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DEVELOPMENT AND VERIFICATION OF AN EMITTER SUPPLY RADIUS EQUATION FOR 3-DIMENSIONAL GREEN-AMPT INFILTRATION

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RESUMEN. *La simulación de la infiltración en el suelo del agua procedente de un gotero es importante de cara a la optimización del riego localizado. Un modelo de simulación prometedor es el de base física basado en la extensión a coordenadas (hemi)cilíndricas de la ecuación de Green-Ampt (3DGA). Una de las desventajas de 3DGA es no incluye explícitamente el caudal del emisor, aunque este puede estimarse implícitamente a través del radio húmedo del suelo en el emisor, r_o, que sí está incluído en 3DGA. Philip propuso una ecuación para la estimación de r_o basada en el concepto del radio húmedo mínimo del suelo necesario para acomodar un caudal de emisor determinado. Sin embargo la evaluación inicial de esta ecuación combinada con 3DGA no produjo buenos resultados para algunos suelos. Se propone la generalización de la ecuación de Philip como función del caudal del emisor, conductividad hidráulica saturada del suelo, y succión en el frente de Green-Ampt. Se compararon los resultados para sucesos de infiltración obtenidos mediante la combinación de 3DGA con la nueva ecuación y la original de Philip, frente a los resultados de la solución en 2-dimensiones de la ecuación de Richards obtenidos con el modelo Hydrus-2D para un rango amplio de suelos. Los buenos resultados obtenidos con la ecuación revisada de r_o indican que su combinación con 3DGA representa un modelo útil para el riego localizado.*

ABSTRACT. *Drip irrigation technology has become an increasingly popular agricultural practice. To optimize the water application it is important to accurately describe the 3-dimensional soil infiltration pattern. Numerical models, when sufficiently validated, can become an important tool to optimize the drip irrigation application rate. One such simplified, physically-based model is the Green-Ampt Infiltration method extended to hemi-cylindrical coordinates (3DGA). One drawback to the model, however, is that the flow rate from the emitter is implicit, in that it is built in the emitter supply radius parameter, r_o. Philip developed an equation for calculating the minimum radius needed to accommodate a given flow indefinitely. However, initial testing of this equation showed that it did not provide good results in some cases when used with 3DGA. An equation for the supply radius is proposed based on the generalization of Philip equation as a function of emitter flow rate, saturated hydraulic conductivity and suction at the wetting front. Both Philip's equation and the proposed equation combined with the 3DGA model were compared for a wide variety of soils to results from the Hydrus-2D two-dimensional numerical solution of Richards' equation. The results showed that the latter is a useful method for calculating the supply radius parameter for use in 3DGA.*

1. INTRODUCTION

Modeling of intensive bed management systems (plastic mulch, drip irrigation) has gained increasing interest. The use of Richards' equation (1931), while very accurate, can be computationally inefficient and requires extensive input data that, if available, can lead to parameterization errors. Alternatively, 1-dimensional approximate models have been used in the past, however, studies have shown that in actuality the soil water flow path is quasi-spherical in shape and therefore requires a 2/3-D description (Warrick, 1974; Clark et al., 2006; Healy and Warrick, 1988). With this in mind, it would be desirable to find a quasi-spherical model that is also an approximate physically-based model. One such model is the 3-dimensional Green-Ampt (3DGA) model (Chu, 1994). This model was compared to other quasi 3-dimensional point source models, including two based from Richards' equation, as well as published data, and found to provide good results (Gowdish, 2007). However, one drawback to this model is that the flow rate from the emitter is implicit, in that it is built in the emitter supply radius, r_o, parameter. Chu (1994) also assumes that the supply radius is a known parameter. An equation defining this supply radius was not included in the original development of the model and, therefore, would need to be determined in an alternative manner.

One method for determining the supply radius is to directly measure the saturated wetted radius that develops on the surface of the soil. While this would provide a good estimate, it is not practical in most applications and can be difficult to measure properly. In addition, there is no standard by which one can determine what is considered the supply radius versus the actual wetting front advancing through the soil. Therefore, there is still a need for an equation for calculating the supply radius for use in the 3DGA model. Interestingly, a number of models have been developed that use the assumption of a supply radius (Philip, 1984; Raats, 1971; Warrick and Lomen, 1976; Wooding, 1968; Parlange, 1973; Warrick, 1974), though, very few formulations for an equation describing the supply radius have been attempted.

