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MICRO-IRRIGATION: ADVANCES IN SYSTEM DESIGN AND MANAGEMENT

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WetUp: a software tool to display approximate wetting patterns from drippers

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Abstract Knowledge of the wetted perimeter of soil arising from infiltration of water from trickle irrigation drippers is important in the design and management of efficient systems. A user-friendly software tool, WetUp, has been developed to help highlight the impact of soils on water distribution in trickle-irrigated systems. WetUp determines the approximate radial and vertical wetting distances from an emitter in homogeneous soils calculated using analytical methods, and then uses an elliptical plotting function to approximate the expected wetted perimeter. In this paper we describe WetUp and use examples to demonstrate how it can be applied. We also compare the wetted perimeter predicted using WetUp with that predicted by other methods. Results show that the wetting pattern is well described by the ellipsoidal approximation for slowly permeable soils, but that it tends to underestimate the radial wetting in highly permeable soils, particularly as the volume of applied water increases. The error is, however, small in most cases, and of minimal concern when applying WetUp to illustrate the important role that soil hydraulic properties play in determining wetting patterns.

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Introduction

For trickle irrigation systems to fulfil their promise of efficient delivery of water and nutrients to the root zone they must take into account the actual soil properties in their design and management. At present, if soil properties are taken into account, it is usually only in a rudimentary way, such as recognising two or three broad texture classes. In a companion paper (Thorburn et al. 2003), it has been clearly shown that there can be a wide range of wetting patterns in individual soils, and that the conventional notions relating average wetting behaviour to soil texture do not hold when working with specific soils. The reality is that texture is an unreliable predictor of soil wetting, and site-specific information on soil wetting patterns is required to design efficient trickle irrigation systems. Little attention is currently paid to soil-specific wetting patterns when designing and managing trickle irrigation systems and so one would need to convince trickle irrigation system designers to invest resources into obtaining the required soils information. We felt that development of a user-friendly software tool, or "calculator", that could be used to illustrate the variability in wetting between individual soils would be one way to help people appreciate the need for soil-specific information to be built into the design of trickle irrigation systems (Thorburn et al. 2002).

For a wetting pattern "calculator" to be widely accepted it must be simple, intuitive and easy to use. While complete descriptions of multidimensional infiltration are offered by detailed numerical models such as HYDRUS-2D (Simunek et al. 1999; Cote et al. 2003) they do not satisfy the above criteria for ease of use. Rapid techniques, such as analytically based models, even if approximate, will be better suited. To examine wetting patterns in soils, Thorburn et al. (2003) used an approximate method for calculating the radial wetted perimeter distance in a plane at the source and the vertical wetted maximum depth above and below the dripper. These wetted distances are calculated using approximate analytical equations due to Philip (1984). To calculate these distances a series of programmes written in Maple (Waterloo Maple 2000) were developed. Even a relatively simple model like this can take considerable computational time to complete a set of calculations for a soil, as an iterative procedure is required. This is particularly so if complete wetting patterns are to be displayed, rather than just the radial and vertical coordinates presented by Thorburn et al. (2003).

A simpler method for providing designers and users of trickle irrigation systems that encapsulated the results from the analysis of Thorburn et al. (2003) was sought. This resulted in the software tool WetUp, which uses the radial and vertical distances calculated using the methods described by Thorburn et al. (2003) and assumes that the wetted perimeter can be adequately approximated by an ellipse (Hachum et al. 1976).

This paper describes WetUp (v1.5) and presents some examples of its use. Also, to test the accuracy of the elliptical approximations used in calculating the wetted perimeter in WetUp, we compared the method of calculation of the wetted perimeter used in WetUp to the more physically based approximations of Philip (1984) for contrasting soils. We conclude that WetUp provides accurate estimates of the wetted perimeter in slowly permeable soils, but tends to underestimate the radial wetting in highly permeable soils when large volumes of water are applied.

