Low tension water flow in structured soils

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Received 19 June 1996, accepted 16 May 1997.

Lin, H. S., McInnes, L. P. and Hallmark, C. T. 1997. **Low tension water flow in structured soils**. Can. J. Soil Sci. **77**: 649–654. Water transport through structured clayey soils may be prone to by-pass flow, a mechanism that may lead to rapid transport of contaminants to ground water. To quantify the significance of low-tension water flow in structured soils, apparent steady-state infiltration rates at water potentials from –0.24 to 0 m were measured using tension infiltrometers on 18 soils of varying texture and structure. Each infiltration measurement was conducted sequentially at –0.24, –0.12, –0.06, –0.03, –0.02, –0.01, and 0 m supply potentials (Ψ_{supply}), all at the same soil location, to separate different size pores effective in transmitting water. Results from 96 soil horizons showed that 76 ± 18% (mean ± SD) of the water fluxes at Ψ_{supply} = 0 m (total water flux) were transmitted through macropores (active at $\Psi_{supply} \geq$ –0.03 m), although macropores usually constituted a small portion of a soil's total porosity. Mesopores (active at $\Psi_{supply} \geq$ –0.24 m) contributed 19 ± 13% of total water flux. Micropores dominated the soils' total porosities, but generally contributed < 10% of the total water flux. Macropores and mesopores showed greater influence on water flow in clays than in sands at Ψ_{supply} > –0.24 m. Values of soil macroscopic λ_c and microscopic λ_m capillary length scales were determined from the change in infiltration rates with Ψ_{supply}. Values of λ_c, a hydraulic conductivity-weighted mean capillary water potential, were greater for sands (63 mm) than loams (50 mm), and greater for loams than clays (22 mm). Values of λ_m, the mean hydraulically effective pore size, were greater for clays (0.33 mm) than loams (0.15 mm), and greater for loams than sands (0.12 mm). Most of the soils studied showed hydraulic characteristics associated with by-pass flow.

Key words: Infiltration, tension infiltrometer, macropore flow, by-pass flow, capillary length scale, α parameter

Lin, H. S., McInnes, K. J., Wilding, L. P. et Hallmark, C. T. 1997. **Flux hydrique à basse tension dans les sols structurés**. Can. J. Soil Sci. **77**: 649–654. La circulation de l'eau dans les argiles structurées présente parfois des flux de dérivation, mécanisme qui peut entraîner le transport rapide des contaminants jusque dans les eaux souterraines. Pour quantifier la signification du flux de l'eau à basse tension dans les sols structurés, nous avons mesuré les taux d'infiltration à état constant apparent à des potentiels hydriques de –0,24 à 0 m, au moyen d'un infiltromètre à tension, dans 18 sols de texture et de structure variables. Chaque mesure d'infiltration était prise en séquence à des potentiels d'approvisionnement ($\Psi_{appr.}$) de –0,24, –0,12, –0,06, –0,03, –0,02, –0,01 et 0 m, toutes au même emplacement afin de distinguer les différents calibres de pores capables de transporter l'eau. Les mesures prises dans 96 horizons de sol montrent que 76 ± 18% (moyenne ± ES) des flux hydriques au $\Psi_{appr.}$ de 0 m (flux hydrique total) étaient transportées par les macropores (actives à $\Psi_{approv.} \geq$–0,03 m), bien que les macropores ne constituent normalement qu'une faible portion de la porosité totale. Les mésopores, actives à $\Psi_{appr.} \geq$–0,24 m, comptaient pour 19 ± 13% du flux hydrique total. Les micropores formaient la majeure partie de la porosité totale, mais elles ne comptaient généralement que pour moins de 10% du flux hydrique total. L'influence des macropores et des mésopores sur le flux hydrique était plus forte dans les sols argile que dans le sable à $\Psi_{appr.}$ > –0,24 m. Les valeurs des échelles de longueur des capillaires macroscopiques λ_c et microscopique λ_m étaient obtenues à partir du changement des taux d'infiltration en fonction du potentiel d'approvisionnement Ψ. Les valeurs λ_c, potentiel hydrique capillaire moyen pondéré en fonction de la conductivité hydraulique, étaient plus élevées dans les sables (63 mm) que dans les loams (50 mm) et plus dans les loams que dans l'argile (22 mm). Les valeurs λ_m, calibre moyen des pores hydrauliquement effectives, étaient plus élevées dans les sols argileux (0,33 mm) que dans les loams (0,15 mm) et davantage dans ces derniers que dans les sables (0,12 mm). Presque tous les sols étudiés manifestaient des propriétés hydrauliques associées au flux de dérivation.