One paper developed an equation for calculating the supply radius specifically for the 3DGA model (Sepaskhah and Chitsaz, 2004). The empirical equation was developed using multiple regression analysis, with data obtained by measuring different values of the supply radius for various soils (differing saturated hydraulic conductivities) and varying emitter flow rates. However, the details of the methodology were unclear and the equation did not appear to give good results. An alternative for calculating the supply radius is Philip's equation (1969) which gives the minimum radius needed to accommodate a given flow rate indefinitely. Clothier and Scotter (1982) compared Philip's minimum radius against measured supply radii and found them to be similar. A drawback, however, is that the equation is parameter intensive. Therefore, an alternative equation for calculating the supply radius is needed.

The purpose of this paper is to develop an equation for calculating the supply radius parameter in the 3DGA model that is a function of the emitter flow rate. Furthermore, the results of using the proposed equation within the 3DGA model will be compared to results from using the two other alternative methods presented (Sepaskhah and Chitsaz, 2004; Philip, 1969) within the 3DGA model.

2. METHODS

2.1. 3-dimensional Green-Ampt infiltration

Soil moisture flow can best be described by combining Darcy's Law with the continuity equation, resulting in a theoretical partial differential equation known as Richard's equation (1931). While Richards' equation can produce accurate results, there are drawbacks to using it. Richard's equation does not have a general analytical solution, and therefore must be solved numerically. The numerical solutions of Richards' equation are computationally intensive, require extensive soil property data and generally involve fine spatial and temporal discretization. For this reason approximate, physically based approaches have been developed for modeling infiltration and soil water redistribution.

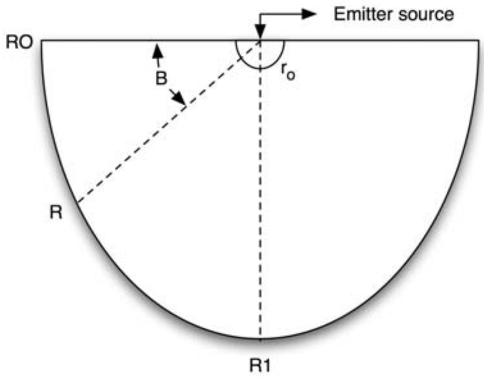

Figure 1. 3-dimensional Green-Ampt point-source wetting front

Under point source emitters a small ponded area on the soil surface can occur. This ponded area is similar to a hemispherical cavity of radius r_o (Fig. 1), which can be considered the source of water flow to the soil profile, having uniform flux from the surface of the cavity. Several methods have been developed, with good results, using this assumption (Raats, 1971; Parlange, 1973; Warrick, 1974). One such model which uses this assumption is the 3-dimensional Green-Ampt (3DGA) model (Chu, 1994). In addition to the cavity source, the 3DGA model assumes: a) water flows in a radial direction from the cavity source; b) water is assumed to enter the soil as a sharp wetting front which separates a saturated wetted zone from an unwetted zone; c) the soil is assumed to be deep and homogeneous; d) the soil is assumed to be at a uniform initial water content.

The sharp wetting front is of particular interest. It comes from studies which have shown that point source systems exhibit an average water content within the wetted area which changes very little in a given time period (Ben-Asher et al., 1986). This same concept is related to a sharp wetting front in that there is an infiltrated water content in the wetting front and beyond, the soil remains at initial water content.

From the principle of conservation of mass, the water flux through the wetted front is inversely proportional to the square of the radial distance, so that (Chu, 1994),

$$f = CR^{-2} \tag{1}$$

where f is the water flux density; C is the proportional constant; and R is the radial distance from a point along the wetted front to the source center.

Substituting Darcy's law in Eq. (1) rearranging, and integrating from $r = r_o$ to R and $h = 0$ to $-(S_{av} + R\sin B)$ results in,

$$C(r_o^{-1} - R^{-1}) = K_s(S_{av} + R\sin B) \tag{2}$$

where K_s is the saturated hydraulic conductivity of the soil; S_{av} is the average suction at the wetting front; r_o is the supply radius of the hemispherical cavity source; and B is the angle between the ground surface and wetted radius R.