Methods

Theory

In developing the theory we consider a source of strength Q (m^3 s^{-1}) located at $(s, z) = (0, 0)$, where s is the radial distance (m) and z is depth (m). The radial distance in the plane of the source ($z = 0$) and the maximum vertical distance ($s = 0$) are described by Thorburn et al. (2003) and are not repeated here. For a buried source, the distance to the wetted perimeter at dimensionless time, T, is given by equation (30) of Philip (1984):

$$T(R,\phi) = \frac{\exp\left(2R\sin^2\frac{1}{2}\phi\right)}{2\cos^2\frac{1}{2}\phi}\left\{\begin{array}{l} R^2 - R + \left[\ln\left(\cos\frac{1}{2}\phi\right) - R\sin^2\frac{1}{2}\phi + \frac{1}{2}\right] \\ .\ln\left(\dfrac{\exp\left[2R\sin^2\frac{1}{2}\phi\right] - \cos^2\frac{1}{2}\phi}{\sin^2\frac{1}{2}\phi}\right) \\ -\frac{1}{2}\left[L\left(\sec^2\frac{1}{2}\phi\exp\left[2R\sin^2\frac{1}{2}\phi\right]\right) - L\left(\sec^2\frac{1}{2}\phi\right)\right] \end{array}\right\} \quad 0<\phi<\pi \tag{1}$$

where r, ϕ are the spherical polar coordinates ($s = r\sin\phi$, $z = r\cos\phi$), $R = \alpha r/2$, α is the reciprocal of the macroscopic capillary length scale (White and Sully 1987), $L(x)$ is the dilogarithm defined by:

$$L(x) = -\int_1^x \frac{\ln x}{x-1}\mathrm{d}x \tag{2}$$

and the dimensionless time T is given by:

$$T = \frac{\alpha^3 Qt}{16\pi\Delta\theta} \tag{3}$$

where Q is the dripper flow rate, t is time and $\Delta\theta$ is the average change in volumetric water content behind the wetting front (Revol et al. 1997; F.J. Cook, P.J. Thorburn, K.L. Bristow and C.M. Cote, unpublished). The macroscopic capillary length scale is a hydraulic conductivity weighted scaling factor that relates the matric potential to the hydraulic conductivity (Philip 1985), and can be thought of as the "mean" height of capillary rise above a water table (Raats and Gardner 1971). The maximum value of s (referred to here as s_m) for a buried source was obtained by solving Eq. 1.

For a surface source, T is related to the wetted perimeter by equation (44) of Philip (1984):

$$T(R,\phi), = \exp[R(1-\cos\phi)] \times \left\{\begin{array}{l} R^2\left(1 - \dfrac{1}{2}\cos\phi\right) - R + \} \\ \dfrac{1}{\cos\phi}\left[\begin{array}{l} R(1-\cos\phi)\ln(1-\cos\phi) \\ +\ln\left(\dfrac{1-\cos\phi\exp[R(\cos\phi-1)]}{1-\cos\phi}\right) \\ -L(1-\cos\phi\exp[R(\cos\phi-1)]) + L(1-\cos\phi) \end{array}\right] \end{array}\right\} \quad 0<\phi<\frac{1}{2}\pi \tag{4}$$

The radius at the surface ($z = 0$) and maximum vertical depth ($r = 0$) are described by Thorburn et al. (2003). The maximum value of s (already defined above) for a surface source was obtained from the solution of Eq. 4.

For given values of T, values of (R, ϕ) were obtained by solving Eqs. 1 and 4 iteratively, which then yielded the wetted perimeter. For the same values of T, values of r_m (r at $z = 0$) and z_{m+} and z_{m-} (z at $r = 0$) were obtained using methods described in Thorburn et al. (2003). For these cases the wetted perimeter was then calculated with the equation for an ellipse:

$$\left(\frac{z}{z_m}\right)^2 + \left(\frac{r}{r_m}\right)^2 = 1 \tag{5}$$

For the buried source the ellipse for the wetted perimeter above the source uses $z_m = z_{m-}$ and below the source $z_m = z_{m+}$. The relative error in the estimated radius, from Eq. 5, was obtained by comparison with that from either Eq. 1 or Eq. 4. Hourly values were calculated for the wetted perimeter for a range of soils (Clapp and Hornberger 1978; Verburg et al. 2001) for a 24-h period. The maximum error was calculated at 1 and 4 h with an application rate of 1.65 l h^{-1} (1.65 and 6.5 l of total irrigation applied, respectively) for each soil. These irrigation application times (volumes of water) equate to a range likely to be applied on a daily basis in trickle irrigation systems.

