

One-Dimensional Model to Evaluate the Performance of Wick Samplers in Soils

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ABSTRACT

Wick samplers have become a valuable device for collecting soil pore water samples from the unsaturated zone. However, one of the problems with wick samplers has been that water and solutes bypass the samplers. Little work has been done on the nature of soil-wick interrelations. Based on an analytical solution for a layered soil profile, a steady-state solution was developed to predict the pressure head in a wick-soil continuum. The solution was also used to match wick properties to a given soil type in order to minimize the bypass flow. The results of this analysis show that for a good match between wick and soil types, (i) their capillary length (α^{-1}) needs to be similar, and (ii) the ratio of their saturated hydraulic conductivities should be similar to the inverse ratio of their cross section for flow. Examples for wick type selection based on these two requirements are given for two soil types and two wick types. For sandy soils, the optimal wick length is 30 to 40 cm, while for silt loams, the optimal length is >100 cm. Sampling with wick samplers in coarse-textured soils was found to be less disturbing of the soil pressure head and moisture profile than sampling in fine-textured soils. Hydraulic properties of fine-textured soils require a large sampling area in order to create an undisturbed zone above the wick sampler.

WICK SAMPLERS have proven useful for measuring the solute concentration in the vadose zone (Holder et al., 1991; Boll et al., 1991; Steenhuis et al., 1994). Several researchers have studied hydraulic characteristics of the wicks. Holder et al. (1991) found that fiberglass wicks did not absorb organic compounds. Boll et al. (1992) and Knutson and Selker (1994) showed that wicks behave like a porous medium. Knutson et al. (1993) found that cleaned wicks resulted in improved performance.

Only a few studies and limited analyses have been made on the effect of the wick sampling device on the observed solute concentration. Based on travel time moment analysis, Poletika et al. (1992) postulated that travel time and its variance are only minimally influenced by the wick. Knutson and Selker (1994) used Gardner's (1958) solution of the Richards equation to find the moisture content and pressure head in the wick. In the approaches of both Poletika et al. (1992) and Knutson and Selker (1994), an assumption is made that moisture content and the pressure head remain constant with depth in the soil above the sampler (unit gradient flux, i.e., the wick has no effect on the pressure head in the soil). This assumption is not valid under all circumstances, as will be shown below.

Our objective in this study was to better understand soil-wick relationships. To this end, we derived a one-dimensional steady-state solution for pressure head and hydraulic conductivity in the soil and wick sampler (unsaturated flow). Our approach, in which the soil-wick

interface affects the soil pressure head, is consistent with the analysis of a two-layer soil profile, and leads to a more rigorous selection of desirable wick characteristics than previous approaches. Our analysis is especially useful for soil columns drained by wicks, and multicell wick samplers (Boll et al., 1991).

THEORY

The basic assumption employed in the one-dimensional solution of the wick-soil system is that there is no horizontal flow near the point of interface between the wick and the soil. The analysis employed here is a first approximation for the behavior of the system. Sampler performance in two- and three-dimensional flow fields and under preferential flow will be the subject of a detailed analysis in the future. The steady-state assumption used in this case is a reasonable approximation because at depth (60 cm or more), and under high-frequency irrigation or frequent rainfall where wicks are usually installed, the temporal fluctuations in water flux near the soil surface are dampened by the overlying soil (Jury et al., 1991). Using steady-state flow is a necessary assumption in this case in order to obtain analytical solutions that serve as design tools.

To find the flux equations, let z be the vertical axis; at the bottom of the wick $z = 0$, and $z = L_w$ is where the wick is connected to the soil (Fig. 1). Based on Darcy's law and the modified Gardner's (1958) exponential conductivity equation (Rijtema, 1965), $K(h) = K_{sat} \exp[\alpha(h - h_c)]$, where K_{sat} is the saturated hydraulic conductivity (L/T), h and h_c are the pressure head and the air-entry value (L), respectively, and α^{-1} (L) is the "capillary length" (Wallach et al., 1989). The steady-state flux, q (L/T), can be expressed by

$$-q_s = K_s + \frac{1}{\alpha_s} \frac{dK_s}{dz} \quad z > L_w \quad [1a]$$

$$-q_s \frac{A_s}{A_w} = K_w + \frac{1}{\alpha_w} \frac{dK_w}{dz} \quad 0 < z < L_w \quad [1b]$$

The subscripts s and w represent the soil and wick, and A is the cross-sectional flow area.

