New Water-Saving Production Technologies: Advances in Trickle Irrigation

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Abstract

Increasing demand is being placed on the world's water resources with resultant pressure on food production to use water with increasing efficiency. It is recognized that trickle irrigation systems can deliver water (and chemicals) to the root zone of plants more efficiently than most other forms of irrigation. In common with other irrigation systems, however, a poorly designed and operated trickle irrigation system will not deliver the desired efficiencies. For trickle irrigation systems to operate efficiently, the two variables most easily manipulated when designing trickle irrigation systems, the distance between emitters and emitter flow rates, must be matched to both the soil's wetting characteristics and the amount and timing of water to be supplied to the crop. This principle is rarely adopted during system design, possibly because most practitioners do not realize the variability in wetting patterns amongst different soils. To illustrate this variability, an analysis of wetting patterns was undertaken based on hydraulic properties of a wide range of soils from an area in which row crops and small crops are trickle-irrigated. There was a wide range of wetting patterns in these soils, but there was no relationship between the wetting pattern and texture, indicating that texture is an unreliable predictor of wetting. Practical implications of the results are illustrated by considering that they suggest that emitter spacings and flow rates commonly used in row and small crops in northeastern Australia are unlikely to be well matched to the wetting patterns. To demonstrate the variability in soil wetting for trickle system designers and irrigators, a simple software tool "**WetUp**" has been developed based on the models and databases used in the analysis. Once it is seen that the soil structure allows a sand to "behave" as a clay and vice versa, more effort will be put into obtaining site-specific information on soil wetting prior to designing and installing trickle irrigation systems. Then, trickle irrigation may deliver the irrigation efficiencies expected from the system.

Introduction

Trickle irrigation is a means of both increasing the efficiency of irrigation water use and reducing leaching of chemicals from the root zone. These are important goals for irrigated agriculture, which faces pressure to reduce environmental impacts and increase the efficiency of irrigation water use (Oster, 2002). To achieve these goals, however, trickle irrigation systems must be designed (e.g., tape lateral spacing, emitter spacing, emitter discharge rates) and operated (e.g., irrigation scheduling, fertigation) properly (Phene, 1995) so that rates and location of delivery of water and chemicals in the root zone are matched to crop requirements.

Wetting patterns are usually characterized by the radial distance (r) of the wetting front from the emitter

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and the depth of wetting below (z_+) or, with buried tape, above (z_-) the emitter (Fig. 1). Generally, the criteria for trickle system design are based on soil texture classes (Reddy, 1988; Hung, 1995) modified by local experience of system designers and farmers. An example of this is the Australian sugar industry where two soil texture classes are recognized — the recommended dripper spacing is 0.4 m in sandy soils and 0.6 m in other soils (Hewson *et al.*, 1995). A problem with classification systems based on texture is that soil hydraulic properties, which control wetting patterns, are not simply a function of texture (or soil type) — they may be dominated by the effect of soil structure (Haverkamp *et al.*, 1999). For example, wetting patterns have been recently measured at three sites in the Australian sugar industry (McDougall and Hussey, 1999). After application of ~ 5 L (equivalent to 5.5 mm) of water, a common irrigation application in that industry, the diameter (i.e. 2r) of the wetted area was 0.24, 0.38 and 0.47 m in a "sand", "sandy loam" and a "clay", respectively. These results do not support either the binary classification or the spacings recommended by Hewson *et al.* (1995).

In addition, apart from the study by Bailie and Dart (1997), there is little consideration of the distances that water moves vertically (i.e. z_+ or z_-) from the emitter. Yet both these distances are important: z_+ determines the likelihood that water and fertigation chemicals will move below the root zone during irrigation; z_- determines if the seedbed will be wet, which is vitally important during germination. Both of these processes depend on soil hydraulic properties and are thus likely to be quite variable between soils with different hydraulic properties. If the hydraulic properties of a given soil are poorly related to its texture, the texture/soil type criteria for delivering efficient trickle irrigation systems are likely to be inadequate.

In this study we examined the variability in wetting from a point source in soils with widely ranging texture to analyze the relationship between wetting pattern dimensions and soil texture. We used the analytical model of Philip (1984) to calculate wetting patterns because it is simple and has been found to provide good predictions of the radius and depth of the unsaturated wetted zone in a field study (Revol *et al.*, 1997). We conclude that wetting patterns are poorly related to the soil texture due to the effects of the soil structure on hydraulic properties. To demonstrate the variability in soil wetting for trickle system designers and irrigators, a simple software tool "**WetUp**", based on the models and databases used in the analysis, is described. Implications of the results for designing and managing trickle irrigation systems are discussed.