The assumption of a constant $\Delta\theta$ in Eq. 3 was questioned by Revol et al. (1997). They used a method developed by Clothier and Scotter (1984) based on Raats' (1971) solution for flow from a point source to obtain a time dependent value for $\Delta\theta$. F.J. Cook, P.J. Thorburn, K.L. Bristow and C.M. Cote (unpublished) used this approach to compare a constant and time dependent $\Delta\theta$ on the wetting patterns. Their results suggest that for short times the use of a constant $\Delta\theta$ will overestimate and at long times underestimate the wetted perimeter. However, for most practical irrigation applications, the use of a constant $\Delta\theta$ will result in very good estimates of the wetted perimeter (Revol et al. 1997; Cook et al., unpublished).

WetUp (v1.5)

The WetUp program is a Microsoft Windows MDI (multiple document interface) application written in Microsoft visual basic. WetUp displays (Fig. 1) elliptical simulations of the wetted perimeter for the set of soils listed in Thorburn et al. (2003), for a range of flow rates, application times, antecedent water contents and emitter locations (surface or buried at a user-specified depth). As a MDI application, multiple child screens (simulation windows) can be displayed simultaneously, allowing different sets of parameters to be selected and the resulting wetted perimeters to be compared (Fig. 1). This allows the user to compare the consequences of changing various factors such as the depth of the dripper, the flow rate, the initial potential, application time, etc. Up to four simulation windows can be displayed in the application main window; this can be altered if in the future it was decided that more windows are required. By being able to rapidly compare effects of different soil properties and management decisions on wetting pattern behaviour, it is hoped that more effort will be invested in improving the design and management of trickle irrigation systems

The application is operated using either the main menu or by way of the button toolbar. For each window, users specify soil type, initial water content (i.e. initial matric potential), maximum water application time, and water application flow rate. The range of flow rates available to the user are typical of those commonly used in trickle irrigation systems in north-eastern Australia (0.503–2.7 l h^{-1}). Maximum irrigation water application times ranged from 1 to 24 h in steps of 1 h. Three different initial water contents were used, corresponding to initial soil matric potentials of −10 m ('dry soil'), −6 m ('moist soil') and −3 m ('wet soil'). The parameter selections are displayed in drop-down lists. Global display options include the depth (from 0.1 to 1.5 m) of buried emitters and axis conditions (maximum value, line width, line colour, number of displayed decimal places, etc.). These options allow the simulation windows to be easily tailored to any number of user preferences. Once a simulation has been completed, it can be previewed for printing, and then printed using any printer attached to the user PC. The cursor position (depth and radius) is continuously given on the application's status bar. This information can be used to quantitatively identify the position of the wetting front by moving the cursor to that position on the display.

A basic HTML help system has been developed to accompany WetUp, which provides references and simple instructions.