Using a new variable K_w^* defined by

$$K_w^* = K_w \frac{A_w}{A_s}$$

Eq. [1b] can be rewritten in the form

$$-q_s = K_w^* + \frac{1}{\alpha_w} \frac{dK_w^*}{dz} \quad [3]$$

The variable K_w^* can be defined as the apparent hydraulic conductivity of a soil layer that is replacing the wick region. An analytical solution for steady-state flow into a layered soil profile was used by Zaslavsky (1964, 1969), Zaslavsky and Sinai (1981), and Yeh (1989) for various cases of unsaturated flow. It can be achieved by direct integration of the flux (Eq. [1a] and [3]) to yield the integral form of the Buckingham-Darcy Law (Jury et al., 1991). In our case, the appropriate boundary conditions are

$$\begin{aligned} 1. K_s(z) &= -q_s & z &= \infty \\ 2. K_w(z) &= K_{wsat} & z &= 0 \end{aligned}$$

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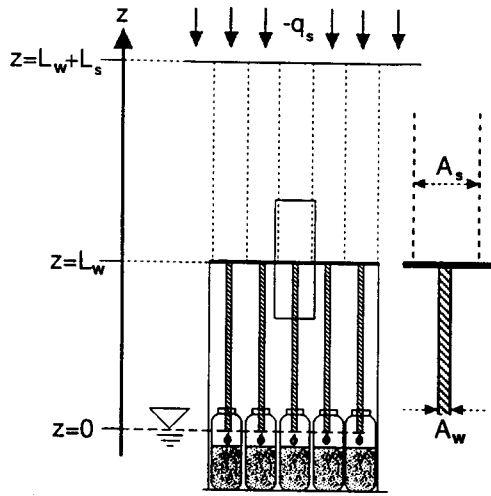


Fig. 1. Structure of the wick-soil system (schematic).

$$\begin{aligned} 3. q_s(z) &= q_w(z) & z &= L_w \\ 4. h_s(z) &= h_w(z) & z &= L_w \end{aligned}$$

Condition 1 states that the hydraulic conductivity of the soil at some distance above the wick interface is equal to the recharge rate, Condition 2 relates that the wick is saturated at the lower end where the water drips into the sampling bottle; and Conditions 3 and 4 state that the flux and pressure head are continuous at the soil-wick interface ($z = L_w$).

Taking $h_c = 0$ for the wick (Knutson and Selker, 1994), the solution for the wick section can be expressed by

$$K_w(z) = -q_s \frac{A_s}{A_w} + \left(q_s \frac{A_s}{A_w} + K_{wsat} \right) \exp(-\alpha_w z) \quad [5a]$$

$$h_w(z) = \frac{1}{\alpha_w} \ln \left(\frac{K_w(z)}{K_{wsat}} \right) \quad [5b]$$

and the solution for the soil section is

$$K_s(z) = -q_s + C \exp[\alpha_s(L_w - z)] \quad [6a]$$

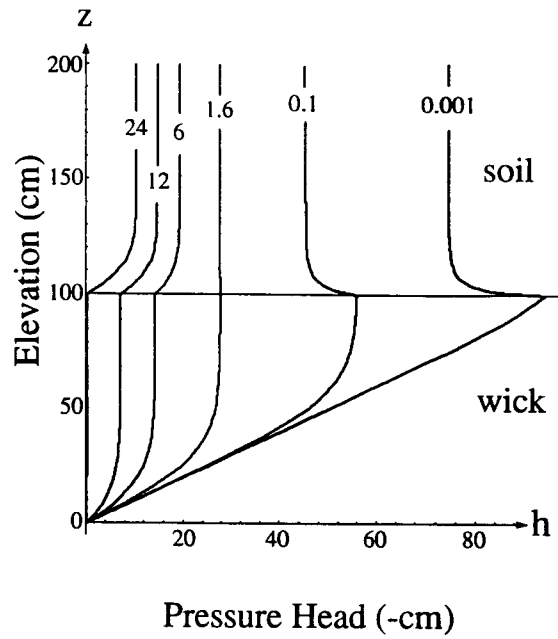
$$h_s(z) = h_{cs} + \frac{1}{\alpha_s} \ln \left[\frac{K_s(z)}{K_{ssat}} \right] \quad [6b]$$

where C can be expressed as

$$C = K_{ssat} \exp[-\alpha_s(h_{cs} - h|_{L_w})] + q_s$$

The second term on the right-hand side of Eq. [6a], not included in the Knutson and Selker (1994) analysis, describes the influence of the wick on the K , and h , distribution above the soil-wick interface. Equations [5] and [6] are valid only as long as the wick and the soil are both unsaturated. Further analysis, such as for the saturated-unsaturated case, can be found in Zaslavsky (1964).