Methods

Theory

For infiltration from the soil surface, the travel-time of the wetting front away from a point source

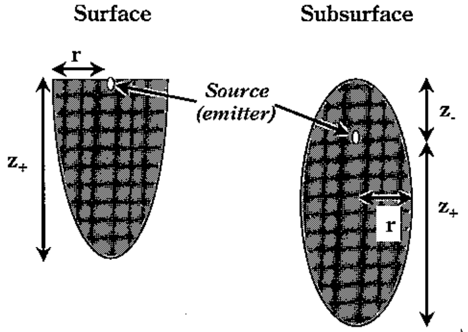

Fig. 1 Schematic representation of the dimensions of wetted soil from surface and subsurface trickle irrigation emitters. r is the radius of wetting, z_+ is the depth of wetting below the emitter, and z_- the distance wetted above the emitter

vertically downwards and radially is given for dimensionless time (T), vertical distance (Z_+) and radial distance (R) by (Philip, 1984),

$$T = \frac{Z_+^2}{2} - Z_+ + \ln(1+Z_+) \qquad (1)$$

and

$$T = 2\exp(R)[1 - R + R^2/2] - 2\,, \qquad (2)$$

where

$$T = \alpha^3 qt/(16\pi\Delta\theta), \qquad (3a)$$

$$Z_+ = \alpha z_+/2, \qquad (3b)$$

$$R = \alpha r/2, \qquad (3c)$$

t is the time, z_+ is the vertical distance below (positive downward), r is the radial distance, α is the inverse of the macroscopic length scale (defined by White and Sully, 1987), q is the source strength (i.e. emitter flow rate), $\Delta\theta = \overline{\theta} - \theta_n$, $\overline{\theta}$ is the average volumetric water content in the soil behind the wetting front, and θ_n is the initial volumetric water content prior to wetting.

For infiltration from a buried source, the dimensionless travel times of the wetting front in the vertical downward (Z_+) and upward directions (Z_-) are given by (Philip, 1984);

$$T = \frac{(Z_+^2 - Z_+)}{2} + \frac{\ln(1+2Z_+)}{4}\,, \qquad (4a)$$

$$T = [\exp(2Z_-)(1 - 2Z_- + 2Z_-^2) - 1]\,/2\,, \qquad (4b)$$

where

$$Z_- = \alpha z_-/2. \qquad (5)$$

For the radial travel-time for a buried source the solution is (Thorburn *et al.*, 2002),

$$T(0, R) = e^R[R^2 - R + \frac{1}{2}(1 - R - \ln(2)) \cdot \ln(2e^R - 1) - \frac{1}{2} L(2e^R) - \frac{\pi^2}{24}]\,, \qquad (6)$$

where L(x) denotes the dilogarithm defined by

$$L(x) = -\int_1^x \frac{\ln x}{x-1}\,dx\,. \qquad (7)$$

To solve T in equation 6, the integral in equation 7 must be solved, which we do numerically.

For a soil, values of r, z_+ or z_- at a given value of t and q for either surface or buried sources can be obtained from equations 1, 2, 4 or 6 by finding the root of the relevant equation. More details on these solutions are given by Thorburn *et al.* (2002).

Soils

Soil hydraulic properties were collated for 18 soils (Table 1). The soils had been used in a study of soil hydraulic properties in the Bundaberg region, Queensland, Australia (Verburg *et al.*, 2001), an important irrigation area in coastal northeastern Australia. At nine sites, hydraulic properties were determined in different horizons with minimal disturbance. Hydraulic conductivity at (and near) saturation was determined *in situ* and the moisture characteristic was determined in the laboratory on intact cores, with much of the natural soil structure retained. Moisture characteristic and hydraulic conductivity data were expressed as functions of θ (Brooks and Corey, 1964, 1966; Campbell, 1985). Values of α, θ_n and $\overline{\theta}$ were derived from these functions for surface (< 0.1 m depth) and deeper (0.2 − 0.5 m) horizons, providing 18 soils with a wide range of hydraulic properties. The soils also showed a considerable range in bulk density (1.2 – 1.8 Mg m^{-3}) and clay content (6 – 46 %).