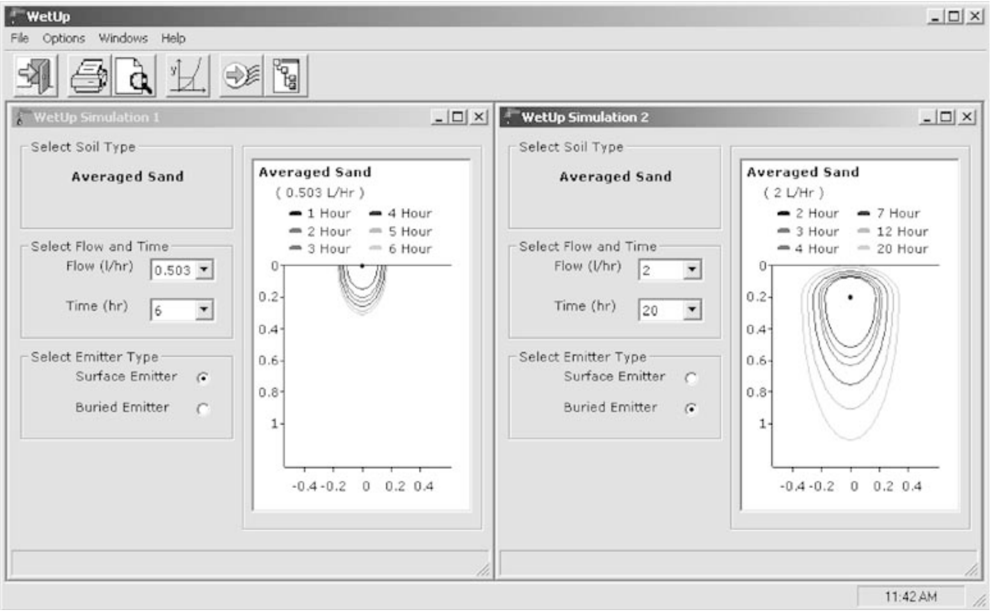
Rather than calculating values of r_m, z_{m+} and z_{m-} in real time, WetUp contains a database of pre-calculated values for the pre-defined soils flow rates, application times, antecedent water contents and emitter locations. Once these parameters have been set by the user, values of r_m, z_{m+} and z_{m-} are drawn from the database and the wetted perimeter calculated using Eq. 5 for up to six evenly spaced times between 0 and the maximum application time chosen, and displayed. Use of a database allows for easy addition or modification of soil types or data, as no additional coding is required. The software uses a Microsoft Access database, which provides a simple software interface and allows easy modification of data.

Accuracy of wetting patterns estimated using WetUp

The accuracy of the elliptical wetted perimeters calculated using Eq. 5 were compared with more exact solutions of Eqs. 1 and 4. For these analyses the flow rate and initial matric potential were set at 1.65 l h^{-1} and −10 m, respectively. The wetted perimeters were calculated for all soils used by Thorburn et al. (2003) at hourly intervals from 1 to 24 h. The values at 1 and 4 h were selected from these data and the wetted perimeters at these times calculated using Eqs. 1 and 4 for the average hydraulic properties for the clay and sand soils given by Clapp and Hornberger (1978). These soils have contrasting physical properties, which illustrate the range of error likely to be introduced by the ellipsoidal approximation.

Results and discussion

The wetted perimeters calculated for the average clay soil at both times using Eq. 5 compared well with the wetted perimeters calculated using Eqs. 1 and 4 (Figs. 2, 3). These wetted patterns are relatively spherical (for the buried emitter) or semi-spherical (for the surface emitter) in shape due to capillary forces dominating the flow, as expected for soils with a low value for α. In these cases capillarity plays a more dominant role than gravity, especially at relatively short times.



WetUp Simulation 1

Select Soil Type: Averaged Sand

Select Flow and Time: Flow (l/hr) 0.503; Time (hr) 6

Select Emitter Type: Surface Emitter ● Buried Emitter ○

WetUp Simulation 2

Select Soil Type: Averaged Sand

Select Flow and Time: Flow (l/hr) 2; Time (hr) 20

Select Emitter Type: Surface Emitter ○ Buried Emitter ●

Fig. 1 WetUp window showing wetting perimeters at different times for different flow rates from a surface emitter (*panel 1*) and buried emitter (*panel 2*)