Substituting C from Eq. (2) into Eq. (1) describes the equation for calculating the water flux density at any point along the wetted boundary as

$$f = \frac{K_s r_o R(S_{av} + R\sin B)}{R - r_o} R^{-2} \tag{3}$$

Applying the principle of conservation of mass

$$M\frac{dR}{dt} = \frac{K_s r_o (S_{av} + R\sin B)}{(R - r_o)R} \tag{4}$$

where M is the water content difference between the inside and outside of the wetting front. Rearranging Eq. (4) and integrating provides an equation for describing the change in shape of the wetting front as

$$\frac{1}{2}(R^2 - r_o^2) - (R - r_o)\left(r_o + \frac{S_{av}}{\sin B}\right) + \frac{S_{av}}{\sin B}\left(r_o + \frac{S_{av}}{\sin B}\right)\ln\left(\frac{R\sin B + S_{av}}{r_o\sin B + S_{av}}\right) = \sin B\frac{K_s r_o}{M}t \tag{5}$$

Given any angle from the ground surface, $0 < B < \pi$, the wetted radius can be calculated from Eq. (5). In particular, if $B = \pi/2$, $\sin B = 1$, and the calculated R would give the maximum depth of the wetting front ($R1$) as

$$\frac{1}{2}(R1^2 - r_o^2) - (R1 - r_o)(r_o + S_{av}) + S_{av}(r_o + S_{av})\ln\left(\frac{R1 + S_{av}}{r_o + S_{av}}\right) = \frac{K_s r_o}{M}t \tag{6}$$

Since Eq. (5) cannot be used to calculate the wetted radius at the ground surface, $B = 0$ or π so that $\sin B = 0$, an additional equation needs to formulated. Setting $\sin B = 0$ in Equation (4) and integrating provides the equation for calculating the radius of the wetting front at the ground surface radius ($R0$) as

$$\frac{1}{3}(R0^3 - r_o^3) - \frac{r_o}{2}(R0^2 - r_o^2) = \frac{K_s S_{av} r_o}{M}t \tag{7}$$

Eqs. (5) and (7) were solved for *R* and *R0* for set times of *t*, using a program written in FORTRAN. In order for this methodology to be valid, the water content of the wetting front needs to be at or very near saturation meaning that the emitter discharge rate needs to equal the average infiltration capacity rate. This assumption makes sense for drip irrigation systems since quite often drip irrigation systems are designed so that emitter discharge rate equals infiltration capacity in order to minimize water losses.

2.2. Source radius calculation

2.2.1. Empirical approach

In order to validate the 3DGA method described by Chu (1994), Sepaskhah and Chitsaz (2004) developed an equation for calculation of the supply radius, r_o. The source radii of various soils, having different saturated hydraulic conductivities, K_s, for different emitter discharges, Q, were measured. A multiple linear regression analysis was then used to obtain an equation for r_o as a function of K_s and Q and found to be

$$r_o = 45.1 - 1196 \cdot K_s + 67.9 \cdot Q \tag{8}$$

with a coefficient of determination, r^2, of 0.61, where K_s has units of $\mathrm{mms^{-1}}$ and Q has units of $\mathrm{mm^3s^{-1}}$.

While the graphical results provided in the paper appear to give good results, it is not possible to verify this due to the fact that some of the input data are missing. To test the applicability of this equation, it was compared to published data from an experiment described by Angelakis et al. (1993). Water was applied at a rate of 2,100 $\mathrm{cm^3h^{-1}}$ to a clay loam soil. At six predetermined times, 55, 170, 350, 590, 950 and 1545 minutes, the soil profile was sampled at various depths and distances from the source. Saturated and residual water content measured 0.52 $\mathrm{cm^3cm^{-3}}$ and 0.28 $\mathrm{cm^3cm^{-3}}$, respectively, and the saturated hydraulic conductivity was calculated to be 0.85 $\mathrm{cmh^{-1}}$. The fitted value of $\Delta\theta = 0.36$ $\mathrm{cm^3cm^{-3}}$ was used for theoretical calculations. The suction at the wetted front for the 3DGA model was calculated to be $S_{av} = 11.82$ cm.

Using the above data, the Sepaskhah and Chitsaz (2004) r_o is calculated to be 3,965 cm. From this extremely large value alone we can see that this r_o will not provide acceptable results. Furthermore, the supply radius was measured to be approximately 8 cm, which is markedly smaller than the calculated value from Eq. (8). Lastly, when used in the 3DGA model with the above data and compared to the published data, the Nash and Sutcliffe (1970) coefficient of efficiencies for the ground surface wetted radius, *R0*, and the vertical wetted depth, *R1*, are -148420.0 and -524.64, respectively. Similar results were obtained for additional cases; therefore, this method for calculating the source radius for use in the 3DGA model has been excluded as a viable option.