The macroscopic length scale was calculated from the hydraulic property functions of each soil, following equation 17 of White and Sully (1987). θ_n was taken as the water content at a soil matric potential of -100 kPa, a potential likely to be reached in soils prior to the commencement of irrigation. θ_n was calculated from relationships between matric potential and water content for each soil. $\overline{\theta}$ was defined as (θ_s - θ_f)/2, where θ_s is the saturated water content and θ_f is the water content at the wetting front. The value of θ_f was taken as the value of θ when the soil hydraulic conductivity is 1 mm hr^{-1} and it was calculated from the water content – hydraulic conductivity relationship of each soil. The assumption of a constant θ (= $\overline{\theta}$) in the wetted area seems reasonable (Revol *et al.*, 1997; Bar-Yosef, 1999; Cook *et al.*, 2002).

Table 1 Details of the soils studied (from Verburg *et al.*, 2001)

Soil number	Texture	Clay (%)	Silt (%)
1	loamy sand	6	13
2	loamy sand	6	12
3	loamy sand	7	13
4	loamy sand	8	19
5	loamy sand	9	17
6	loamy sand	9	8
7	loamy sand	10	20
8	loamy sand	10	13
9	sandy loam	15	8
10	loam	22	14
11	loam	22	14
12	loam	22	14
13	clay loam	23	14
14	clay loam	26	25
15	silty clay loam	31	25
16	clay loam	32	13
17	silty clay	42	31
18	silty clay	46	28

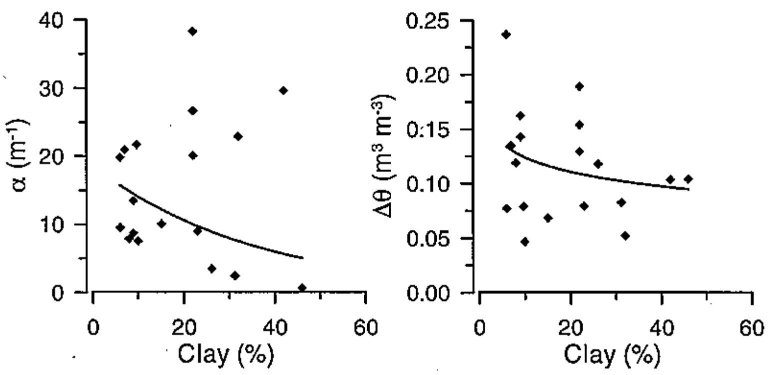

Fig. 2 Change in α and $\Delta\theta$ with increasing clay content in the 18 soils analyzed.

Analysis of wetting patterns

Calculated wetting dimensions

Wetting dimensions were calculated for each soil for two volumes (i.e. q.t) of applied water, 1.65 and 6.6 L. These volumes were chosen as they gave realistic water application amounts for daily irrigation of sugarcane and horticultural crops, the dominant irrigated crops in coastal northeastern Australia. For example, 6.6 L is equivalent to 7 mm of applied water for a common trickle tape layout in sugarcane (0.6 m emitter spacing and 1.57 m between tapes).

Wetting pattern results

Values of α and $\Delta\theta$, the soil hydraulic properties upon which wetting patterns calculations are based, were poorly correlated with clay content in the soils (Fig. 2). The curves shown in Fig. 2 accounted for 12 % of the variation in α and 7 % of the variation in $\Delta\theta$. Given that clay and silt contents of these soils are highly ($P < 0.002$) correlated, the inclusion addition of silt content with clay to improve the description of soil texture is unlikely to provide a better statistical relationship between soil hydraulic properties and texture for these soils.

The radius and depth of the wetted volume for surface emitters were always larger than those for buried emitters (means across all soils shown in Table 2), as some water moved upward from buried emitters, resulting in the reduction of the volume moving horizontally and downwards. However, the difference was generally small. Because of this similarity in wetted volume dimensions for surface and buried emitters, detailed results for r and z_+ will only be given for surface emitters.

There was a large variation in the wetted volume dimensions between the soils. Across the different soils and volumes of applied water, values of r varied from 0.1 to 0.5 m, while z_+ varied from 0.2 to 0.6 (Fig. 3). Values of z_- with a buried source were slightly less variable, ranging from 0.1 to 0.4 m (Fig. 4). Variations in wetting between soils were not well related to the soil type or texture. For example, soils 10 to 13 showed a similar classification and texture (Table 1) but similar variations in r (Fig. 3b) and z_- (Fig. 4) as most other soils. Also, both soils 17 and 18 are silty clays (Table 1), but have contrasting values of r and z_+ (Fig. 3). There was also a poor relationship between r and z_+ (Fig. 5).