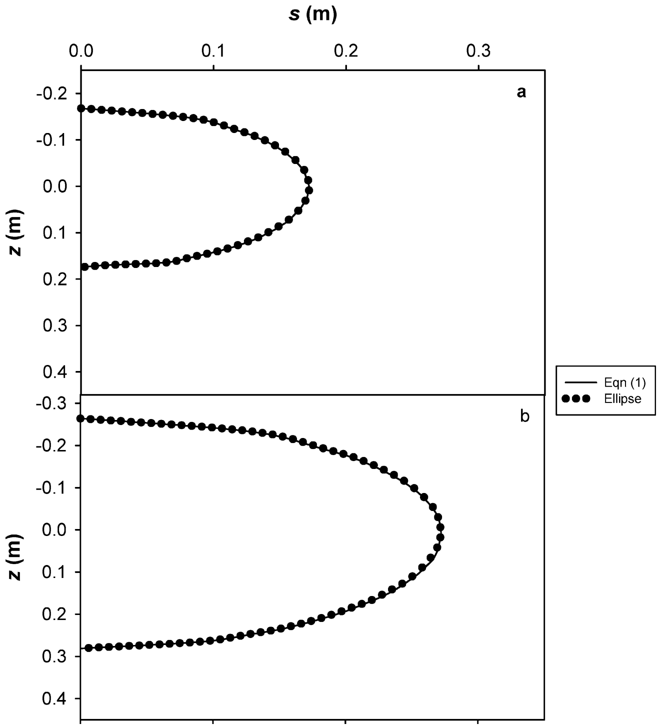


Fig. 2 Wetted perimeters predicted for a buried dripper using Eq. 1 (*solid line*) and an elliptic approximation (*symbols*) for an average clay soil with **a** $Q = 1.65\ \mathrm{l\,h^{-1}}$, $t = 1$ h and **b** $Q = 1.65\ \mathrm{l\,h^{-1}}$, $t = 4$ h

In the average sand there is a discrepancy between the ellipsoidal representation of the wetted perimeter and that calculated using Eqs. 1 and 4 which becomes more pronounced as the volume of water increases (Figs. 4, 5). This discrepancy is due to the lower value of α which means that gravity has a significant and more important influence on flow than capillarity.

The relative error for the radial wetted perimeter for a surface source at 1 and 4 h into the irrigation event for the two groups of soils analysed by Thorburn et al. (2003) shows that the maximum error using the elliptical assumption (i.e. Eq. 5) compared to the more physically based solutions of Philip (1984; Eq. 4) varies greatly between soils for both surface (Fig. 6) and buried (Fig. 7) emitters. At 1 and 4 h, respectively, the average error in Group 1 soils is 2 and 3%, and 16 and 23% in Group 2 soils for surface emitters (Fig. 6). Corresponding values for buried emitters are 1 and 2% in Group 1 soils and 11 and 15% in Group 2 soils (Fig. 7). The higher errors in the Group 2 soils reflect the higher average value of α in Group 2 ($14.8\ \mathrm{m^{-1}}$) than in Group 1 ($5.7\ \mathrm{m^{-1}}$). Similarly, the greatest relative errors occur in the individual soil with highest values of α, e.g. soil 2 (loamy sand) in Group 1 ($\alpha = 4.4\ \mathrm{m^{-1}}$) and soils 10, 16 and 17 ($\alpha = 38.3$, 22.9 and $29.6\ \mathrm{m^{-1}}$, respectively) in Group 2 (Figs. 6, 7).

The relative error in both surface and buried sources increases with volume of water applied and is shown for a maximum irrigation time of 24 h for an average clay (soil 1 and Group 1, $\alpha = 0.46\ \mathrm{m^{-1}}$) and an average sand (soil 11 in Group 1, $\alpha = 3.3\ \mathrm{m^{-1}}$) in Fig. 8. For the