Mots clés: Infiltration, infiltromètre à tension, flux dans les macropores, flux de dérivation, échelle de longueur des capillaires, paramètres α

Clayey soils occupy a significant area of North America. About 6 million ha of clayey soils are located in the interior plains of Canada (Onofrei et al. 1990). Structured clayey soils present unique problems in evaluation of land resources in regard to water related issues. Clayey soils are commonly though to have low permeability (Rawls 1982), but pedalogical pores associated with structured clayey soils are potential paths for rapid water movement through the rootzone. This rapid movement of water (by-pass flow) may lead to rapid transport of weakly sorbed waterborne contaminants to ground water, but chemicals not intimately associated with flow paths may be protected from loss by leaching. Desiccation cracks, biopores, and interpedal pores in structured clayey soils are most active when water is supplied at positive head or low tension (Ψ_{supply}), as might occur with irrigation or rainfall. Improved understanding of low-tension water flow in structured clayey soils could improve future land management in many regions of the world.

Department of Soil and Crop Sciences, Texas A&M University, College Station, TX 77843-2474. Contribution from the Texas Agricultural Experimental Station, The Texas A&M University System. Research supported by the USDA-CSRS Special Grants Research Program on Water Quality under grants No. 90-34214-5123 and No. 93-34214-8902.

Recent improvements in tension infiltrometers have facilitated the field study of soil hydraulic properties when water is supplied at low tension (Watson and Luxmoore 1986; Jarvis et al. 1987; Perroux and White 1988; Ankeny et al. 1990; Sauer et al. 1990; Dunn and Phillips 1991; Jarvis and Messing, 1995). Tension infiltrometers allow easy uninterrupted measurement of infiltration rates at different tensions, thus eliminating some uncertainty in the effect of Ψ_{supply} caused by spatial variability (Lin and McInnes 1995). Supplying water at tension allows pores larger than a size corresponding to the tension from participating in flow. For pores of radius r to be fully conductive, Ψ_{supply} (m) must be greater than $2\sigma/(\rho g r)$, where σ is the surface tension (kg s^{-2}), ρ is the density of water (kg m^{-3}), and g is the gravitational acceleration (m s^{-2}). For example, supplying water for infiltration at Ψ_{supply} = –0.03 m excludes pores of r > 0.5 mm from actively transmitting water.

One means of characterizing low-tension flow is to report the microscopic capillary length scale λ_m. The microscopic capillary length represents an estimate of the mean pore size active in flow and is related to the macroscopic capillary length scale λ_c (White and Sully 1987, 1992) through

$$\lambda_m = \sigma/(\rho g \lambda_c). \tag{1}$$

Taking the properties of water at 298 K, $\lambda_m = 7.3 \times 10^{-6}/\lambda_c$. Values of λ_c can be determined as

$$\lambda_c = \left[K(\Psi_i) - K(\Psi_{i+1})\right]^{-1} \int_{\Psi_{i+1}}^{\Psi_i} K(\Psi)\mathrm{d}\Psi \tag{2}$$

where K is the hydraulic conductivity, and Ψ_i and Ψ_{i+1} are the upper and lower matric potentials of interest, respectively. The $K(\Psi)$ relationship may be derived from sequential measurements of steady-state infiltration rates (Ankeny et al. 1991; Reynolds and Elrick 1991). From Eq. 2 it is apparent that λ_c is a K-weighted mean capillary water potential (Meyers and van Bavel 1963; Philip 1987).