The dimensions of the wetted volumes are consistent with those measured previously in the region fromwhere the soils were sampled. For example, after application of 5 L of water from a trickle irrigation emitter, values of r in the three soils studied by McDougall and Hussey (1999) ranged from 0.12 – 0.25 m, a comparable range to that in this study (Fig. 3b). However, direct comparisons are difficult to make because of

Table 2 Statistics of calculated wetted volume dimensions (defined in Fig. 1) in 18 soils after application of 1.65 and 6.6 L of water

	Surface				Subsurface					
	1.65 L		6.6 L		1.65 L			6.6 L		
	R	Z_+	r	z_+	r	z_+	z_-	r	z_+	z_-
Mean	0.16	0.25	0.23	0.44	0.14	0.22	0.11	0.21	0.40	0.16
Maximum	0.33	0.35	0.52	0.58	0.27	0.29	0.26	0.43	0.56	0.40
Minimum	0.10	0.20	0.13	0.35	0.09	0.18	0.07	0.13	0.31	0.08

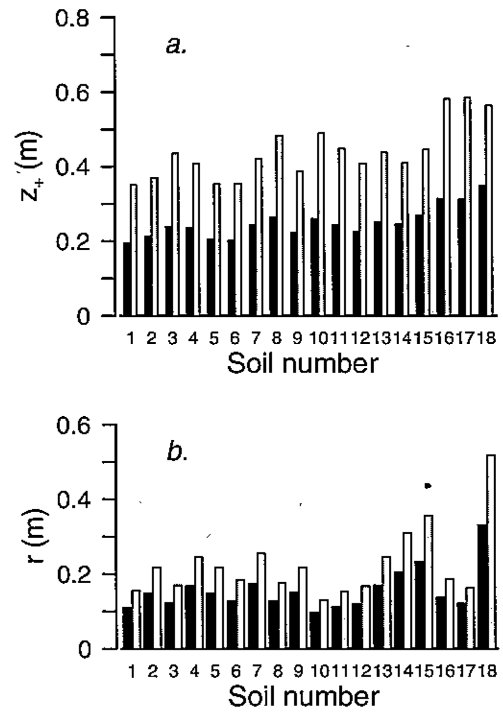

Fig.3 Depth (z_+) and radius (r) of wetted volume for all the soils after 1.65 L (striped) and 6.6 L (stippled) of water applied from a surface source.

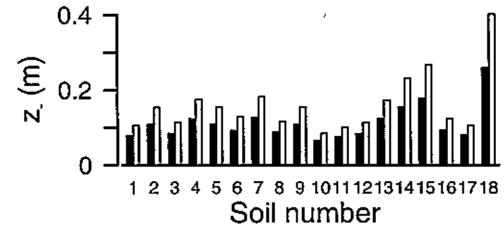

Fig. 4 Distance (z_-) of the wetted volume above the emitter for all the soils after 1.65 L (striped) and 6.6 L (stippled) of water applied from a buried source.

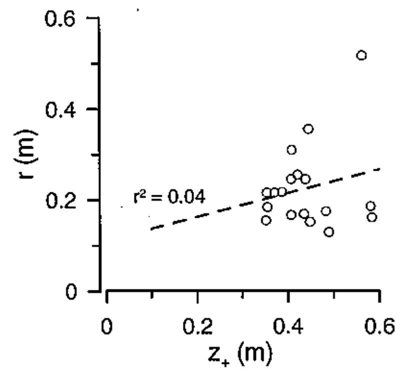

Fig. 5 Relationship between depth (z_+) and radius (r) of the wetted volume for all the soils after 6.6 L of water applied from a surface source.

the lack of detail given about soils in the previous studies. While it is not a rigorous test, the general agreement between the measured and calculated wetting patterns is encouraging, particularly considering the assumptions underlying the analyses.