2.2.2. Philip equation

Before Chu developed his 3DGA model, Philip (1969) developed a steady-state absorption solution in which the minimum cavity radius needed to accommodate a given Q indefinitely is calculated as

$$r_o^{\min} = Q\left[2\pi \int_{\theta_i}^{\theta_s} D d\theta\right]^{-1} \tag{9}$$

where D is the diffusivity that can be expressed by an exponential function of the form

$$D = a\exp(b\theta) \tag{10}$$

Using the scaling technique from Brutsaert (1979), a and b are defined as

$$a = \gamma S^2 \exp[-\beta\theta_i/(\theta_s - \theta_i)]/(\theta_s - \theta_i)^2 \quad \text{and} \quad b = \beta/(\theta_s - \theta_i) \tag{11}$$

where S is the sorptivity, θ_s and θ_i are saturated and initial water content, respectively, and γ and β are mutually dependent constants. The relationship between γ and β proposed by Brutsaert (1979) is

$$\gamma = \left\{\left[e^{\beta}(2\beta - 1)/\beta^2\right]\left[1 + e^{-\beta} M(-0.5, 0.5, \beta)/(2\beta - 1)\right]\right\}^{-1} \tag{12}$$

where $M(-0.5,0.5,\beta)$ is the confluent hypergeometric function, tabulated by Abramowitz and Stegun (1964).

Substituting Eq. (10) into Eq. (9) and integrating yields

$$r_o^{\min} = \frac{Qb}{2\pi a}\left[\exp(b\theta_s) - \exp(b\theta_i)\right]^{-1} \tag{13}$$

As presented in the results section below, testing of this equation as the supply radius parameter for the 3DGA model shows that it provides good results for sandy loam and loamy sand soils, but provides poor results for other soil types.

2.3. Proposed supply radius equation

Another drawback to Eq. (13) is that it requires more parameters than the 3DGA model. These additional parameters may not be known or have uncertainty, which can increase parameterization errors and thereby lead to a reduction in the accuracy of the model. Additionally, one of the benefits to using a simplified approximation solution, such as the 3DGA model, is the minimal number of parameters. Therefore, the next question would be can we simplify Philip's Equation? Substituting and rearranging components allowed a simplification of Eq. (13).

In order to simplify Philip's Equation (13) it was necessary to breakdown all the components, including the sorptivity parameter. Philip (1969) computed sorptivity as

$$S^2 \approx 2K_s S_{av}(\theta_s - \theta_i) \tag{14}$$

Eqs. (11), and (14) are then substituted into Eq. (13) and this rearranged and reduced to a simplified form

$$r_o^{simplified} = \zeta \cdot \frac{Q}{2\pi} \cdot K_s^{-1} S_{av}^{-1} \qquad \text{with} \qquad \zeta = \frac{\beta}{2\lambda\left[\exp(\beta) - 1\right]} \tag{15}$$

Since β and γ are mutually dependent constants (Eq. 12), Eq. (15) is simply a function of Q, K_s, S_{av} and a constant. Furthermore, Reichardt et al. (1972) proposed that β is a universal constant where $\beta = 8$. By using Eq. (16), γ is calculated to be 1.44×10^{-3}, and by using Eq. (15), ζ is calculated as 0.932.

While we have successfully simplified Philip's Equation, there is still the issue of poor results in some cases. Therefore, using the simplified form of Philip's Equation as a starting point, can we come up with a similar equation that will provide better results?

In order to obtain a similar equation to the Philip (1969) supply radius equation a Levenberg-Marquardt (LM) (Press, 1996) optimization method was used in combination with the 3DGA model. First, a numerical solution of Richards' equation was used to obtain *R0* and *R1*'s for the 11 USDA soil textural classifications (Table 1). The Richards' solution does not explicitly output *R0* and *R1* values, therefore, these wetting front locations must be calculated from the water content data. The water content used for defining the wetting front location is an arbitrary choice due to the fact that in multiple dimensions the area behind the wetting front does not have a uniform value (Healy and Warrick, 1988). Similar to a methodology used by Healy and Warrick (1988), the wetting front for the Richards' solution was assumed to be defined by the set of points such that $W_{wf} = 1.25W_{fc}$, where W_{wf} and W_{fc} are defined by

$$W_{wf} = (\theta_{wf} - \theta_r)/(\theta_s - \theta_r) \qquad \text{and} \qquad W_{fc} = (\theta_{fc} - \theta_r)/(\theta_s - \theta_r) \tag{16}$$

where θ_{wf} and θ_{fc} are the wetting front and field capacity water content, respectively.

