15 cm h^{-1} corresponding to the emitter discharge of 2 l h^{-1} was assumed within the emitter boundary surface. The irrigation duration was 12 h and the initial water content was set to be uniform within the whole flow domain and equal to 0.10 cm^3 cm^{-3}.

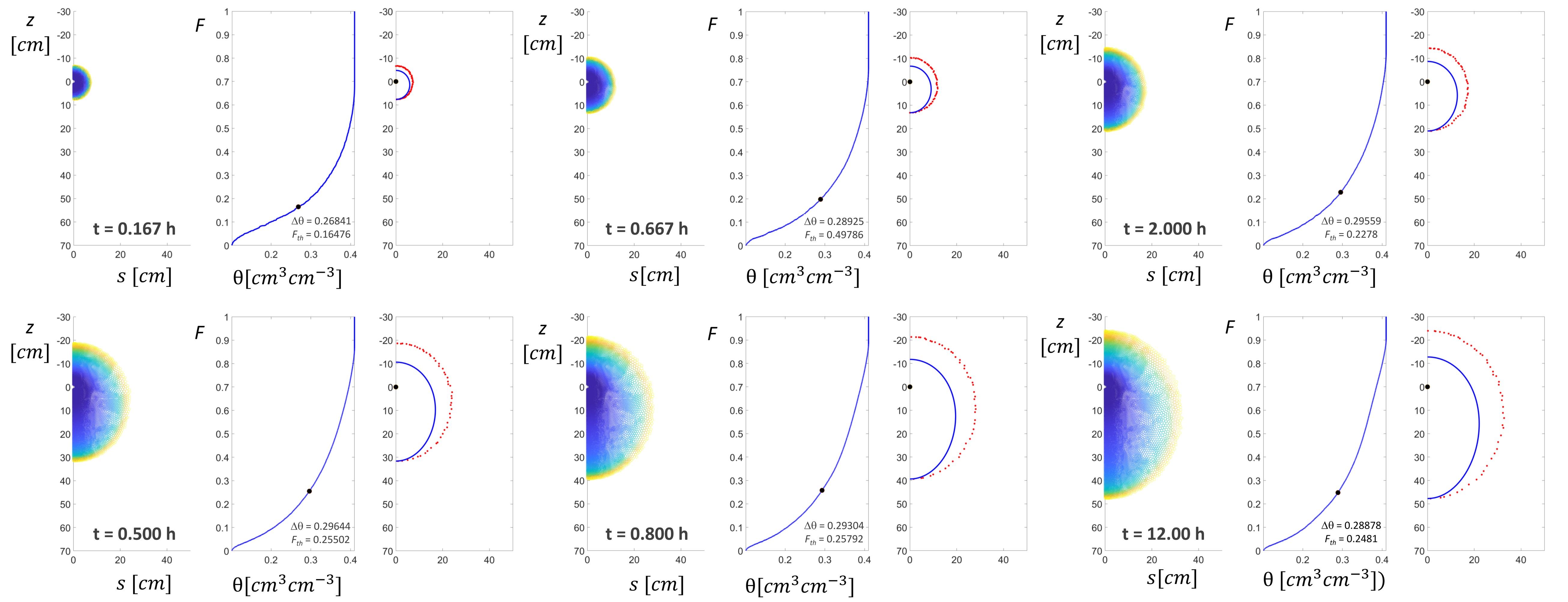
Finally, the simulated value of z_{dn} has been implemented into equation 2 to estimate the value of $\Delta\theta$ for the 12-hour simulation.

Results

A few minutes after the simulation starting, the value of $\Delta\theta$ stabilized stabilizes around 0.39 cm^3 cm^{-3} and remains nearly constant throughout the simulation duration. The initial increase in $\Delta\theta$ at the beginning of the simulation is probably related to the dimension of the emitter unlike the Philip model that assumes a point source.

Considering the frequency distribution of θ within the bulb simulated by Hydrus 2D/3D over time, the estimated $\Delta\theta$ equals to θ values that are in between the frequency range [17% - 25%].

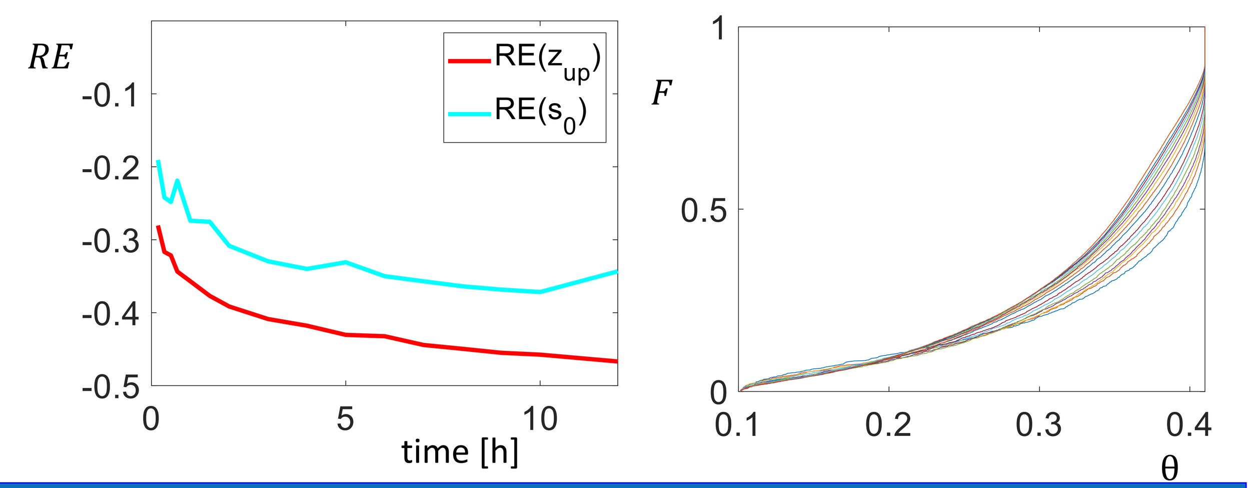




The Philip model consistently underestimates S_0 and z_{up} compared to Hydrus, with errors ranging from 20% to 35% for S_0 and from30% to 45% for z_{up}.

S_0 is particularly crucial in micro-irrigation system design as it influences the choice of emitter spacing, thus properly overlapping the wetted bulbs. According to Montalvo (2003), it is advisable to have a minimum overlap percentage of 15% and a maximum of 50%. In light of these considerations, a design criterion using Philip model, could be to consider the distance between emitters as twice the value of S_0.

Regarding the z_{up}, it has implications for the installation depth of the emitter line, which should ensure that the wetted bulb remains below the soil surface to prevent losses due to evaporation. In this case, a design criterion could be to install the emitter line at a depth of 2 z_{up}.



Conclusions

The Philip model is a simple tool that allows estimating variations in wetting patterns in homogeneous soils, requiring only two soil parameters for a given emitter position and applied water volume, thus it is much easier to be applied than numerical models. The model was applied by imposing z_{dn} obtained by Hydrus 2D/3D, and estimating the corresponding $\Delta\theta$. Although this model underestimates upper and lateral expansion of the wetting bulb, it appears much simpler than numerical models, thus it could be suitable to be applied by accounting for the errors in the bulb size, which in this work have been evidenced. Future perspectives could be aimed at deepening the application of the Philip model by evaluating the effect of θ_i and K_s.

Funding

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

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