The above steady-state solution shows that any regular one-dimensional solution of the Richards equation for a layered soil profile can be used for wick analysis when the wick is conceptualized as a layer in the profile. No new analytical or numerical efforts are needed; all that is required are a few adaptations and definitions. With these definitions, one-dimensional solutions of non-steady state can also be adapted for wick analysis.


 Fig. 2. A solution of pressure-head distribution in the wick-soil profile for six flux rates (cm h^{-1} , absolute value).

RESULTS AND DISCUSSION

Soil Moisture Profile as a Function of Flux

In order to show the effect of the wick on the pressure head in the soil, we plotted, as an example (Fig. 2), the pressure head distribution (Eq. [5b] and [6b]) vs. z for six values of q_s , where the wick type was 1.27 cm in diameter (1/2 inch, no. 1381, Pepperell Braiding Co., Pepperell, MA [PEP1/2]) and the soil type was Rehovot sand. Hydraulic characteristics of the wick (A_w , K_{wsat} , and α_w) were taken from Knutson and Selker (1994), and for the soil from Mualem (1976) (Table 1). Wick length, L_w , and soil profile length, L_s , were both 100 cm, and the area ratio was $A_s/A_w = 48.5$. The results confirm that at some distance above the wick-soil interface, pressure head is constant, while close to the interface the soil moisture is affected by the wicks. When flow rates are $>1.6 \text{ cm h}^{-1}$, the soil becomes wetter at the wick interface. At 1.6 cm h^{-1} , the soil moisture content remains constant, and at lower flow rates, the soil becomes drier. Extrapolating these results to an actual wick sampler, when the moisture content is different above the wicks than in the surrounding soil, diversion or conversion of streamlines will occur.

Table 1. Wick and soil hydraulic properties used to demonstrate the mathematical solution.

	h_c	K_{sat}	α	A_w
	cm	cm h^{-1}	cm^{-1}	cm^2
Wicks				
PEP1/2	0	1168	0.098	1.6513
AM3/8HI	0	273	0.047	0.8825
Soils				
Ida silt loam	0	0.105	0.026	
Rehovot sand	-9.5	27.5	0.157	

Wick Length and Sampling Area Selection

When constant flux is applied to the soil surface, and if the water table is considered to be far below the soil-wick interface, the pressure head of a uniform soil profile, undisturbed by a wick sampler, is constant (unit gradient). Therefore, the best sampling results are obtained if the soil moisture above the wick is not altered by the wick itself, i.e., remains constant. (Under these conditions, the solute travel time is the same above the wick and in the remaining soil). From Eq. [5] and [6], this requirement is met when $C = 0$ for a range of fluxes.

Since the soil hydraulic characteristics are determined, but the wick sampler is subject to choice, $C = 0$ can be achieved by selection of the appropriate wick length, L_w , wick capillary length, α_w^{-1} , and sampling area, A_s . Assume first that $h_{cs} = 0$. Then, from Eq. [5] and [6], whenever the wick is long enough (three times α_w^{-1} or more), the exponential term in Eq. [5a] is minimized and the pressure head at the wick side of the wick-soil interface is determined mainly by the flux entering the wick. A sampling area of $A_s = A_w K_{w\text{sat}}/K_{s\text{sat}}$ and $\alpha_w = \alpha_s$ will then result in $C = 0$ and Eq. [5b] and [6b] will be identical for all q_s at $z = L_w$. Therefore, the basic conditions for an undisturbed flow field in the soil are: (i) a long wick, (ii) a sampling area of $A_w K_{w\text{sat}}/K_{s\text{sat}}$, and (iii) similar values of capillary length for both wick and soil.

Further analysis of this simplified case shows that if $K_{w\text{sat}} \gg K_{s\text{sat}}$, then the required $C = 0$ occurs only when the ratio A_s/A_w is very large. This is an important point, because when the preferred sampling area is very large compared with the wick area, there will be a significant dispersion of the solute flow signal (Boll et al., 1992). Moreover, since the capillary length of most wicks is ≈ 10 cm and $K_{w\text{sat}}$ is >200 cm h^{-1} (Knutson and Selker, 1994), the potential for using wicks in fine-textured soils (usually with a higher capillary length and much lower hydraulic conductivity) without flow field disturbances is actually very limited. A practical solution to this problem is to use tighter wicks, with a larger cross-sectional area, for which the saturated conductivities of wicks and soil are more alike.

If $\alpha_w \neq \alpha_s$, saturated conductivities do not match, $h_{cs} < 0$, and wick length is <100 cm because of practical consideration, then $h(z)$ in Eq. [5b] and [6b] are equal at $z = L_w$ for all values of q_s , as required by the boundary conditions, but the pressure head distribution in the soil is certainly disturbed. In that case, which is more likely the real case, numerical analysis is required to find optimal α_w , A_s , and L_w .