Within the LM procedure, the saturated hydraulic conductivity, K_s, and supply radius, r_o, are optimized to give the best Nash and Sutcliffe (1970) coefficient of efficiencies for *R0* and *R1* for a given suction at the wetting front, S_{av}, and flow rate, Q. The S_{av} is then varied from 10 to 150 cm in 10 cm increments and the resulting optimized K_s and r_o found. This same procedure is repeated for two additional flow rates, for a total of 3 flow rates (0.5, 0.75 and 1.0 Lh^{-1}). This process is used to provide a range of values for all the parameters. A non-linear least-squares curve fitting search procedure (TableCurve 3D, SYSTAT Inc., Richmond, CA) was used to fit the data to a proposed supply radius equation similar in form to the Simplified Philip Eq. (15).

2.4. Verification of supply radius equations

The performance of the simplified Philip and proposed supply radius equations is assessed by comparison with a two-dimensional numerical solution of Richards' (1931) equation. The HYDRUS-2D (H2D) (Simunek et al., 1999) program was used in this comparison. The governing equations are solved numerically using a Galerkin type linear finite element method applied to a network of triangular elements. H2D has several options for the parameterization of the unsaturated soil hydraulic properties, including Brooks and Corey (1964) and van Genuchten (1980).

Eleven soil types from the USDA's soil textural classifications were selected (Table 1). All the profiles were considered homogeneous, isotropic and of semi-infinite depth. Each soil is assumed to have an initial water content equal to the wilting point water content given in Table 1. The parameters (θ_s, θ_r, h_b, λ, K_s and θ_{wp} = wilting point water content) were selected for each soil texture according to Rawls et al. (1982, 1983). The value for S_{av} was calculated from those of Brooks and Corey (1964) according to

$$S_{av} = -h_b \cdot \frac{(2 + 3 \cdot \lambda)}{(1 + 3 \cdot \lambda)} \tag*{17)}$$

where h_b is the bubbling pressure and λ is the pore size distribution index.

Table 1. van Genuchten water characteristic curve parameters used in Richards' numerical solutions (refer to Appendix for nomenclature)

Soil #	USDA texture	θ_s	θ_r	θ_{wp}	K_s (cm/h)	a^1 (cm^{-1})	n^1
1	Sand	0.417	0.020	0.033	23.56	0.07661	1.85371
2	Loamy sand	0.401	0.035	0.055	5.98	0.07142	1.63868
3	Sandy loam	0.412	0.041	0.095	2.18	0.04697	1.42072
4	Loam	0.434	0.027	0.117	1.32	0.06330	1.27539
5	Silt loam	0.486	0.015	0.133	0.68	0.03312	1.26035
6	Sandy clay loam	0.330	0.068	0.148	0.30	0.02413	1.36097
7	Clay loam	0.390	0.075	0.197	0.20	0.02612	1.27227
8	Silty clay loam	0.432	0.040	0.208	0.20	0.01988	1.20244
9	Sandy clay	0.321	0.109	0.239	0.12	0.02281	1.25269
10	Silty clay	0.423	0.056	0.250	0.10	0.01859	1.17254
11	Clay	0.385	0.090	0.272	0.06	0.01690	1.19104

In order to obtain convergence for all the soils, it was necessary to use the van Genuchten (1980) model to describe the soil water hydraulic properties. The corresponding van Genuchten parameters, α and n, were obtained using the RETC program (van Genuchten et al., 1991) based on the curves described by the Brooks-Corey parameters (Table 1). Once the parameters were obtained, the soil water retention curves for both models were compared to ensure that they were equivalent. Similar methods for converting Brooks and Corey (1964) parameters to van Genuchten (1980) parameters have been researched and shown to provide similar results (Stankovich and Lockington, 1995; Lenhard et al., 1989; van Genuchten and Nielsen, 1985; Morel-Setoux et al., 1996).

Two simulated irrigation events, with constant flow rates, were run for each soil type for 465 minutes. The two flow rates were 0.5 and 1.0 L/h. The goodness-of-fit of the entire simulation against the Richards' results were evaluated using the Nash and Sutcliffe (1970) coefficient of efficiency (C_{eff}) and the root mean squared error (RMSE) to demonstrate the effectiveness of the two supply radius calculations presented for *R0*, the ground surface radius, and *R1*, the vertical wetting front depth.