If the relationship between hydraulic conductivity and water potential may be expressed as:

$$K(\Psi) = K_i \exp[\alpha(\Psi - \Psi_i)], \tag{3}$$

then from Eq. 2 $\lambda_c = \alpha^{-1}$ and from Eq. 1 $\lambda_m = \alpha\sigma/(\rho g)$ (Philip 1987). Ankeny et al. (1991) and Reynolds and Elrick (1991) suggest that Eq. 3 may be used to fit the $K(\Psi)$ relationship in a piecewise manner. In a piecewise fit, α and K_i may vary between different segments of the $K(\Psi)$ relationship. From sequential infiltration measurements at different Ψ_{supply}, estimates of $\alpha(\Psi)$ (m^{-1}) may be made through (Reynolds and Elrick 1991)

$$\alpha_{i,i+1} = \frac{\ln\left[Q(\Psi_i)/Q(\Psi_{i+1})\right]}{\Psi_i - \Psi_{i+1}} \tag{4}$$

where $Q(\Psi_i)$ and $Q(\Psi_{i+1})$ are steady-state fluxes (m^3 s^{-1}) at Ψ_{supply} (m) of Ψ_i and Ψ_{i+1}, respectively. Flows dominated by gravity have larger αs than flows characterized by capillarity (Philip 1969, 1985; Pullan 1990; Reynolds and Elrick 1991). In clayey soils, flow dominated by gravity is synonymous with by-pass flow. A large α indicates a large mean pore dimension (i.e. λ_m) effective in transmitting water. Lin and McInnes (1995) demonstrated the need to define the geometry of flow when modeling water flow in clayey soil systems where large αs exist.

This study was conducted to characterize low-tension water fluxes in selected Claypan Area, Blackland Prairies, and Coast Prairie soils of Texas to determine the potential for these soils to exhibit by-pass flow. Many soils in these areas have one or more highly structured horizons. Most Vertisols and vertic intergrades in the US are in these areas of Texas (Soil Survey Staff 1975) and the areas encompass three large US cities, Dallas, Houston, and San Antonio. Maintenance of quality ground water in these areas is important as regional development continues. Quantification of the significance of by-pass flow was sought through changes in low-tension infiltration rates with water potential (tension).

MATERIALS AND METHODS

Soils

Eighteen soil series in the Claypan Area, Blackland Prairies, and Coast Prairie Major Land Resource Areas of Texas were selected for this study. Detail information about these soils can be found in Lin (1995). Infiltration measurements were made by soil genetic horizons exposed in freshly-dug pits in each of the 18 soils. Among a total of 96 horizons investigated, there were 42% A, 3% E, 36% B, and 19% C or CB horizons. One-third of the A horizons were cultivated. Of the B horizons, two-thirds had angular or subangular blocky structure, and the remainder were split between prismatic and massive structure. Clay-textured horizons accounted for half of the horizons investigated. Well-expressed slickensides, desiccation cracks, gilgai microrelief, moderate to strong pedality, and biological features existed in many of the clayey soils. Three to 13 (average of 5) replicated sequential tension infiltration measurements were made within each soil horizon. The method of moments was used to estimate the mean values of soil hydraulic parameters within each soil horizon (Parkin and Robinson 1992).

Infiltration Measurements

Tension infiltrometers with a base 0.245 m in diameter were used to measure infiltration rates at Ψ_{supply} of –0.24, –0.12, –0.06, –0.03, –0.02, –0.01, and 0 m. The design of infiltrometers followed that of Perroux and White (1988). Water level in the infiltrometer reservoir was measured electronically every 5 s, and average values were recorded at the end of minute intervals.

Infiltration measurements were conducted first at Ψ_{supply} = –0.24 m, then sequentially at –0.12, –0.06, –0.03, –0.02, –0.01, and 0 m. After preliminary measurements, we chose the following temporal measurement scheme: first at –0.24 m for 30 min, followed by –0.12 and –0.06 m for 20 min each, then at –0.03, –0.02, –0.01, and 0 m for 10 min each (Lin and McInnes 1995).

Four of five tension infiltrometers, usually placed about 1 to 2 m apart, were used simultaneously to obtain replicated data in each soil horizon. A level soil surface was prepared with care to minimize the disturbance of the soil structure. When the measurement was in a subsoil horizon, the soil was excavated from the walls of a freshly-opened trench to about 0.05 m above the desired depth and at least 0.5 m into the wall. The rest of the soil was carefully removed to avoid smearing the soil surface and blocking the macropores. The resulting soil surface was cleaned by blowing away any loose soil. Exposed roots above the soil surface were removed with scissors. Adjacent soil was sampled to determine bulk density. As suggested by previous researchers (Watson and Luxmoore 1986; Perroux and White 1988; Ankeny et al. 1988), a very thin layer of fine sand was placed on the soil surface to provide good contact between the base of the infiltrometer and the soil surface. The tension infiltrometer, preset to –0.24 m water potential, was then placed on the sand, and the sequential infiltration rates were recorded.