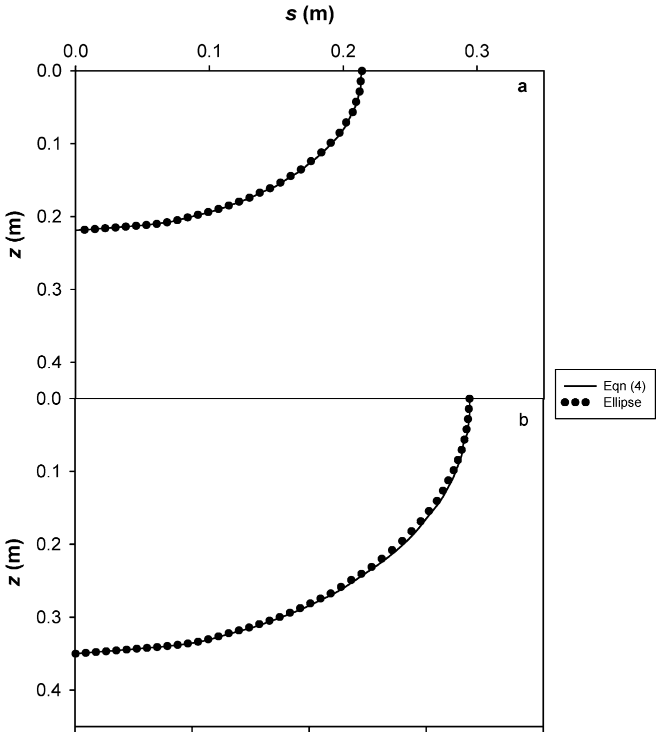


Fig. 3 Wetted perimeters predicted for a surface dripper using Eq. 1 (*solid line*) and an elliptic approximation (*symbols*) for an average clay soil with **a** $Q = 1.65\ \mathrm{l\,h^{-1}}$, $t = 1$ h and **b** $Q = 1.65\ \mathrm{l\,h^{-1}}$, $t = 4$ h

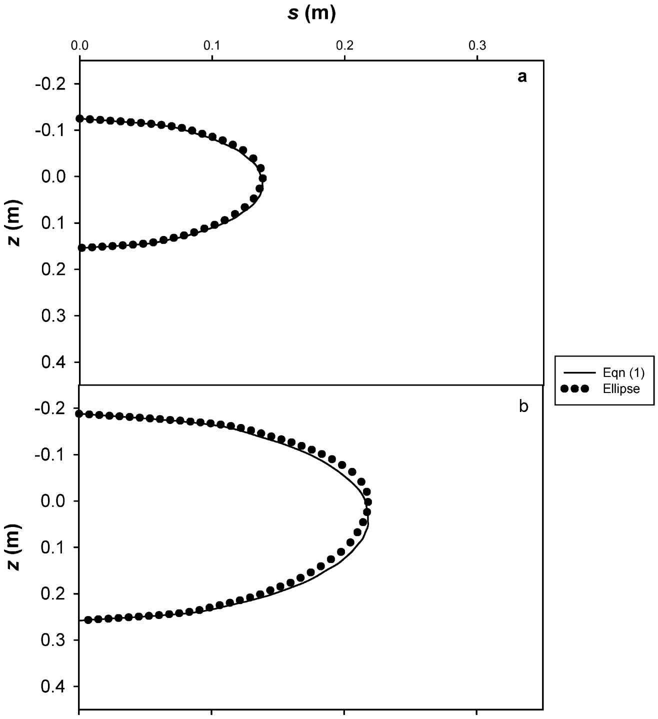


Fig. 4 Wetted perimeters predicted for a buried dripper using Eq. 1 (*solid line*) and an elliptic approximation (*symbols*) for an average sand soil with **a** $Q = 1.65\ \mathrm{l\,h^{-1}}$, $t = 1$ h and **b** $Q = 1.65\ \mathrm{l\,h^{-1}}$, $t = 4$ h