First, the requirement for unit gradient distribution in the soil for all fluxes, i.e., $C = 0$, is determined. This causes the pressure head on the soil side of the interface to be only a function of the flux, expressed by $h_s(q_s)|_{L_w}$, while the pressure head on the wick side of the interface, $h_w(q_s, A_s, L_w)|_{L_w}$, depends on the wick's sampler properties. Then, it is required that $h_s(q_s)|_{L_w} = h_w(q_s, A_s, L_w)|_{L_w}$ and optimal values should be solved for the wick properties and sampling area. Figure 3 shows $h(q_s)|_{L_w}$ functions

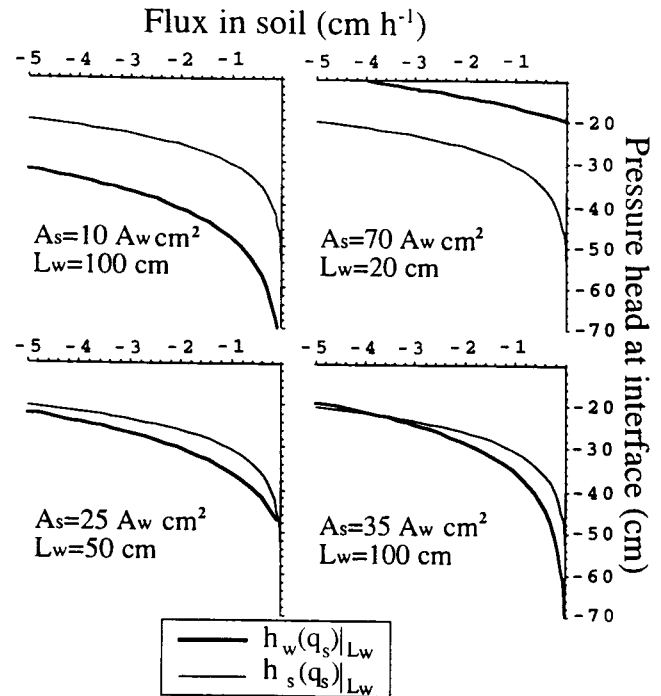


Fig. 3. Pressure-head distribution at the wick-soil interface as a function of flux, assuming unit gradient flow at the soil region. A_w and A_s are the cross-sectional areas of the wick and soil, respectively, L_w is the wick length, and h_w and h_s are the pressure head of the wick and soil, respectively.

for both the wick and the soil side of the interface in four combinations of L_w and A_s . The calculations were done with Rehovot sand, and a PEP1/2 wick for a range of fluxes between zero and the highest constant flux expected under natural experimental conditions. This was chosen as 5 cm h^{-1} for the sand, which is less than the soil's saturated hydraulic conductivity, but still a very high flow rate under natural conditions. The $h_s(q_s)|_{L_w}$ function is the same in all combinations since it is independent of L_w and A_s , while $h_w(q_s, A_s, L_w)|_{L_w}$ changes with L_w and A_s . At each combination, the flux at which these functions intersect (if there is any) is the only flux that results in a nondisturbance condition. Other fluxes will result in either an overwetted, $[(dh/dz)|_{L_w+} < 0]$, or a drier $[(dh/dz)|_{L_w+} > 0]$ area above the wick.

The best wick properties for a given soil and wick type are those that result in the h_w function of flow rate being as close to h_s as possible for a range of fluxes, i.e., minimize the integrated residual $h_w(q_s, A_s, L_w)|_{L_w} - h_s(q_s)|_{L_w}$ for that range of fluxes. Since h_w can be both larger and smaller than h_s across the given range of q_s (Fig. 3), a general form of objective function was defined by

$$F(A_s, L_w) = \frac{\alpha_w \alpha_s}{q_{\text{max}}} \int_0^{q_{\text{max}}} [h_w(A_s, L_w, q_s) - h_s(q_s)]^2 p(q_s) dq_s \quad [7]$$

where $p(q_s)$ is a flow weighting function. Given the soil type and the hydraulic properties of the wick, the desired value is the minimum of F with respect to L_w and A_s . Using Eq. [5] and [6], large L_w , and $h_{cs} = 0$, it can be