3. RESULTS AND DISCUSSION

A general supply radius equation similar in form to the Simplified Philip equation (19), as a function of S_{av}, K_s and Q, for the supply radius was found to be (adj-R^2=0.80-1.0),

$$r_o = 0.0265 \cdot Q \cdot S_{av}^{-0.6098} \cdot K_s^{-0.6555} \tag{18}$$

The goodness-of-fit of the entire simulation against the Richards' results were evaluated using the Nash and Sutcliffe (1970) coefficient of efficiency (C_{eff}) and the root mean squared error (RMSE). Results obtained from using the simplified Philip and Proposed supply radius equations in the 3DGA model are compared to the Richards' model in Table 2.

The C_{effs} for the Simplified Philip equation for ground surface radius, R0, ranged from -13.46 to 0.96 with an average of -2.76 and the C_{effs} for maximum wetted depth, R1, ranged from -13.96 to 0.98 with an average of -2.54. For both R0 and R1 the extreme C_{effs} occurred in the Sandy Loam case (high) and the Clay case (low). The C_{effs} for the Proposed equation for R0 ranged from 0.52 to 0.96 with an average of 0.73 and the C_{effs} for maximum wetted depth R1 ranged from 0.60 to 0.97 with an average of 0.84. While the Simplified Philip equation performed well in some of the cases, it can be seen that the Proposed supply radius equation (Eq. 18) does a markedly better job at predicting *R0* and *R1* when used within the 3DGA model.

Lastly, Figs. 2 (a-c) provide a graphical comparison of the wetting front shape at *t* = 1h and 6h for the Clay, Loam and Sand soils chosen to provide a range from coarsest to finest soils. Both the Philip and Proposed equation result in an elongated wet bulb shape for the Sand soil and a more symmetrical shape for the Clay soil which we would expect for these flow rates. However, it can be seen that for all three soils, the Proposed equation does a better job at predicting the overall shape of the wetting front, including not only the R0 and R1 points, but points along the entire wet bulb.

Table 2. Coefficient of efficiency and root mean square error (in parentheses) results of simulations for comparing Simplified Philip and Proposed supply radius equations in the 3DGA model for typical flow rates

USDA texture	Flow (Lh^{-1})	*R0*		*R1*	
		Philip	Proposed	Philip	Proposed
Sand	1.0	-0.030 (4.166)	0.570 (2.691)	0.827 (2.662)	0.988 (0.703)
Loamy sand	1.0	0.854 (1.551)	0.637 (2.446)	0.979 (0.793)	0.962 (1.076)
Sandy loam	1.0	0.977 (0.592)	0.679 (2.233)	0.997 (0.275)	0.807 (2.225)
Loam	0.5	0.598 (1.875)	0.873 (1.052)	0.280 (3.084)	0.955 (0.772)
Silt loam	0.5	0.146 (2.647)	0.986 (0.340)	-0.017 (3.203)	0.995 (0.234)
Sandy clay loam	0.5	0.239 (3.221)	0.726 (1.931)	0.173 (3.833)	0.749 (2.112)
Clay loam	0.5	-2.872 (6.583)	0.890 (1.110)	-2.245 (7.433)	0.864 (1.521)
Silty clay loam	0.5	-3.093 (6.204)	0.557 (2.041)	-2.694 (6.734)	0.671 (2.010)
Sandy clay	0.5	-3.635 (7.980)	0.541 (2.513)	-3.676 (9.186)	0.620 (2.620)
Silty clay	0.5	-9.942 (10.942)	0.849 (1.286)	-7.712 (11.737)	0.885 (1.350)
Clay	0.5	-13.544 (15.574)	0.918 (1.172)	-13.201 (17.084)	0.921 (1.273)