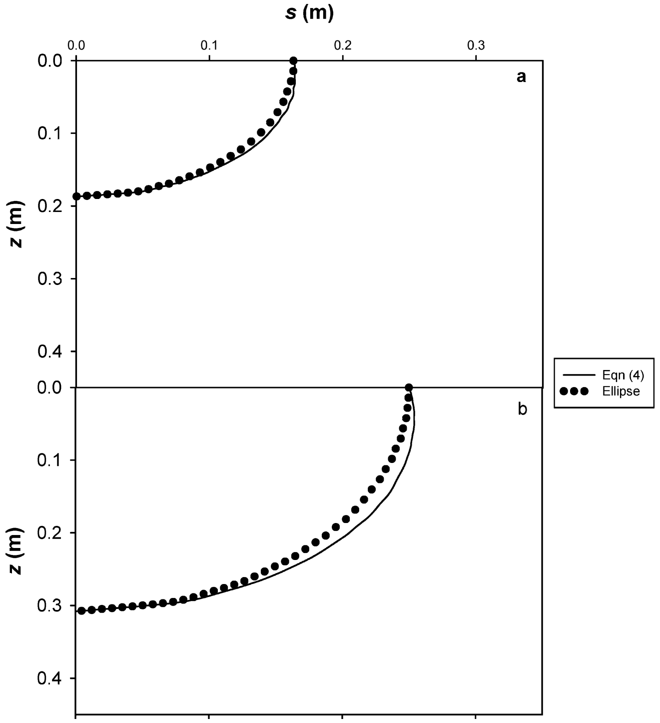


Fig. 5 Wetted perimeters predicted for a surface dripper using Eq. 1 (*solid line*) and an elliptic approximation (*symbols*) for an average sand soil with **a** $Q = 1.65\ \mathrm{l\ h^{-1}}$, $t = 1$ h and **b** $Q = 1.65\ \mathrm{l\ h^{-1}}$, $t = 4$ h

average clay soil there is little increase in error with volume of water applied, while for the average sand a steady increase in the relative error in the radial wetted perimeter occurs with volume of water applied.

In general the underestimation of wetting patterns in WetUp resulting from the display of elliptical wetting patterns (Figs. 2, 3, 4, 5) will depend on the soil hydraulic properties, especially α, and the volume of water applied. In contrast to this potential underestimation of radial wetting, the assumption of a constant value of $\Delta\theta$ in Eq. 3 leads to an overestimation of radial wetting at large application volumes (Qt) in soils with high α (F.J. Cook, P.J. Thorburn, K.L. Bristow and C.M. Cote, unpublished). This will therefore mitigate, to some extent, the slight underestimation in predicting wetting as described above. One needs to be aware of these errors if WetUp is to be used to approximate wetting patterns in specific soils. However, these errors, and others arising from other assumptions (such as uniformity of soil hydraulic properties), mean that WetUp should not be blindly applied as a "design tool", but used rather as a tool to help illustrate the variability in wetting between individual soils. The display of this variability and the lessons to be learned from it is not hindered by errors arising from the elliptical approximation or constant $\Delta\theta$. Variability in soil physical properties, and especially soil hydraulic properties (Warwick and Nielsen 1980), can also impact significantly on wetting from emitters (Cote et al. 2003). Simple ways of displaying wetting variability due to heterogeneous soil hydraulic properties are also necessary to illustrate the potential variability in wetting in trickle irrigation systems, and that it will, in general, be difficult to design efficient systems based on simple assumptions about wetting.

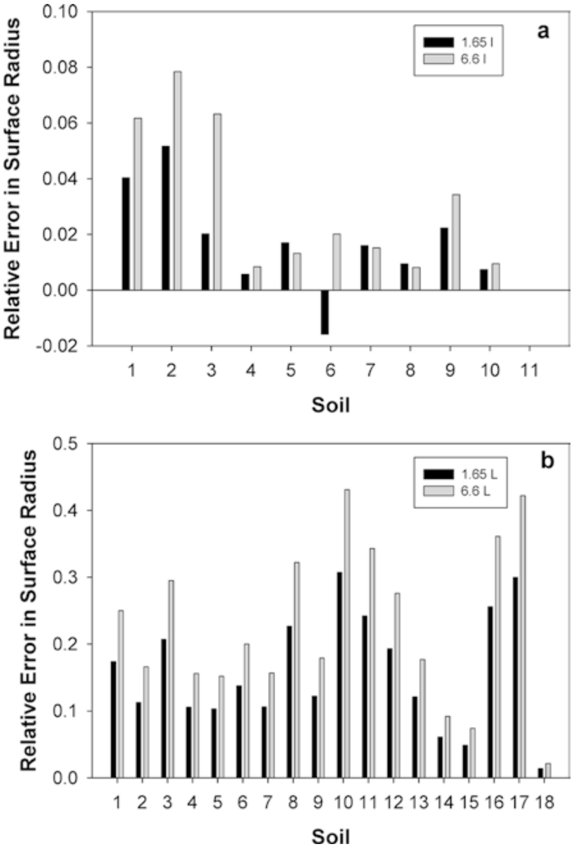


Fig. 6 Relative error in radial extent of wetted perimeter for a surface source ($Q = 1.65\ \mathrm{l\ h^{-1}}$) between Eq. 4 and Eq. 5: **a** Group 2 soils and **b** Group 1 soils of Thorburn et al. (2003) for $t = 1$ and 4 h