Soil pores may be generally grouped into two broad size classes in terms of their geometry: cylindrical pores (e.g. channels) and planar pores (e.g. cracks). To handle these two basic pore shapes simultaneously, we described pore size as cylindrical pore radius or planar pore width corresponding to a given water potential. For cylindrical pores of radius r (mm) or planar pores of width w (mm), the Ψ_{supply} (m) needed at the soil-infiltrometer interface for these pores to be fully conductive is $r = w \approx -0.015/\Psi_{supply}$. Soil macroporosity and mesoporosity were estimated from field description of the abundance and size of visible pores (Lin 1995; Soil Survey Staff 1993). Pores > 20 µm were visible with the hand lens used, but the lower limit in classification was chosen as 63 µm to coincide with pores active at our lowest supply water potential, Ψ_{supply} = –0.24 m. Total porosity f_t was approximated from bulk density ρ_b measurements and an assumed particle density of 2.65 Mg m^{-3} ($f_t \approx 1.0 - \rho_b/2.65$).

Calculations

The contribution to total water flux by different pore size ranges was determined by $\Delta Q/Q_0$, where ΔQ (m^3 s^{-1}) is the difference of apparent steady-state flux between two pore sizes (corresponding to two Ψ_{supply}s), and Q_0 (m^3 s^{-1}) is the apparent steady-state flux contributed presumably by all size pores (Ψ_{supply} = 0 m). Following the suggestion by Luxmoore (1981) and Smettem and Ross (1992), we used 0.5 mm (Ψ = –0.03 m) as the lower limit of macropores. We defined pores active at Ψ_{supply} > –0.24 m, but smaller in size than macropores, as mesopores (63 µm to 0.5 mm). This lower limit of 63 µm was considerably larger than the 10 µm limit proposed by (Luxmoore 1981). Pores < 63 µm were considered as micropores in this study. The fraction of total water flux contributed by a pore size range was calculated as the ratio of the difference between fluxes at two Ψ_{supply}s (two pore sizes) to Q_0.

To compare capillary length scales between soils with different texture, an estimate of λ_c (Eq. 1) was made as:

$$\lambda_c \approx \left[Q(\Psi_0) - Q(\Psi_{-0.24})\right]^{-1} \int_{\Psi_{-0.24}}^{\Psi_0} Q(\Psi)\mathrm{d}\Psi \qquad (5)$$

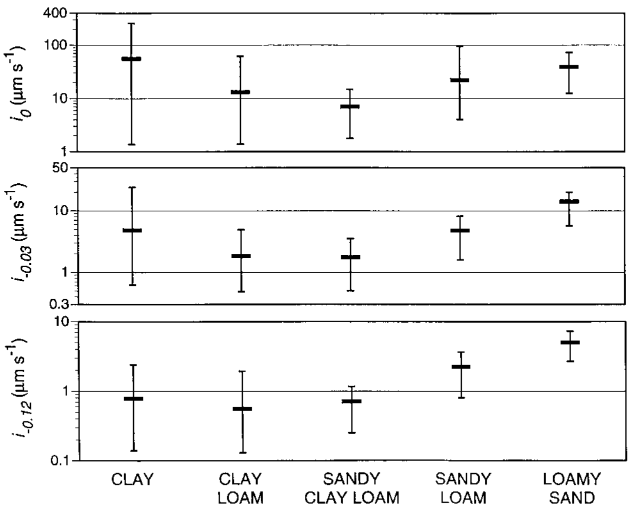

Fig. 1. Variability of steady infiltration rates i (shown on log-scale) with soil texture and at three supply water potentials, 0 m (all pores active), –0.03 m (pores with r < 0.5 mm active), and –0.12 m (pores with r < 0.125 mm active). Error bars represent the range of values.