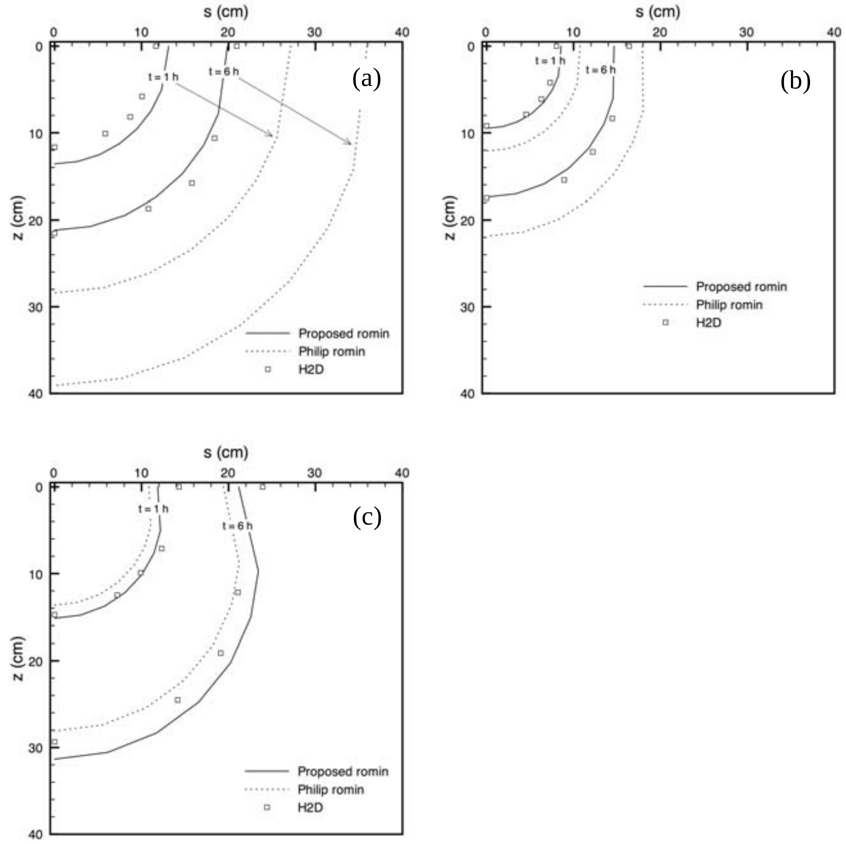

Figure 2. Wetting front shape at t = 1h and 6h for 3DGA and Richards' model, H2D, for: Clay soil (Q = 0.5 Lh-1); Loam soil (Q = 0.5 Lh-1); and Sand soil (Q = 1.0 Lh-1)

4. CONCLUSIONS

Drip irrigation technology has become an increasingly popular agricultural practice. Modeling of this technology has, therefore, become important in order to utilize this technology to its optimum potential. One such model is the 3DGA model; however, the emitter flow rate is not explicitly included in the model, but rather built into the supply radius parameter. Therefore, in order to use the model, a supply radius, r_o, must be determined. The most straightforward method is directly measuring the saturated radius that forms on the surface of the soil. However, since this is not convenient outside of a laboratory setting, equations that are a function of flow rate, Q, were examined. The equation developed by Philip (1969), was initially found to provide good results, however, it is parameter intensive. Therefore, a simplified form of the Philip Equation was developed and generalized for a wide range of soils. The proposed equation is valid for a wide range of soils and is a function of saturated hydraulic conductivity, K_s, effective suction at the wetting front S_{av} and emitter flow rate, Q. This equation provided good results for all the soils tested and, therefore, proved to be a viable method for calculating the supply radius parameter in the 3-dimensional Green-Ampt model.

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REFERENCES

Abramowitz, M., Stegun, I.A., Eds., 1964. Handbook of Mathematical Functions. *Applied Math Serial* Vol. 55, National Bureau of Standards, Washington, D.C.

Angelakis, A., Rolston, D., Kadir, T., Scott, V., 1993. Soil-Water Distribution Under Trickle Source. *J, of Irrigation and Drainage Engineerin*g 119(3), 484-499.

Ben-Asher, J., Charach, Ch., Zemel, A., 1986. Infiltration and Water Extraction from Trickle Irrigation Source: The Effective Hemisphere Model. *Soil Sci. Soc. Am. J.* 50, 882-887.

Brooks, R.H., Corey, A.T., 1964. Hydraulic Properties of Porous Media. Hydrology Paper 3 Colorado State University, Fort Collins, Colorado.

Brutsaert, W., 1979. Universal Constants for Scaling the Exponential Soil Water Diffusivity. *Water Resources Research* 15, 481-483.

Chu, S.T., 1994. Green-Ampt Analysis of Wetting Patterns for Surface Emitters. *J. of Irrigation and Drainage Engineering* 120(2), 414-421.