Conclusions

WetUp is a user-friendly software tool that provides visualisation of wetting patterns and how changing the soil properties, position of the emitter, or the volume of water applied will change the wetting patterns in homogeneous soils. Detailed analyses have shown that WetUp gives a reasonable estimation of the wetted perimeter arising from infiltration from both buried and surface point sources. Although WetUp tends to underestimate the radial wetting at large values of Qt (volume of applied water) for soils with high values of α (coarse textured or highly aggregated soils), this error is likely to be offset to some extent by the assumption of constant $\Delta\theta$ behind the wetting front, and is small when compared with potential impacts of spatial variability and depth differences in soil hydraulic properties of most field soils. This means that WetUp can be used with confidence in highlighting the importance of using site-specific soil information in the design and management

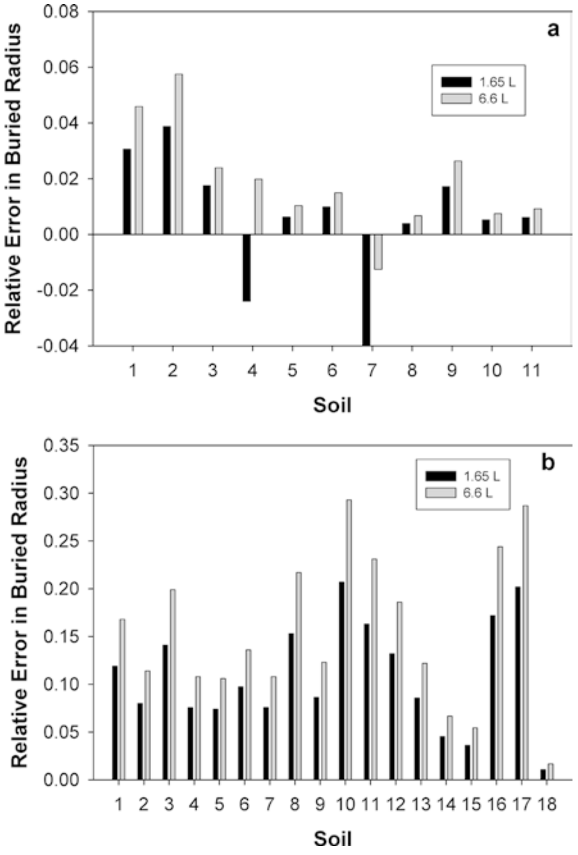


Fig. 7 Relative error in radial extent of wetted perimeter for a buried source ($Q = 1.65$ l h^{-1}) between Eq. 1 and Eq. 5: **a** Group 2 soils and **b** Group 1 soils of Thorburn et al. (2003) for $t = 1$ and 4 h

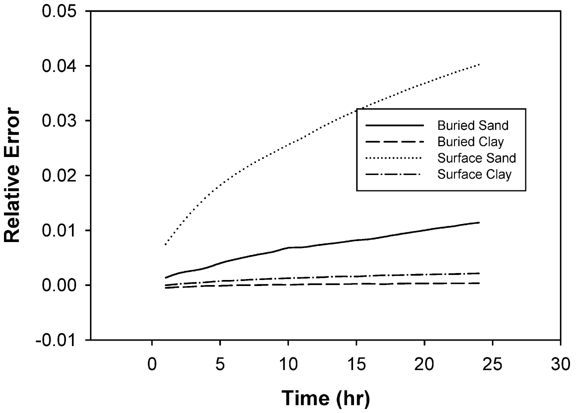


Fig. 8 Relative error in radial extent of wetting as related to irrigation time with $Q = 1.65$ l h^{-1} for clay and sand soils

of trickle irrigation systems. A version of WetUp can be obtained at http://www.clw.csiro.au/products/wetup/.

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