Table 1. Contributions to total porosity by pore-size ranges among textural groups

Pore size range (mm)	$\Delta f/f_t$ All soils (%)	Clays	Loams	Sands
< 0.06	87.2[z] (99.6, 37.0)	86.8 (99.6, 37.0)	89.2 (99.5, 60.3)	58.9 (66.9, 52.5)
0.06 to 0.5	9.9 (47.5, 0.4)	9.1 (32.6, 0.4)	8.9 (39.8, 0.4)	40.5 (47.5, 31.1)
> 0.5	2.9 (30.4, 0)	4.1 (30.4, 0)	1.9 (17.5, 0)	0.6 (1.9, 0)

[z]Means are followed by maximum and minimum values.

This decision was based on the assumption that $Q(\Psi)/Q_0 \approx K(\Psi)/K_0$ and because the complex flow path geometry in structured soil makes extraction of $K(\Psi)$ from $Q(\Psi)$ uncertain (Lin and McInnes 1995). Only the λ_cs from the texturally averaged $Q(\Psi)$ relationships were determined. Infiltration rates were also reported on a unit area basis as $i = Q/A$, where A is the area of the infiltrometer base (0.047 m^2).

RESULTS AND DISCUSSION

Steady state infiltration rates at zero tension were greatest for clay-textured soils (Fig. 1) with well-developed soil structure and macroporosity (Table 1). This supports the research of Jarvis and Messing (1995) who found saturated hydraulic conductivities to be greater in finer-than coarser-textured soils, contrary to the normally accepted relationship with texture (Rawls et al. 1982). Not all the clayey soils, however, had well-developed structure as indicated by the high variability in macroporosity (Table 1). Clayey soils with poorly developed structure had low infiltration rates; hence the high variability in i_0 (Fig. 1). Also, because of the shrink-swell characteristics of the vertic soils, we noticed temporal variability in infiltration rates. Ponded infiltration

Table 2. Contributions to total water flux by pore-size ranges among textural groups

Pore size range (mm)	All soils	Clays	Loams	Sands
	$\Delta Q/Q_0$ (%)			
≤ 0.06	4.5[z] (35.1, 0.1)	1.6 (9.6, 0.1)	6.9 (35.1, 0.2)	6.5 (9.9, 2.9)
0.06 to 0.13	4.5 (25.8, 0.2)	2.0 (10.9, 0.2)	7.0 (25.8, 0.5)	10.5 (15.5, 4.1)
0.13 to 0.25	5.9 (24.4, 0.6)	3.8 (12.4, 0.6)	8.2 (24.3, 0.7)	13.9 (22.9, 8.03)
0.25 to 0.5	8.4 (25.4, 1.5)	7.9 (24.2, 1.5)	8.5 (19.8, 2.4)	12.4 (15.9, 7.9)
0.5 to 0.75	6.0 (17.9, 0.1)	7.1 (17.9, 1.7)	4.7 (17.5, 0.1)	7.8 (8.8, 6.2)
0.75 to 1.5	17.0 (35.6, 5.4)	19.5 (35.6, 5.6)	13.9 (30.2, 5.4)	18.3 (23.6, 13.2)
≥ 1.5	53.7 (85.8, 10.3)	58.1 (85.8, 30.3)	50.8 (82.8, 10.3)	30.6 (47.3, 17.2)

[z]Means are followed by maximum and minimum values.

rates on vertic soils, where the soil has a chance to swell, can be considerably lower than those reported here (Ritchie et al. 1972). At more negative Ψ_{supply}, where macropores were not active, infiltration rates were greatest for soils dominated by sand.

The fractions of total water flux contributed by macropores and mesopores were much greater than the fraction of water flux contributed by micropores. For the 96 soil horizons measured, macropores (pores with sizes > 0.5 mm) occupied 3% of the porosity, but contributed 77% of the total water flux (Table 2). Mesopores (pores with sizes < 0.5 mm but > 0.06 mm) accounted for 10% of the porosity and contributed 19% of the total water flux, while micropores (pores < 0.06 mm) dominated the soil's total porosity, but contributed only 5% of the total water flux.