Management implications of wetting patterns

It is a common notion that texture (through its impact on hydraulic properties) controls wetting patterns from trickle emitters (Reddy, 1988; Hung, 1995; Hewson *et al.*, 1995). It is possible that this concept holds when hydraulic properties are average over many soils of given texture (Thorburn *et al.*, 2002). However, when the properties of individual soils are considered, no such relationship was apparent (Figs. 3 and 4). These results are likely to be due to the impact of the soil structure on hydraulic properties (Haverkamp *et al.*, 1999), as the structure was retained to a large degree in the determination of hydraulic properties of the soils in this study (Verburg *et al.*, 2001). If the relationship between texture and wetting patterns holds for the average behavior of different texture classes but not for individual soils, which information provided the most useful basis for designing trickle irrigation systems? We argue that the results for individual soils are more directly relevant to irrigated soils than those based on either general "average" soil behavior or "rules of thumb". It is clear from our results (Figs. 3 and 4) that, in the absence of site-specific information to the contrary, dripper spacings should not be varied in response to the soil texture.

The practical relevance of the results is illustrated by considering the common dripper spacings used in sugarcane and horticultural crops in the region from where the soils were sampled. The recommended dripper spacing for sugarcane of 0.6 m (Hewson *et al.*, 1995) was larger than the equivalent value of 2r in most soils after application of 6.6 L (or 7 mm) of irrigation water. Thus, the results suggest that it is too large to generally give complete lateral soil wetting with daily application of irrigation water. Adopting the dripper spacing recommended for sandy soils (0.2 m) would be a "safer" option when designing trickle irrigation systems for sugarcane. Conversely, the common dripper spacing used in horticultural crops (e.g., tomatoes) is 0.2 m (J. Olsen, personal communication). This spacing is less than the equivalent value of 2r in all soils after application of 1.65 L of water, an amount necessary for daily irrigation. Thus, a greater dripper spacing could be adopted in many soils for irrigation of horticultural crops.

There are implications for the loss of water and chemicals below the root-zone, an aspect not often considered in trickle irrigation systems (Thorburn *et al.*, 1998). The depth to which the soils are wetted ranges from 0.3 to 0.6 m (Table 2), or more if the tape is buried (i.e. 0.6 − 0.9 m if the tape is buried at 0.3 m). Unless roots are active at these depths, water and chemicals will be lost below the root zone on each irrigation application. In horticultural (small crop) systems, since it is unlikely that roots would be active at these depths, the potential for losses is great. Another situation in which chemical losses are likely to occur is in trickle systems where irrigation frequencies are lower (e.g., weekly) and hence higher volumes of water applied upon each irrigation. This is a common management practice in trickle-irrigated sugarcane (Ridge and Hillyard, 2000). Low frequency-high volume water applications should be avoided to minimize the loss of water and chemicals below the root zone.

Thus in neither the sugarcane nor horticultural examples are current trickle irrigation systems likely to be optimally designed, giving maximum production, maximum water and nutrient use efficiency while concurrently minimizing off-site impacts.

WetUp - A software tool to illustrate soil specific wetting patterns

Given the results of this study, the question must be asked, why is so little attention paid to soil-specific wetting patterns when designing trickle irrigation systems? A possible answer is that information on the variability of wetting in soils is scarce. Most soil physics textbooks and trickle irrigation manuals promulgate the concepts of "average" soil behavior. For the findings of this study to be relevant to trickle irrigation systems designers, the range of conditions under which wetting patterns can be calculated must be wider. For people without formal training in applied mathematics, since solving equations 1, 2, 4 and 6 will be challenging, a wetting pattern "calculator" may help illustrate the variability in wetting between individual soils under relevant conditions.

We have developed a software tool, **WetUp**, to perform this function. **WetUp** contains a database with values of r, z_+ and z_- calculated for the set of soils listed in Table 1 and the average hydraulic properties for different soil texture classes described by Clapp and Hornberger (1978), and analyzed by Thorburn *et al.* (2002). The values were calculated for a range of flow rates (0.5 − 2.7 L hr^{-1}) of common drippers, for application times from 1 to 24 hours (in steps of 1 hour) and for buried and surface sources. The user selects a soil, flow rate and maximum time using radio buttons in the windows interface (Fig. 6). For this set of parameters, the values of r, z_+ and z_- are selected from the database and the wetted perimeter is then calculated assuming that wetting patterns are elliptical, defined by r and z_+ for downwards wetting and r and z_- for upwards wetting. Wetting patterns are displayed for up to six values of time evenly spaced between 0 and the maximum time specified. Multiple screens can be displayed allowing different sets of parameters to be selected and the resulting wetted perimeters compared. This allows the user to see the consequences of changing parameters; for example, the depth of the dripper, the flow rate, soil type and/or application time. We expect that this information will result in the design of more efficient trickle irrigation systems.