Clark, G., Smajstrla, A., Munoz-Carpena, R., 2006. Application Volumes and Wetting Patterns for Scheduling Drip Irrigation in Florida Vegetable Production. IFAS Circular 1041, University of Florida, Gainesville, Florida.

Clothier, B.E., Scotter, D.R., 1982. Constant-Flux Infiltration from a Hemispherical Cavity. *Soil Sci. Soc. Am. J.* 46, 696-700.

Gowdish, L., 2007. An Improved Green-Ampt Soil Infiltration and Redistribution Method and Its Application to 1-Dimensional and Quasi 3-Dimensional (Point Source) Flow Domains. Unpublished PhD Dissertation, University of Florida, Gainesville, Florida.

Healy, R.W., Warrick, A.W., 1988. A Generalized Solution to Infiltration from a Surface Point Source. *Soil Sci. Soc. Amer. J.* 52, 1245-1251.

Lenhard, R., Parker, J., Mishra, S., 1989. On the Correspondence Between Brooks and Corey and van Genuchten Models. *J, of Irrigation and Drainage Engineering* 115(4), 744-751.

Morel-Seytoux, H., Meyer, P., Nachabe, M., Touma, J., van Genuchten, M.Th., Lenhard, R., 1996. Parameter Equivalence for the Brooks and Corey and van Genuchten Soil Characteristics: Preserving the Effective Capillary Drive. *Water Resources Research* 32(5), 1251-1258.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part 1-A Discussion of Principles. *Journal of Hydrology* 10, 282-290.

Parlange, J.-Y., 1973. Theory of water movements in soils: 10. Cavities with constant flux. *Soil Science* 116, 1-7.

Philip, J.R., 1969. Theory of Infiltration. *Advances in Hydroscience* 5, 215-296.

Philip, J.R., 1984. Steady Infiltration from Spherical Cavities. *Soil Sci. Soc. Amer. J.* 48, 724-729.

Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T., 1996. Numerical Recipes in Fortran: The Art of Scientific Computing. Cambridge University Press, Port Chester, New York.

Raats, P.A.C., 1971. Steady Infiltration from point sources, cavities and basins. *Soil Sci. Soc. Am. Proc*. 35, 689-694.

Rawls, W.J., Brakensiek, D.L., Miller, N., 1983. Green-Ampt Infiltration Parameters from Soils Data. *Journal of Hydraulic Engineering* 109(1), 62 – 70.

Rawls, W.J., Brakensiek, D.L., Saxton, K.E., 1982. Estimation of Soil Water Properties. *Transactions of the ASAE* 25(5), 1316 – 1330.

Reichardt, K., Nielsen, D.R., Biggar, J.W., 1972. Scaling of Horizontal Infiltration into Homogeneous Soils. *Soil Sci. Soc. Amer. Proc*. 36, 241-245.

Richards, L.A., 1931. Capillary Conduction through Porous Mediums. *Physics* 1, 313-318.

Sepaskhah, A.R., Chitsaz, H., 2004. Validating the Green-Ampt Analysis of Wetted Radius and Depth in Trickle Irrigation. *Biosystems Engineering* 89(2), 231-236.

Simunek, J., Sejna, M., van Genuchten, M. Th., 1999. The HYDRUS-2D Software Package for Simulating the Two-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. IGWMC-TPS 53, Version 2.0, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colo.

Stankovich, J.M., Lockington, D.A., 1995. Brooks and Corey and van Genuchten Soil-Water Retention Models*. J, of Irrigation and Drainage Engineering* 121(1), 1-7.

van Genuchten, M.Th., 1980. A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Sci. Soc. Am. J.* 44, 892-898.

van Genuchten, M.Th., Leij, F.J., Yates, S.R., 1991. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils. EPA Report: EPA/600/2-91/065, Ada, Oklahoma.

van Genuchten, M.Th., Nielsen, D.R., 1985. On Describing and Predicting the Hydraulic Properties of Unsaturated Soils. *Ann. Geophysics* 3(5), 615-628.

Warrick, A.W., 1974. Time-Dependent Linearized Infiltration : I. Point Sources. *Soil Sci. Soc. Am. J.* 38(3), 383-386.

Warrick, A.W., Lomen, D.O., 1976. Time-Dependent Linearized Infiltration: III. Strip and Disc Sources. *Soil Sci. Soc. Amer. J.* 40(5), 639-643.

Wooding, R.A., 1968. Steady Infiltration from a Shallow Circular Pond. *Water Resources Research* 4(6), 1259-1273