Among three broad textural groups, clays (clay, silty clay, and sandy clay), loams (clay loam, silty clay loam, sandy clay loam, loam, silt loam, and sandy loam) and sands (sands and loamy sands), macropores generally showed greatest influence on water flow in clays. Because of more uniform pore-size distribution, flow in coarse-textured soils was more evenly transmitted through various sizes of pores. Shrinkage cracks, well-developed pedality, plant roots, animal burrows, and tillage impacts were more common in many of the clayey soils. Greater spatial and temporal variability also existed in clayey soils.

Values of α increased as Ψ_{supply} approached 0 (Fig. 2), thereby demonstrating the inadequacy of a one-line form of Eq. 3 in the description of $K(\Psi)$ in structured soils. Like both Keng and Lin (1982) and Jarvis and Messing (1995) suggested, if Eq. 3 were to be used to represent $K(\Psi)$ then it must be used in a piecewise manner. Jarvis and Messing (1995) suggested a break-point potential between –0.025 and –0.06 m for a two-line exponential model. While our data could be used to support a two-line model, it is obvious that increasing the number of segments in the $K(\Psi)$ relationship will improve the fit.

For repacked laboratory soils, values of α are commonly in the range of 0.8 to 16 m^{-1} [λ_m from 0.06 to 0.12 mm; see

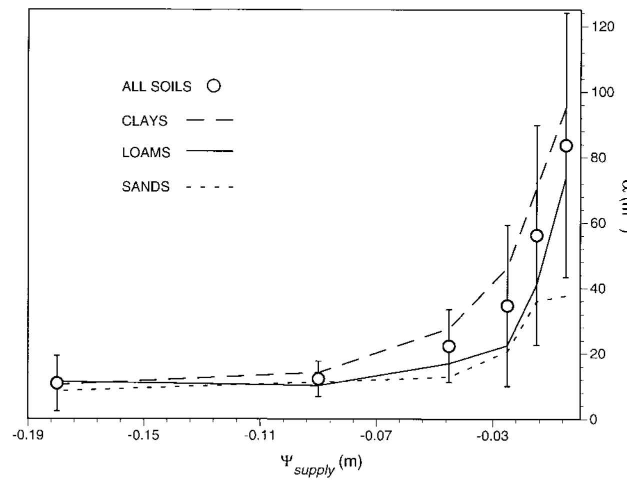

Fig. 2. Relationship between α (from Eqs. 3 and 4) and supply water potential for all soils and three textural classes. The larger the value of α the larger the mean hydraulically effective pore size. Error bars represent one standard deviation in each direction.

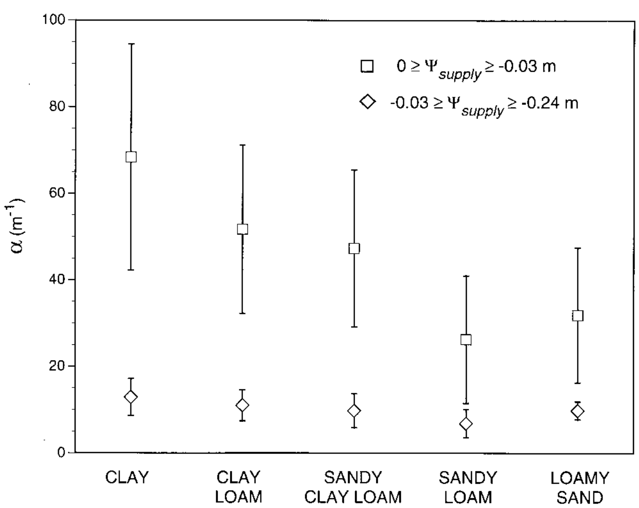

Fig. 3. Variation of α with soil texture and at two supply water potential ranges. The larger the value of α the larger the mean hydraulically effective pore size. Error bars represent one standard deviation in each direction.

Philip (1983) and White and Sully (1987)]. Values of $\alpha_{\Psi>-0.03\ m}$ measured in the 96 soil horizons were well above this range, i.e., λ_m ranged from 0.5 mm for clays to 0.2 mm for sandy loams (Fig. 3). Other studies have shown that undisturbed field soils have higher α values than repacked materials (Bouwer 1966; White and Sully 1987, 1992). Values of α were close to those of repacked soils at lower Ψ_{supply}, i.e., λ_m range from 0.09 mm for clays to 0.05 mm for sandy loams, with α greater for clays than for loams, and greater for loams than for sands. As noted by White and Sully (1992), when Ψ_{supply} is close to zero, α values depend more on soil macrostructure and less on packing voids.