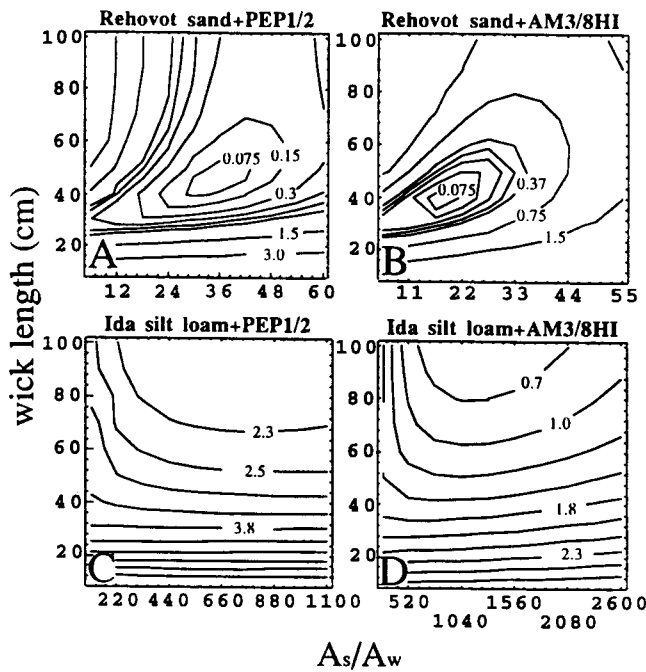


Fig. 4. Contour maps of F values as a function of the ratio of soil to wick sampling areas (A_s/A_w) and wick length for a sand and a silt loam soil and PEP1/2 and AM3/8HI wick types. Actual A_w are given in Table 1.

shown that if $\alpha_w = \alpha_s$, F is a function of the hydraulic conductivities and cross-sectional area ratios, while if $A_s = A_w K_{wmat}/K_{ssat}$ and $\alpha_w \neq \alpha_s$, F increases with the increase of capillary lengths ratio. The analytical integration in Eq. [7] is not simple; therefore, a numerical procedure was adopted (using the computer program Mathematica, Wolfarm Research, Champaign, IL) to calculate the integrals on a grid (10×10 points) where $100 \leq L_w \leq 10$ cm and A_s did not exceed values that would cause saturation in the wick. The variable $p(q_s)$ was considered to be a uniform-weighting function.

An additional wick type (AM3/8HI [0.95 cm (3/8 inch) high-density, Amatex Co., Norristown, PA]; Knutson and Selker, 1994) and soil type (Ida silt loam [fine-silty, mixed (calcareous), mesic Typic Udorthent]; Amoozegar-Fard et al., 1984) hydraulic characteristics (Table 1) were used to demonstrate this part of the analysis.

The results for Rehovot sand and Ida silt loam soils, tested with PEP1/2 and AM3/8HI wicks, are presented in Fig. 4. They are shown as contour maps of F values as a function of L_w and A_s . Since A_w for these two wicks are not the same, the horizontal axes in all figures are the dimensionless quantity A_s/A_w . The contour values are given to indicate maximum and minimum values of F at the region. Their actual values can be used to compare between various soil-wick combinations, and especially between different wicks for the same soil.

The F values of Rehovot sand with PEP1/2 and AM3/8HI wicks are presented in Fig. 4A and 4B, respectively. The best wick length is only ≈ 40 cm. Longer wicks will probably result in extreme suction near the interface, causing the moisture content to be lower compared with

the rest of the profile, thus increasing F values. The best sampling area is ≈ 60 ($=36A_w$) cm^2 for the PEP1/2 wick and 15 ($=17A_w$) cm^2 for the AM3/8HI wick. The capillary length of the PEP1/2 wick is close to the soil's value, which is the reason for the small changes in the F function in the region where $L_w \geq 40$ cm. The region of good results (small F function values) for the second wick is small due to a great difference in the capillary length of the soil and the wick. Therefore, the PEP1/2 wick is a better choice in this case.

The results for the Ida silt loam are presented in Fig. 4C and 4D. When very short wicks are used, the size of the sampling area has almost no influence on F , since the pressure head at the top of the wick is determined mainly by the bottom boundary condition (Eq. [5b]). The preferred region of sampling area and wick length presented in these figures show that (i) the longer the wick, in this case, the better and (ii) sampling areas for both kinds of wicks are very large. The large ratio between the K_{sat} of the silt loam and the wicks caused the preferred sampling area to be large compared with the wick area.

The calculated results imply that matching wicks to coarse-textured soil types might be more successful than to fine-textured soil types. The variations of the moisture content near the soil-wick interface create bypass flow around the wick sampler, causing our analysis to be more valid for coarse-textured soil. Further research is needed in creating various types of wicks that differ in their hydraulic properties; determining the nature of the bypass flow; and finally, determining the appropriate adaptations needed for application of the one-dimensional steady-nonsteady numerical model, with both water and solutes transport, to the wick and soil system.

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