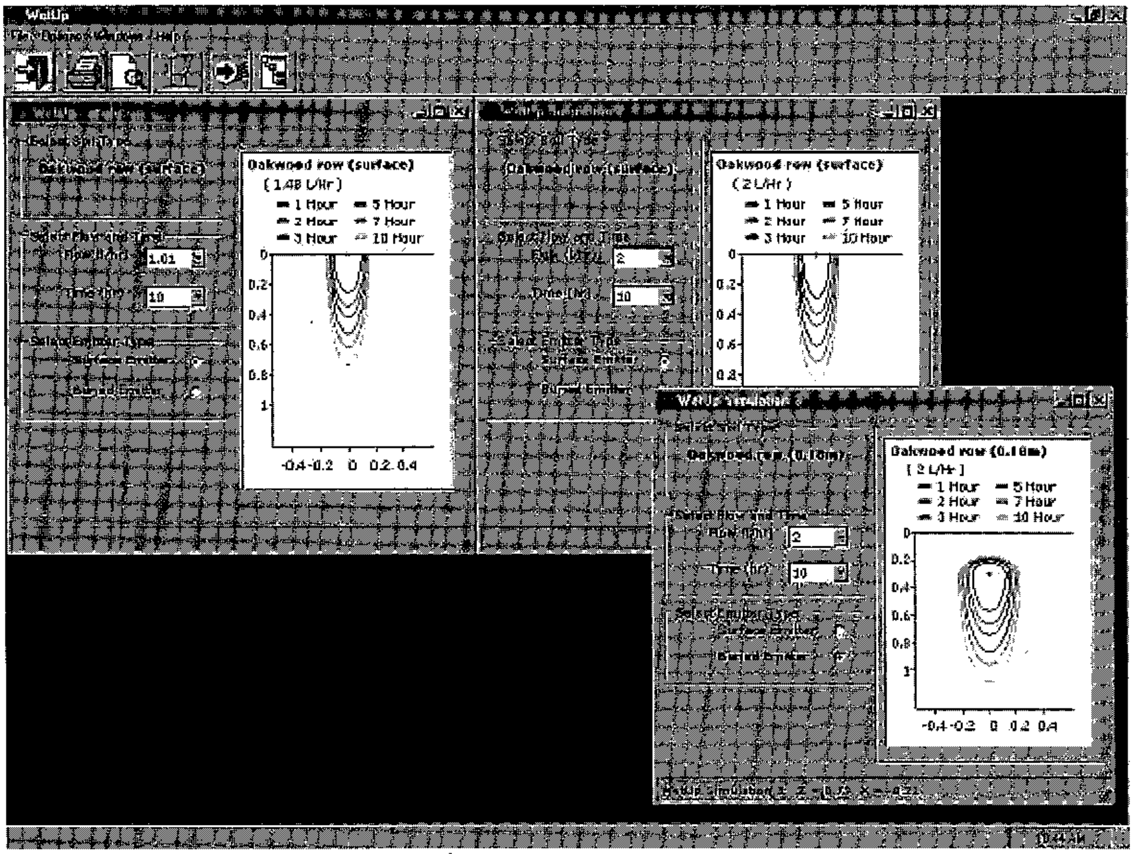

Fig. 6 Example of the WetUp interface screen, depicting wetting patterns calculated under three different conditions.

Discussion

This study highlights the need for site-specific soil information to design efficient systems. If the effects of soil structure allow a sand to "behave" as a clay and vice versa, soil types and textures are of little use in designing trickle irrigation systems. We have developed a software tool (**WetUp**) that displays the wetting patterns of 29 soils under a wide range of conditions set by the user. While the displayed patterns are only indicative because of the assumptions (homogeneous soil hydraulic properties, constant water content in the wetted zone, elliptical-shaped wetting patterns) in the model used to calculate the patterns, exploration of the variability of wetting in **WetUp** may convince users that site-specific information is required to design efficient trickle irrigation systems.

Specific information for designing systems could be gained by observing wetting patterns in the field from tape laid on the surface soil. Values of r could be observed at various times (e.g., 1, 2 and 4 hr) and a trench dug, after water applications had ceased, to determine z. This trenching would also have the benefit of identifying soil horizons and other layers (e.g., plow pans) that would affect wetting patterns. If more general information on wetting is needed, for example, estimation of dimensions at longer times or at different flow rates, soil hydraulic properties (α and $\Delta\theta$) required to calculate wetting patterns can be derived from the observations of wetting (Revol *et al.*, 1997) and used to extrapolate the measurements.

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