We examined the relationships between $\alpha_{\Psi>-0.03\ m}$ and some basic soil properties, and found significant (P = 0.001)

Table 3. Values of λ_m among textural groups at tension-based pore-size limits

$-0.015/\Psi_{supply}$	λ_m ($7.3 \times 10^{-3}\alpha$)			
Active pore size (mm)	All soils	Clays	Loams	Sands
	(mm)			
≤ 0.13	0.08	0.08	0.08	0.06
≤ 0.25	0.09	0.10	0.08	0.08
≤ 0.5	0.17	0.20	0.13	0.10
≤ 0.75	0.26	0.34	0.17	0.15
≤ 1.5	0.42	0.52	0.30	0.27
< ∞[z]	0.62	0.70	0.55	0.28

[z]No size limit.

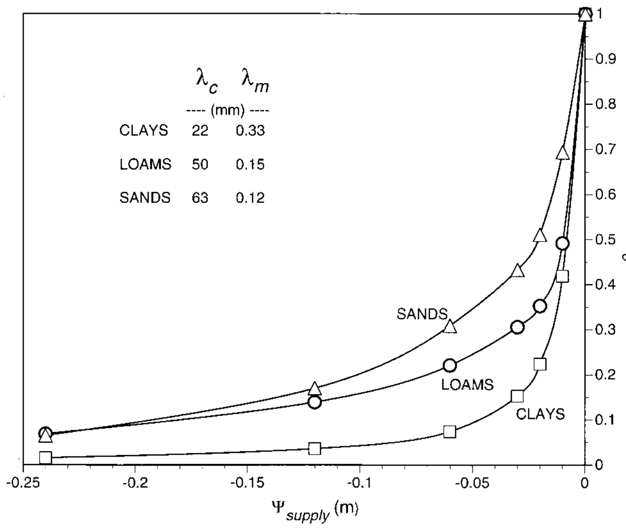

Fig. 4. Relative infiltration rates with supply water potential for three textural groups. Values of λ_c, hydraulic conductivity-weighted mean capillary water potentials, were calculated from Eq. 5 using trapezoidal integration. Values of λ_m, mean hydraulically effective pore sizes, were estimated as $7.3 \times 10^{-6}/\lambda_c$.

positive correlations between $\alpha_{\Psi > -0.03\ m}$ and soil macroporosity (r = 0.550), mass fraction of clay (r = 0.386) and organic carbon content (r = 0.458). This may be explained by increased aggregation and/or improved structure with increased clay and organic carbon contents in soil. The correlation between $\alpha_{\Psi > -0.03\ m}$ and percent sand was negative (r = –0.389). The relationship between $\alpha_{\Psi > -0.03\ m}$ and soil texture implies that well-structured, fine-textured soils have a greater tendency for by-pass flow than coarse-textured soils.

A linear relationship was observed between α and $-1/\Psi_{supply}$. Piecewise values of λ_m were less than the largest pore size included in flow (Table 3). Integral values of λ_c from Eq. 5 were greater for sands than for loams, and greater for loams than for clays (Fig. 4). When λ_c is viewed as a K-weighted capillary fringe height for drainage calculations (Meyers and van Bavel 1963), trends of λ_c with texture are opposite of trends of non-K-weighted capillary fringe heights with texture.

In conclusion, most of the soils chosen from the Claypan Area, Blackland Prairies and Coast Prairie Major Land Resource Areas of Texas showed hydraulic characteristics associated with by-pass flow. Low-tension water fluxes were governed by large pores that occupied only a small fractions of the soils' total porosities. The mean hydraulically active pore size at Ψ_{supply} = 0 m, where all pores were potentially active, was about 0.3 mm for clays and 0.1 mm for sands. On average, changes in infiltration with Ψ_{supply} were greater for clays than for loams, and greater for loams than for sands. Weakly sorbed contaminants applied or spilled on most of the soils studied would have short resident times in the root zone once they entered into the by-pass flow. Conversely, nutrients and chemicals not adjacent to the by-pass flow may have relatively long resident times.

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